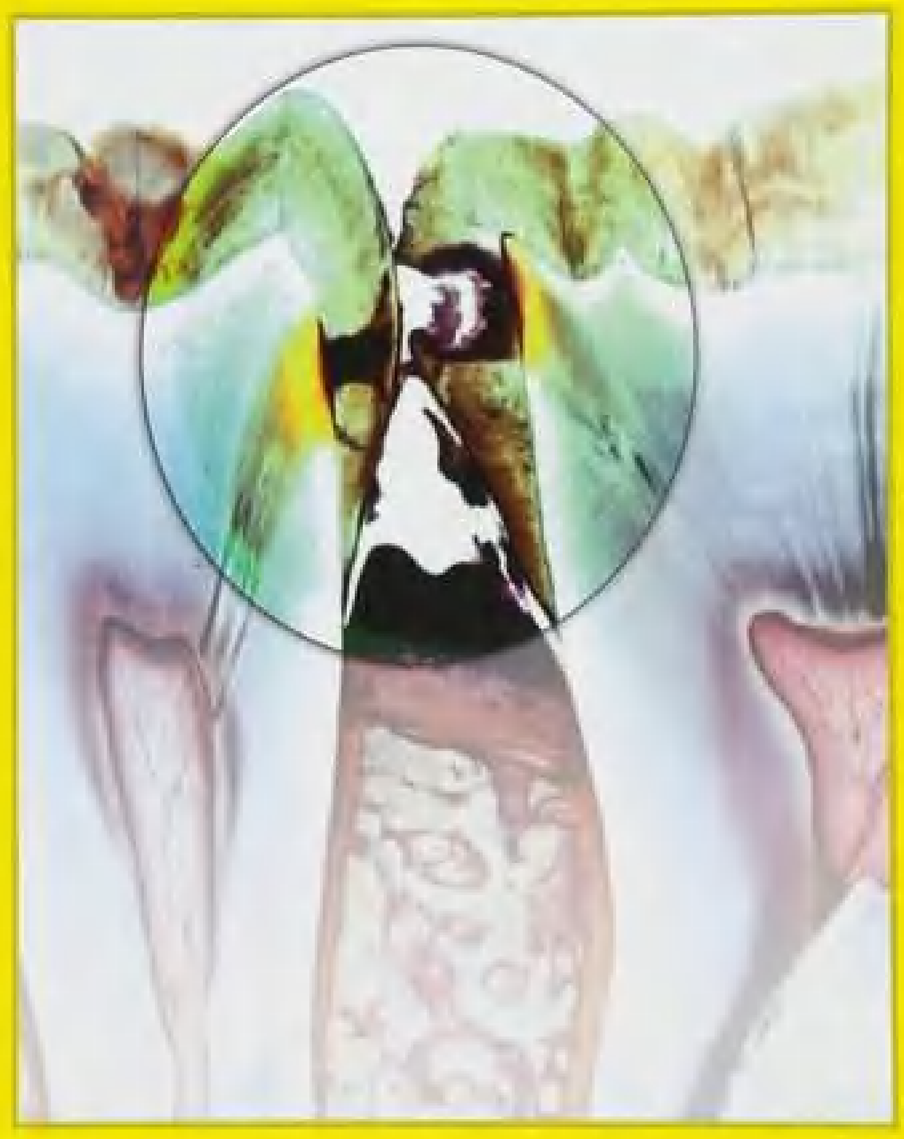
Dental Caries

The Disease and Its Clinical Management

Third Edition



Edited by
Ole Fejerskov, Bente Nyvad and Edwina Kidd

WILEY Blackwell

Dental Caries

Dental Caries

The Disease and Its Clinical Management

Third Edition

Edited by
Ole Fejerskov, Bente Nyvad,
and Edwina Kidd

WILEY Blackwell

This edition first published 2015
© 2015 by John Wiley & Sons, Ltd
© 2003, 2008 by Blackwell Munksgaard Ltd

Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Offices
9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
1606 Golden Aspen Drive, Suites 103 and 104, Ames, Iowa 50010, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell

The right of the author to be identified as the author of this work has been asserted in accordance with the UK Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

The contents of this work are intended to further general scientific research, understanding, and discussion only and are not intended and should not be relied upon as recommending or promoting a specific method, diagnosis, or treatment by health science practitioners for any particular patient. The publisher and the author make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of medicines, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each medicine, equipment, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. Readers should consult with a specialist where appropriate. The fact that an organization or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organization or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

Library of Congress Cataloging-in-Publication Data
Dental caries (Fejerskov)
Dental caries : the disease and its clinical management / edited by Ole Fejerskov, Bente Nyvad, Edwina Kidd. – Third edition.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-1-118-93582-8 (cloth)
I. Fejerskov, Ole, editor. II. Nyvad, Bente, editor. III. Kidd, Edwina A. M., editor. IV. Title.
[DNLM: 1. Dental Caries–diagnosis. 2. Dental Caries–therapy. 3. Dental Restoration, Permanent. WU 270]
RK331
617.6'7–dc23

2014046642

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Set in 10/12pt Minion Pro by SPi Publisher Services, Pondicherry, India
Printed and bound in Singapore by Markono Print Media Pte Ltd

1 2015

Correct citation of this text:

Fejerskov, O., Nyvad, B. & Kidd, E. (eds) (2015) *Dental Caries: The Disease and its Clinical Management*, 3rd Edn. Oxford, Wiley Blackwell.

Contents

Part I Dental caries: what is it and how widespread is it globally?

Part II The caries lesion and its biological determinants

Part III Diagnosis

Part IV Controlling dental caries

Part V Operative intervention

Part VI From chair-side to population caries control

Contributors

Professor Vibeke Baelum
School of Dentistry
Health
Aarhus University
Aarhus, Denmark

Associate Professor Allan Bardow
School of Dentistry
Faculty of Health Sciences
University of Copenhagen
Copenhagen, Denmark

Dr Habib Benzian
University College London and
The Health Bureau Ltd
Milton Keynes, UK

Associate Professor Lars Bjørndal
School of Dentistry
Faculty of Health Sciences
University of Copenhagen
Copenhagen, Denmark

Professor S. Ross Bryant
Faculty of Dentistry
University of British Columbia
Vancouver
British Columbia, Canada

Professor Frédéric Cuisinier
Université Montpellier 1
Montpellier, France

Professor Jaime A. Cury
Piracicaba Dental School
University of Campinas – UNICAMP
Piracicaba, SP, Brazil

Professor Ole Fejerskov
Department of Biomedicine
Health
Aarhus University
Aarhus, Denmark

Professor Jo Frencken
College of Dental Sciences
Radboud University Medical Centre
Nijmegen, The Netherlands

Professor Hans-Göran Gröndahl
Institute of Odontology
Sahlgrenska Academy
University of Göteborg
Göteborg, Sweden

Professor Hannu Hausen
Institute of Dentistry
University of Oulu
Oulu, Finland

Associate Professor Hanne Hintze
School of Dentistry
Health
Aarhus University
Aarhus, Denmark

Dr Christopher Holmgren
Aide Odontologique Internationale
Merigny, France

Dr Marit Jøssing
Chief Dental Officer
Odder Municipal Dental Service
Denmark

Dr Heather Keller
Department of Nutrition and Aging
University of Waterloo
Waterloo
Ontario, Canada

Professor Edwina A.M. Kidd
Emerita, Dental School
King's College
London, UK

Professor Mogens Joost Larsen
Emeritus, School of Dentistry
Health
Aarhus University
Aarhus, Denmark

Professor Peter Lingström
Institute of Odontology
Sahlgrenska Academy
Göteborg University
Göteborg, Sweden

Professor Adrian Lussi
School of Dentistry
University of Bern
Bern, Switzerland

Professor Michael I. MacEntee
Faculty of Dentistry
University of British Columbia
Vancouver
British Columbia, Canada

Professor Vita Machiulskiene
Faculty of Odontology
Lithuanian University of Health Sciences
Kaunas, Lithuania

Professor Valeria C. Marinho
Institute of Dentistry
Barts and The London School of Medicine and Dentistry
Queen Mary University of London (QML)
London, UK

Professor Philip D. Marsh
Microbiology Services Division
Public Health England
Salisbury, and
School of Dentistry
University of Leeds
Leeds, UK

Dr Bella Monse
Fit for School Regional Programme
German Development Corporation (GIZ)
Manila, Philippines

Dr Caroline T. Nguyen
Faculty of Dentistry
University of British Columbia
Vancouver
British Columbia, Canada

Professor Bente Nyvad
School of Dentistry
Health
Aarhus University
Aarhus, Denmark

Dr Niek J.M. Opdam
University of Nijmegen Medical Centre
Nijmegen, The Netherlands

Professor Fernanda Critina Petersen
Faculty of Dentistry
University of Oslo
Oslo, Norway

Associate Professor Vibeke Qvist
School of Dentistry
Faculty of Health and Medical Sciences
University of Copenhagen
Copenhagen, Denmark

Scientist PhD Håkon Valen Rukke
Nordic Institute of Dental Materials
Oslo, Norway

Professor Anne Aamdal Scheie
Faculty of Dentistry
University of Oslo
Oslo, Norway

Professor Vera Mendes Soviero
Faculty of Dentistry
University of the State of Rio de Janeiro
Rio de Janeiro, Brazil

Professor Christian H. Splieth
School of Dentistry
University of Greifswald
Greifswald, Germany

Professor Nobuhiro Takahashi
Division of Oral Ecology and Biochemistry
Tohoku University Graduate School of Dentistry
Sendai, Japan

Associate Professor Livia M.A. Tenuta
Piracicaba Dental School
University of Campinas – UNICAMP
Piracicaba, SP, Brazil

Professor Cor van Loveren
Academic Centre for Dentistry Amsterdam (ACTA)
University of Amsterdam and VU University Amsterdam
Amsterdam, The Netherlands

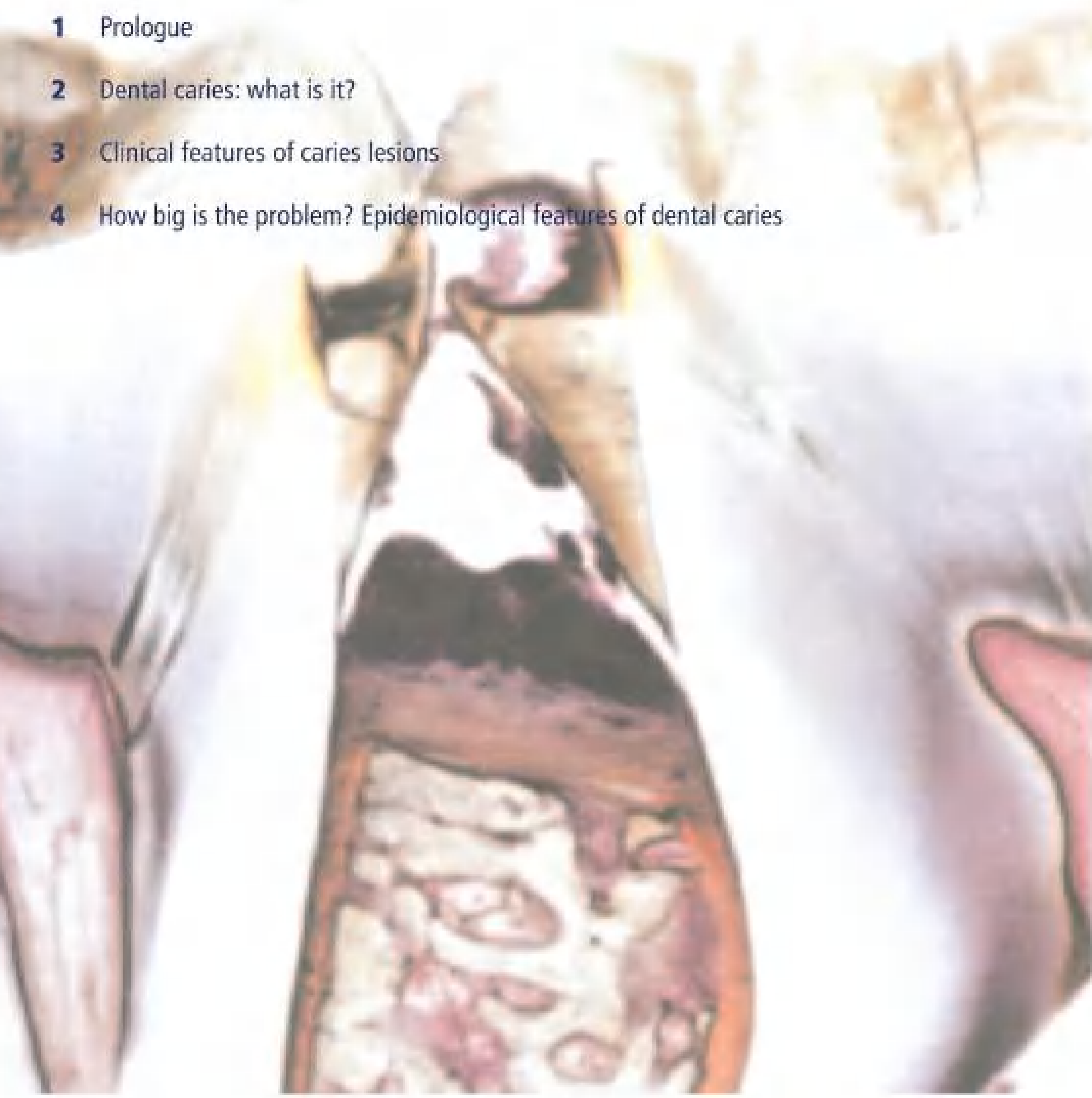
Professor Wim van Palenstein Helderman
Dental Health International Netherlands
Linschoten, The Netherlands

Professor Arjan Vissink
University Medical Center Groningen
Groningen, The Netherlands

Dr Chao Shu Yao
Q & M Dental Group
Singapore

Part I

Dental caries: what is it and how widespread is it globally?



1

Prologue

O. Fejerskov, B. Nyvad, and E.A.M. Kidd

Introduction

Dental caries is ubiquitous – it is omnipresent in all populations and is as old as mankind. The caries incidence rate varies extensively between and within populations. With increasing age, signs and symptoms of dental caries accumulate, and in most adult populations the caries prevalence approaches 100%. Prevention and operative treatment of caries lesions and its sequelae occupy the majority of the dental profession lifelong around the world, and the cost of dental health care is a major societal burden.

The majority of dental restorations are made because of dental caries. Caries and failed restorative care are the main causes for tooth loss in all contemporary populations. So, it is hopefully obvious that there are good reasons for advancing an international textbook on *Dental Caries: The Disease and Its Clinical Management*.

It has been a great pleasure for us that the first two editions of this book have found their way all over the world. In the genesis of this third edition, we have realized that Edwina Kidd has been emerita professor for several years and soon Ole Fejerskov will follow, so it is time for a new generation to take over. Therefore, Professor Bente Nyvad is now a full member of the editorial team.

From the first to the second edition, the book 'put on weight,' becoming much more extensive. However, we have no wish for it to become 'morbidly obese' by continuing to add to the length of text and topics. Rather, we have aimed in this third edition to make a 'slimmer' volume that hopefully makes it more readable for the main target, dental students and practitioners in public health and dental practice. We have invited 34 international colleagues to join us, many of whom are new, to ensure both continuity and novelty in lines of thinking throughout the book.

The role of cariology in restorative dentistry

The content of the book reflects our wish to make the basic knowledge about the bio-physiology of the oral cavity and dental caries applicable in daily clinical practice. When G.V. Black published his comprehensive textbook in 1908 he emphasized that clinical diagnosis and treatment decisions should have a sound biological rationale. Although it became appreciated by the middle of the 20th century that dentistry is a biomedical speciality, the technical advances with high-speed drilling and so on distorted the true application of biological knowledge in optimal treatment of dental caries.

Dental caries became synonymous with 'a cavity' in the tooth – and the automatic reaction was that the treatment should be 'drill and fill.' In the growing field of caries epidemiology, dental caries was recorded as DMF teeth/surfaces, where D stood for decay and decay meant a cavity. The knowledge about etiology and pathogenesis of caries was

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

often taught in dental curricula in departments of microbiology, pathology, and physiology, as well as in the growing disciplines of the 1950s and 1960s of dental public health and departments of pediatrics and preventive dentistry – but the clinical relevance of 'cariology' in restorative clinical departments was unusual, and knowledge to be applied at the chair-side fragmented. To some extent this was understandable, because in a clinical department the students were supposed to produce fillings, and crowns and bridges. *So the appreciation of the need for a concomitant disease control as part of any long-term successful restorative treatment was limited.*

The Keyes so-called triad stressed the components as being: (1) the tooth, (2) the diet, and (3) the microflora.

1. **The tooth.** In the last half of the 20th century much focus in caries research was on improving the 'resistance' of the tooth. Logically, there was an enormous interest in the role of fluoride in the prevention and control of dental caries. There were many attempts to introduce artificial water fluoridation worldwide in order to repeat the very impressive caries reduction that Trendley Dean and collaborators had documented in the USA. However, it proved difficult in many populations to introduce systemic fluoride programs, and by 1980 it became evident that the mechanism of action of fluoride in caries control was not a result of improving enamel resistance. Thus, the topical use of fluoride started to play a key role, particularly fluoride added to toothpaste.
2. **The diet.** The role of sugar in caries development had become evident by the middle of the 20th century,and much effort was invested in trying to reduce the intake, not least in children – with limited success. Total sugar consumption per capita stayed fairly constant and sugar substitutes were introduced. Then the dramatic caries decline became well documented, in particular in the Nordic countries, apparently without a significant reduction in total sugar consumption. So the relative role of diet was reconsidered.
3. **The microflora.** It was well known that 'a clean tooth never decays' – but the consequence of this statement was seldom fully appreciated. When rodent experiments around 1960 clearly indicated that dental caries was 'an infectious and transmittable disease,' extensive research focused on identifying one responsible microorganism – the caries pathogen. In the past, *Lactobacillus acidophilus* had been seen as the main bacterium causing caries, but the focus shifted towards mutans streptococci. This even led to attempts to introduce a caries vaccine against *Streptococcus mutans*! Extensive research was carried out without appreciating that there is a significant difference between the behavior of bacteria in a planktonic (free-floating) phase and the concept of oral ecology, where the single microorganism is part of a complex oral microflora composed of more than 1000 different species. This was the focus around the turn of the century, where, gradually, dental plaque came to be considered an oral biofilm and dental caries seen as a biofilm-induced demineralization of the dental hard tissues.

But even at this stage many questioned the role of tooth cleaning in caries control!

This somewhat simplified overview of the major trends in dental caries research over the last 50 years is important because it will hopefully help new readers to understand how the very different concepts and 'paradigms' of today are influenced by historical tradition. The way in which scientific literature is selected and interpreted and its results introduced into diagnosis, prognostic assessments, treatment decisions, prevention, and public health strategies will profoundly influence *how* successful the dental profession will be in controlling dental caries and maintaining a functioning dentition in every patient from cradle to grave.

The content of this textbook

A textbook reflects the *way* in which the authors interpret scientific data on a given subject, but we do not pretend that this is the 'truth' about the complex disease called 'dental caries.' There are extensive data available on today's Internet, and the stream of information will continue to grow. This is an enormous challenge to clinical students and practitioners. How can sense be made of the bombardment of information? The authors have been asked to carefully present their respective subtopics so that it is not just a compilation of data, but selected data critically brought together in order to explain why dental caries presents itself in the individual and in populations in the way it does in today's world.

The *aim* of this book is to present the dental student and the dental practitioner with an update on the available knowledge about dental caries, and the consequences of this to its diagnosis, and how most appropriately and cost effectively to control caries progression. Clinical decision making and the balance between nonoperative and operative treatments become even more important parts of daily life in clinical practice. An understanding of the caries process is needed to estimate the prognosis of treatment procedures and the possibility of assessing the risk of disease development in individuals and populations.

This book will demonstrate that in real life the processes involved in dental caries are highly complex. In an ideal world there would be a perfect deterministic model that could relate all the potential determinants perfectly to caries outcome. It will appear throughout the book that most of the determinants that influence caries can, at best, be measured only as proxy variables. The most we can hope for, therefore, is to develop probabilistic models that relate determinants to risk of caries progression. However, even under such circumstances, caries would remain unpredictable. Such inputs as:

- variable exposure to fluoride,
- times, lengths, frequencies, and types of sugar consumption,
- quality of tooth cleaning,
- fluctuations in salivary flow rates and composition,
- quality and composition of biofilms,
- the behavior of the individual, and
- the societal context of the individual

are themselves highly variable. It is likely that this variability and unpredictability of the inputs may play a crucial role in the way in which the caries process develops. But all these factors make up the fascination and challenge of our profession.

It is our hope that this book will prepare the reader to become a less dogmatic and more knowledgeable health professional who strives to control dental caries in the most cost-effective way.

The *content* of the book is organized according to our wish to link theory with clinical performance. In other words, making prevention, diagnosis, and restorative procedures evidence based.

In Chapters 2–4 we define what dental caries is and how it most often manifests itself on different tooth surfaces. Then we ask the question 'How big is the caries problem in different parts of the world?' and present basic epidemiological tools.

Part II, 'The caries lesion and it biological determinants' (Chapters 5–9), basically covers the aspects of the Keyes triad. Then this knowledge is applied in Part III, 'Diagnosis' (Chapters 10–12), and Part IV, 'Controlling dental caries' (Chapters13–18). When caries lesions require 'Operative intervention' (Part V, Chapters 19–21), biological knowledge is essential to provide the most careful intervention and not to make unnecessary replacement of restorations. Finally, Part VI, 'From chair-side to population caries control' (Chapters 22–25), brings the principles of dealing with the single tooth surface or the individual patient forward by approaching caries control in whole populations of different kinds. Moreover, this part addresses the very important questions about risk assessment versus prediction. In the final chapter we ask the question: If we were to apply the knowledge we have today on how to control dental caries most cost-effectively in various parts of the world and maintain a functional dentition lifelong, what recommendations would we then formulate?

We hope you will enjoy the book – and interact with us, whether agreeing or disagreeing. As Charles Darwin said: 'All observations must be for or against some view to be of any service.'

2

Dental caries: what is it?

O. Fejerskov, B. Nyvad, and E.A.M. Kidd

The disease

The term *dental caries* is used to describe the results – the signs and symptoms – of a localized chemical dissolution of the tooth surface caused by metabolic events taking place in the biofilm (dental plaque) covering the affected area. The destruction can affect enamel, dentin and cementum. The lesions may manifest themselves clinically in a variety of ways, as will be dealt with in Chapter 3.

In principle, dental caries lesions may develop at any tooth site in the oral cavity where a biofilm develops and remains for a period of time. It is therefore a misconception to talk about more- or less-susceptible surfaces as this may erroneously give rise to the belief that certain parts of a tooth are more 'resistant' or 'less susceptible' to developing caries lesions due to variations in the chemical and structural composition [1, 3].

This is not to say that all tooth surfaces within the oral cavity of an individual develop caries lesions at the same rate. Dental caries lesions develop at relatively 'protected' sites in the dentition where biofilms (dental plaque) are allowed to accumulate and mature over time. Such sites include pits, grooves, and fissures in occlusal surfaces, especially during eruption, approximal surfaces cervical to the contact point/area, and along the gingival margin. Obviously, insertion of foreign bodies to the dentition (e.g., fillings with inappropriate margins, dentures, orthodontic bands) may also result in such 'protected' sites. These areas are relatively protected from mechanical influence from the tongue, the cheeks, abrasive foods, and, not least, toothbrushing. Thus, these are the sites where lesion development is more likely to occur because the biofilm is allowed to stagnate there for prolonged periods of time.

This knowledge is very important, and it is 100 years ago that Black [1] stated:

> *...the beginning of caries of the teeth occurs at such points as will favour such lodgement or attachment in which the microorganisms will not be subject to such frequent dislodgement as would prevent a fairly continuous growth. This is the cause of the localisation of the beginnings of caries on particular parts of the surface of the tooth.*

Dental caries lesions, furthermore, do not develop at the same rate in all parts of the mouth. Thus, openings of the major salivary glands represent areas with a special salivary composition that favors a relative protection towards chemical dissolution because of buffering capacity and chemical composition of the secretory product (see Chapter 6).

Dental caries lesions result from a shift in the ecology and metabolic activity of the biofilm (Chapter 7) whereby an imbalance in the equilibrium between tooth mineral and biofilm fluid has developed. It is important to appreciate that an oral biofilm, which forms and grows ubiquitously on solid surfaces in the oral cavity, does not

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

necessarily result in the development of *clinically visible* caries lesions when grown on dental hard tissues. Thus, a biofilm grown on tooth enamel inserted in palatal devices (so-called in-situ models) has to be 'protected' from abrasion from the tongue movement. Similarly, in-situ models for studying caries lesion development under controlled conditions have preferably to be located so that microbial stagnation areas are created. But the biofilm is a prerequisite for caries lesions to occur. The biofilm is characterized by continued microbial activity, resulting in metabolic events in the form of continuous, minute pH fluctuations. The metabolism may be dramatically enhanced by changing the nutritional conditions (e.g., by adding fermentable carbohydrates) and the outcome of the metabolism can be recorded as pH fluctuations. Any shift in pH will influence the chemical composition of the biofilm fluid and the relative degree of saturation of this fluid with respect to the minerals that are important for maintaining the chemical composition of the tooth surface (see Chapter 9). From the very moment of eruption into the oral cavity, the tooth surface apatite will continue to be subject to these chemical modifications on innumerable occasions. Most of these modifications are so subtle that they can only be recorded at the nano-level. Surfaces that are frequently covered by biofilm (e.g., a cervical enamel surface) will gradually accumulate fluoride in the very surface layers (outermost 100μm) (see Chapter 9, Fig. 9.11). Thus, the enamel surface is in a state of dynamic equilibrium with its surrounding environment. *When the cumulative result of the numerous pH fluctuations over months or years is a net loss of calcium and phosphate of an extent that makes the enamel sufficiently porous to be seen in the clinic, we may diagnose it as a 'white spot' lesion* (see Chapters 3 and 5). It is important to appreciate, however, that, although the metabolic events may result in detectable caries lesion formation, most sequences of metabolic events tend to cancel each other, which is why the metabolic events should be considered intrinsic to biofilm physiology (Chapter 7). The caries lesions arise when there is a drift in the metabolic events, that is, when the pH drops result in a net loss of mineral. Thereby, *the dental caries lesions are a result of an imbalance in physiologic equilibrium between tooth mineral and biofilm fluid.*

These considerations lead to some important points.

- The dissolution (demineralization) when pH drops below a certain level in the biofilm and the redeposition (remineralization) of minerals when pH goes up (see Chapter 9) takes place in the enamel surface at the interface between the biofilm and the tooth surface. These processes occur numerous times during a day and can be modified extensively. If, for example, the biofilm is partly or totally removed, mineral loss may be arrested or even reversed towards mineral gain because saliva is supersaturated with respect to the enamel apatite. This will result in arrest of disease progression – and may even result in some redeposition of minerals in the very surface of the tooth.
- Any factor that influences the metabolic processes, such as the composition (e.g., content of buffering proteins) and thickness of the biofilm, the salivary secretion rate and composition (Chapter 6), the diet (Chapter 8), and the fluoride ion concentration in the oral fluids (Chapters 9 and 13), will contribute to the likelihood of a net loss of mineral – and the rate at which this occurs. Figure 2.1 indicates how the many biological determinants of the caries process may act at the level of the individual tooth surface (inner circle). At the individual/population level (outer circle) the behavior, education, knowledge, and attitudes will have a strong influence on some of the biological determinants (quality of oral hygiene, choice of foods, use of fluorides, salivary flow from chewing gum, etc.).
- At any given point in time the net mineral loss or gain is part of a continuous spectrum of events. The absence of a clinically detectable caries lesion does not necessarily

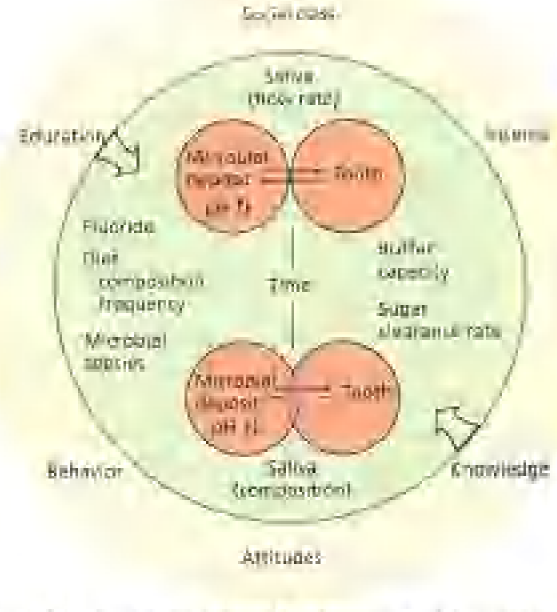


Figure 2.1 Schematic illustration of the determinants of the carious process. Those that act at the tooth surface level are found in the inner circle. With time, an ecological shift in the composition and metabolic activity of the biofilm ('microbial deposit') may result in an imbalance in the equilibrium between biofilm fluid and the mineral of the tooth. Thus, a net loss of mineral results in formation of a caries lesion (overlap of the two small circles). In the outer ring are listed more distant determinants that influence these processes at the individual and population levels. Adapted from [2]. Reproduced with permission of the University of North Carolina School of Dentistry.

mean that no mineral loss has occurred (Chapter 5), it only means that it could not be discerned clinically. If this concept of a continuum is appreciated it will immediately be understood why diagnosis of various stages of lesion progression is a question of *defining* certain 'cut-off' points (Chapter 4).

Terminology

Caries lesions may be classified in a number of ways. Unless the student is familiar with this terminology it can be difficult to understand what is written. This section introduces and defines various terms that will trip off the writers' pens in subsequent chapters.

Carious lesions can be classified according to their *anatomical site*. Remember, there is nothing chemically special about these sites. Thus, lesions may commonly be found in *pits and fissures* or on *smooth surfaces*. Smooth surface lesions may start on enamel (*enamel caries*) or on the exposed root cementum and *dentin* (*root caries*).

Primary caries is used to differentiate lesions on natural, intact tooth surfaces from those that develop adjacent to a filling, which are commonly referred to as *recurrent* or *secondary caries*. These two latter terms are synonyms, but in this textbook we will use the term *recurrent caries* throughout. Recurrent caries is simply a lesion developing at a tooth surface adjacent to a filling. As such, its etiology is similar to primary caries.

Residual caries (as the term implies) is demineralized tissue that has been left behind before a filling is placed.

An important classification is whether a lesion is *cavitated* or *noncavitated*. *A cavity is a physical hole in the tooth*, and it may impinge directly on the management of the lesion (Chapters 16 and 18).

Caries lesions may also be classified according to their activity. This is a very important concept and one that impinges directly on management, although it will be evident from the text that the clinical distinction between *active* and *inactive* (arrested) lesions is sometimes difficult.

A lesion considered to be progressing (you anticipate that the lesion would have developed further at a subsequent examination if not interfered with) would be described as an *active caries lesion*. This distinction is based on a judgment of the features of the lesion in question in combination with an assessment of the oral health status of the patient. In contrast to this is a lesion that may have formed *years* previously and then stopped further progression. Such lesions are referred to as *arrested caries lesions* or *inactive caries* lesions.

You may also meet the terms *remineralized* or *chronic lesions* used to signify arrested lesion; but, as you will appreciate later, the term remineralization should be used with caution (Chapters 5 and 9). The distinction between active and inactive/arrested lesions may not be totally straightforward. Thus, there will be a continuum of transient changes from active to inactive/arrested and vice versa. A lesion (or occasionally part of a lesion!) may be rapidly progressing, slowly progressing, or not progressing at all. This will be entirely dependent on the ecological balance in the biofilm covering the site and the environmental challenge. Clinically, if in doubt, the dentist should always react as if they are dealing with an active lesion.

Despite the diagnostic difficulties, these distinctions are very important to the clinician because if a lesion is not active then no action is needed to control further progression. If, on the other hand, a lesion is considered active, steps should be taken to influence the metabolic activities and possible the ecological balance in the biofilm in favor of arrest rather than further demineralization.

At this point it is also sensible to discuss a possible confusion in terminology. The first sign of a carious lesion on enamel that can be detected with the naked eye is often called a *white spot lesion*. This appearance has also been described as an early, *initial* or *incipient lesion*. These terms are meant to say something about the stage of lesion development. However, a white spot lesion may have been present for many years in an arrested state, and to describe such a lesion as early would be inaccurate. A dictionary definition of incipient is 'beginning', an initial stage. In other words, an initial lesion appears as a white, opaque change (a white spot) – but any white spot lesion is not incipient!

Rampant caries is the name given to multiple active carious lesions occurring in the same patient. This frequently involves surfaces of teeth that do not usually experience dental caries. These patients with rampant caries can be classified according to the assumed causality; for example, *bottle or nursing caries*, *early childhood caries* (ECC) when observed in children, and *bakers' caries*, *radiation caries*, and *drug-induced caries* when seen in adults. ECC is simply caries on teeth that are not clean, exposed to carbohydrates, and located in an area of the mouth where oral clearance is low (for details, see Chapter 16).

Hidden caries is a term used to describe lesions in dentin that are missed on a visual examination but are large enough and demineralized enough to be detected radiographically. It should be noted that whether a lesion is actually hidden from vision depends on how carefully the area has been cleaned and dried and whether an appropriate clinical examination has been performed.

Background literature

Baelum V, Fejerskov O. Caries diagnosis: 'a mental resting place on the way to intervention'? In: Fejerskov O, Kidd EAM, eds. *Dental caries. The disease and its clinical management*. 1st ed. Blackwell Munksgaard 2003: 101–10.

Fejerskov O. Changing paradigms in concepts on dental caries: consequences for oral health care. *Caries Res* 2004; 38: 182–91.

References

1. Black GV. *Operative dentistry*. Vol. 1. *Pathology of the hard tissues of the teeth*. London: Claudius Ash, Sons & Co. Ltd, 1914.
2. Fejerskov O, Manji F. Risk assessment in dental caries. In: Bader J, ed. *Risk assessment in dentistry*. Chapel Hill, NC: University of North Carolina Dental Ecology, 1990: 215–17.
3. Weatherell JA, Robinson C, Hallsworth AS. The concept of enamel resistance – a critical review. In: Guggenheim B, ed. *Cariology today*. Basel: Karger, 1984: 223–30.

3

Clinical features of caries lesions

O. Fejerskov and B. Nyvad

What do caries lesions look like clinically?

Dental caries lesions are the outcome or symptoms of innumerable metabolic events in biofilms which have covered a tooth surface. When this outcome results in a cumulative loss of mineral from the tooth of such a magnitude that the porosity in the enamel (see Chapter 5) gives rise to a decrease in enamel translucency we can diagnose white opaque lesions. Early stages in enamel lesion formation will therefore manifest themselves as white spot lesions. Because these are indicative of increased porosity of the enamel it is to be expected that food stain will sieve into the enamel, and hence a white spot lesion may over time change color to brown and even almost black.

The shape of the lesion reflects where the biofilm has been allowed to grow and remain for prolonged periods of time. In the days – not long ago – where children had no or very poor oral hygiene it was common to see 'kidney-shaped' lesions beneath contact facets proximally extending onto buccal and lingual surfaces as a band of dull, chalky white enamel along the gingival margin. With the much better oral hygiene in contemporary populations the extent of lesions is much reduced, and the shape will be determined by the particular shape of the stagnation area.

In the following we shall demonstrate a spectrum of manifestations of caries lesions in children, adults, and the elderly. Be aware that what you see here is photographed and magnified and reproduced at high quality. In the clinic, visual inspection is much more difficult! Therefore, we are devoting several chapters in this book to cover various aspects of diagnosis of dental caries lesions (Chapters 10–12) and in particular focus on what it means to learn good diagnostic practice (Chapter 12).

Most illustrations are of single teeth! But in the clinical situation you should never decide on a treatment by only considering a single tooth – the tooth is a part of an oral environment of a patient. The choice of treatment and the assessment of the prognosis of the dentition must be based on a 'total patient assessment'.

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

The deciduous dentition

Figures 3.1–3.8 Figure 3.1: A 3-year-old child with thick accumulations of dental plaque along the gingival margin of the buccal surfaces covering active caries lesions, some of which present with distinct cavities. Figure 3.2: Inactive/arrested caries lesions on buccal surfaces of upper central incisor teeth in a 5-year-old child. Note that the shape of the lesions indicates where the gingival margin was located at the time when these lesions developed. The oral hygiene has improved and the surfaces of these noncavitated opaque lesions are now smooth and shiny. Figure 3.3: Upper deciduous canine from a 5-year-old with an active, cavitated lesion along the gingival margin. On probing it would be soft, *but* there is no reason to probe such a lesion unless you wish to provoke a pain reaction! Figure 3.4: Upper incisors in a 5-year-old child. Several narrow, white opaque inactive caries lesions are located 1–2 mm from the gingival margins. One of the lesions exhibits a large cavity that is hard on probing. This is an example of an inactive, cavitated lesion. Figure 3.5: Deciduous first lower molar in a 2½-year-old child with two cavitated active caries lesions. Note the peripheral white, opaque rim of enamel surrounding the cavities. Figure 3.6: Lower first deciduous molars with active, cavitated lesions in the distal and disto-occlusal surfaces of a 6-year-old child. Figures 3.7 and 3.8: A 2-year-old child with extensive, active, partly cavitated caries lesions encircling the teeth. This is an example of so-called nursing bottle caries – or 'bottle caries.' Figures 3.1–3.8 courtesy of I. Mejare.

3.9

3.10

Figures 3.9 and 3.10 Slightly discolored lesions on approximal and buccal surfaces of an exfoliated deciduous molar. Note that the shape of the lesions reflects the areas where dental plaque has been retained above the position of the gingival margin. Note also the opaque kidney-shaped part of the approximal lesion cervically to the brown-stained center of the lesion in Fig. 3.9.

The permanent dentition

The free smooth surfaces

3.11

© Nyvad

3.12

© Nyvad

3.13

© Fejerskov

3.14

© Nyvad

Figures 3.11–3.14 Figure 3.11: Active, noncavitated carious lesion on lower second premolar. The shape is typical, as it follows the curvature of the marginal gingiva and corresponds to where a narrow band of dental plaque has been located in a stagnant area. The surface is dull and chalky. It is called a 'white spot lesion,' although it extends from the approximal amalgam filling all along the gingival margin. On the mesio-buccal surface of the lower first molar another noncavitated lesion has taken up brown stain. Note also the very thin lesion on the buccal surface of the first premolar along the gingival margin. Figure 3.12: Active, noncavitated carious lesion at lower second premolar with a typical banana-shape of the white, opaque lesion with the cervical border following the shape of the slightly inflamed marginal gingiva. A 1 mm rim of normal enamel between the lesion and gingiva indicates that the gingivitis, with swelling of the tissue, has been reduced as a result of attempts to control the oral hygiene. Note also the remains of a white opaque lesion on the lower first premolar along the mesial and distal margin of the amalgam filling. On the lower first molar a band of partly discolored, noncavitated lesion extends from an amalgam filling. This could be classified as secondary caries (recurrent caries), but is obviously the remains of a primary lesion. *Figure 3.13*: Arrested/inactive, noncavitated ('white spot') lesion on the lower first molar. The lesion exhibits a localized circular surface defect. The position of this lesion corresponds to where the marginal gingiva would have been at some stage during eruption of this tooth 30 years earlier. When viewing the lesion from different angles it is apparent that the surface is shiny and smooth, although the tip of a probe will clearly detect the defect (which is also hard). Figure 3.14: Extensive active, white, opaque and chalky buccal lesions which are noncavitated on the upper central incisors. A large superficial defect is seen on the upper right lateral incisor. Notice the obvious difference between the chalky, dull appearance of the carious lesion along gingiva and the creamy appearance of the white, opaque hypomineralized lesion of developmental origin (impaired enamel maturation) on the incisal third of this tooth. If a probe tip is moved gently across the surface, an obvious difference in surface texture is felt between the smooth (and shiny) surface of the developmental defect and the chalky texture of the carious lesion.

Approximal smooth surfaces

Figures 3.15–3.21 Figure 3.15 and 3.16: Active, noncavitated 'early white spot' lesions on mesial surfaces of upper and lower first molars are easily observed following shedding of primary teeth. The shape of each lesion indicates the stagnant areas where the biofilm (dental plaque) remained undisturbed. In the most demineralized areas in the center of the lesions, the porous enamel has taken up stain. The lesion in Fig. 3.15 was treated nonoperatively and has remained as an inactive, noncavitated lesion for almost 35 years! Figure 3.17: Active, discolored lesion on first molar with small cavity containing microbial deposits (dental plaque). Figure 3.18: Different stages of active, cavitated lesions in upper premolars. Note that undermined enamel in the second premolar is reflected by a yellow-whitish translucency of the enamel. Figures 3.19–3.21: Approximal lesions may be difficult to detect by direct visual inspection (Fig. 3.21), but inactive, severely discolored lesions can easily be diagnosed once the neighboring tooth is extracted (Figs 3.19 and 3.20).

Figures 3.22–3.26 Figures 3.22 and 3.23: In incisors, approximal lesions are easily discerned either directly or by reflected light, as shown in the distal surfaces of the incisors (Fig. 3.22). The cervical black rim of discoloration is a result of cigarette smoking and can be removed by polishing. Figures 3.24 and 3.25: In the premolar and molar regions it is much more difficult to see approximal lesions by direct inspection, even with careful training and experience. In this example the cavity in the first premolar came as a surprise, considering the relatively shallow enamel lesion recorded on the bitewing radiograph – a so-called iatrogenic damage when the dentist was drilling in the neighboring tooth. Figure 3.26: Even extensive active, cavitated lesions can remain difficult to detect until the adjacent tooth is lost. Such lesions may, however, reveal themselves by a bluish or yellowish discoloration of the undermined occlusal enamel ridge – compare with Fig. 3.18.

Figures 3.27 and 3.28 Dental caries is a local destructive lesion that, if not controlled or treated operatively, will continue to progress until the entire crown is destroyed and the lesions penetrate further into the root dentin.


3.29


3.30


3.31


3.32


3.33


3.34


3.35


3.36

Figures 3.29–3.36 Figure 3.29: Parts of the irregular occlusal surface in molars represent plaque stagnation areas and hence predispose to lesion development. Active, noncavitated lesions appear as chalky white, opaque lesions along the groove, fossa, pits and fissure systems. Figure 3.30: In the clinic the plaque must be removed gently from the occlusal surface either with a brush or explorer as otherwise this active, noncavitated lesion might not be seen. Figures 3.31 and 3.32: Arrested, noncavitated lesions often present as darkly stained pits and fissures. In Fig. 3.32, the cloudy, opaque areas in the premolars with a shiny enamel surface on cusps and enamel ridges represent dental fluorosis. Figures 3.33 and 3.34: Active carious lesions with small and large cavities. Note in Fig. 3.34 how the enamel appears bluish along the fissures as a result of the undermining nature of the occlusal caries lesions. When opened with a bur the occlusal surface is likely to show substantial destruction of the dental tissues. Figure 3.35: Active carious lesion with large cavity extending deep into dentin. Figure 3.36: Arrested occlusal caries lesion. The partly undermined enamel margins have been fractured and abraded away by mastication, and the dental plaque in the dentin cavity has been removed because the surface is in functional occlusion. The dark-brown dentin is hard and painless.

Occlusal caries lesions

Figures 3.37–3.43 The figures demonstrate lesions that clinicians had misdiagnosed as an arrested lesion and sound. The lesions might be easy to miss unless the tooth surface is absolutely well illuminated and dry. The radiographs in both cases demonstrate extensive radiolucent areas in the occlusal dentin indicative of rather deep carious lesions (Figs 3.38 and 3.40). The bluish appearance of the disto-lingual cusp in Fig. 3.37 should make the clinician aware of a possible undermining larger lesion. Likewise, there is an obvious cavity in the central fossa in Fig. 3.39. These cases represent examples of so-called hidden caries because the dentist had overlooked the clinical signs of lesions and the patient had not complained of any symptoms. The fact that these patients had otherwise very few fillings, and no other signs of active or arrested carious lesions despite being 18–20 years old, probably led the dentists to perform a more superficial dental examination. Figures 3.41–3.43: Example of an inactive occlusal lesion that the dentist assumed to be in need of operative treatment. The lesion in both enamel and dentin was hard on probing and in fact did not extend far into the dentin.

Root-surface caries

Figures 3.44–3.49 Anywhere on root surfaces where dental plaque accumulates (along the cervical margin at the enamel–cementum junction and along the gingival margin), active root surface lesions may develop with or without distinct cavities. Cavities may be soft (Fig. 3.46) or leathery (Fig. 3.47) and partly filled with microbial deposits. The color of the lesions may vary from yellowish to brownish or black. Figure 3.48: Meticulous oral hygiene can arrest root surface caries lesions and make the root surface appear shiny, although small surface cavities may remain. Arrested root surface lesions feel hard on gentle probing and show a brownish or black discoloration. Figure 3.49: Root surface lesions in the transition stage from active to arrested often exhibit a dull, leathery appearance. Lesion arrest is often a slow process that continues over years. The changes comprise surface abrasion and polishing, as well as mineral uptake (see Chapter 5).

Figures 3.50–3.53 These cases represent a dentist's nightmare! There are extensive active root surface caries lesions. Figs 3.50 and 3.51 show a patient who has undergone radiation of the head and neck. Although only very small amounts of biofilm can be seen, the lack of saliva results in extensive cervical and approximal active caries lesion. Note how the enamel is undermined along the cavity margins. The patient in Figs 3.52 and 3.53 had received antidepressants for a long time and presented with heavy soft microbial deposits on all exposed root surfaces. These teeth are very difficult if not impossible to restore. Figure 3.53 shows the patient at 4 months following intensive plaque control with a fluoride toothpaste. The lesions are now mostly arrested. The previously soft surface is leathery to hard, and from a biological point of view restorative dentistry has no role to play. Any restorative treatment would still be difficult, even using contemporary adhesive materials. Restorations might help the patient to improved cosmetics, but they would not contribute to better tooth survival – rather the opposite.

Figures 3.54–3.59 Examples of caries sequelae. The total destruction of the crows of a tooth may result in a local pyogenic granuloma of the gingiva (Fig. 3.54). In Fig. 3.55 the pulpal tissue has survived but is freely exposed to the oral cavity and covered by squamous epithelium (pulpal polyp). Most often, untreated dental caries results in necrosis of the pulp and development of a periapical abscess that may penetrate the bone to the oral cavity (Fig. 3.56) or in rare cases even directly to the surface of the skin (Figs 3.57, 3.58, and 3.59). The abscess from the lower central incisor has penetrated the mandible and pus is emptied regularly through a fistula. As long as the duct of the fistula remains open there is hardly any pain.

4

How big is the problem? Epidemiological features of dental caries

V. Baelum and O. Fejerskov

Introduction

Epidemiology is the scientific discipline that studies the distribution and determinants of health problems in populations and seeks to apply the results to the control of health problems. Thereby, epidemiology seeks to describe the *what*, *who*, *where*, *when*, and *why/how* of health problems and events, such as caries lesion formation (Box 4.1).

In this chapter we will review key aspects of the epidemiology of dental caries with a main emphasis on describing the caries occurrence. Descriptive caries epidemiology is concerned with the assessment of caries in relation to *what* (case definitions), *who* (person), *where* (place) and *when* (time/trends), whereas the *why/how* aspect is the key question for analytical caries epidemiology.

What? Defining the health issue at hand

In Chapter 2, dental caries was defined as the result of a localized chemical dissolution of a tooth surface resulting from metabolic events in a biofilm (dental plaque) on the tooth surface. Taking this definition to the ultimate would lead us to conclude that caries is present whenever a calcium phosphate crystal has been dissolved from the enamel. We also know that the actual state of the tooth surface at any given time point is determined as the net result of a dynamic process in which events of dissolution and remineralization are alternating (see Chapter 9). When there is no drift in this process – that is, no long-lasting trend favoring one or the other type of event – we need not be the least concerned. In the absence of a drift, the process is self-limiting and the degree of demineralization or remineralization (calculus

Dental Caries: The Disease and its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

What:	*Health issue of concern* – for many diseases there is no global consensus on the defining criteria for the disease. The study of disease epidemiology, therefore, necessitates a *clear-cut case definition*, that is, a set of standard criteria for classifying whether a person has a particular disease, syndrome, or other health condition.
Who:	*Person* – disease occurrence varies according to personal characteristics. Age and gender are *inherent* characteristics that are relevant to disease occurrence, but personal characteristics may also include *biologic* characteristics (other diseases, frailty), *acquired* characteristics (marital status), *behaviors* (smoking, medication use), or *living conditions* (socioeconomic status, access to care).
Where:	*Place* – disease occurrence varies according to geographic location, such as country, region, urban vs rural, institutional or noninstitutional, school district, dental clinic, operator.
When:	*Time* – disease occurrence changes over time and disease occurrence may be monitored to alert to possible public health threats or to assess the effect of public health interventions.
Why/how:	*Causes, risk factors* – whereas descriptive epidemiology is used to identify disease patterns, analytic epidemiology is used to test hypotheses about the causes of such disease patterns or about factors that increase disease risk. The key feature of analytical epidemiology is the comparison group.

Box 4.1 The five 'W' questions addressed by epidemiology.

formation) is unlikely to exceed any clinically relevant threshold. Moreover, from a practical and clinical standpoint it makes no sense to try to detect or describe dental caries at the level of very early crystal dissolution. None of the detection tools available to us, whether the visual–tactile clinical examination (Chapter 10) or the radiographic examination or other detection measures (Chapter 11), even in the hands of the most diligent dental clinician, are remotely able to reflect dental caries at these very early stages. The issue remains, however, to agree on the *clinically relevant threshold(s)* for caries lesion detection.

In the clinic, we talk about caries diagnosis and caries detection as if we were diagnosing a disease entity. That is a mistake, since what we are doing is essentially detecting lesions for treatment. Other lesions may be present, which are considered to need no treatment, and many lesions are subclinical and therefore do not come to the clinician's attention. It took a pioneer in epidemiology, Geoffrey Rose, to point out to us the implications of the fact that most diseases come in all sizes [163]. Most diseases, including the oral diseases, form a continuum ranging from signs that are barely perceptible using high-tech tools to overt and tangible manifestations perceived by the patients as symptoms. In the clinic we use the term 'dental caries' as a collective designation for a set of signs and symptoms that range from barely clinically perceptible alterations in the outermost enamel to the ultimate stage of complete decay of all the dental hard tissues (see Chapter 9). One implication is that the process we call caries 'diagnosis' or 'detection' is our diagnosis or detection of 'lesions for treatment' and not diagnosis of disease. Geoffrey Rose coined an iceberg metaphor (later taken to cariology by Pitts [155, 156]) to point out that 'the visible tip of the iceberg of disease [which in our case could be the carious cavities] can be neither understood nor properly controlled if it is thought to constitute the entire problem' [163]. In other words, we will make a serious mistake if we disregard the fact that what we see as clinically overt caries lesions are lesions that have been fathered by a drift or a trend towards demineralization in the continuously ongoing, subclinical de- and remineralization processes (see Chapter 5). Another implication is that our understanding of the magnitude of the caries 'problem' in a given population will depend on the thresholds set for the detection of lesions, as well as on the actual detection method used, whether visual-tactile, radiographic, or other adjunct methods (Chapters 10–12). Finally, Rose's iceberg metaphor shows us that the term 'caries free' is a misnomer. Everybody has got at least a touch of caries (see Chapters 5 and 9), and any statement about the epidemiological features of dental caries is invariably conditional on the measurement methods and the detection thresholds used.

What counts as caries?

It is essential to appreciate that there is no global consensus on the criteria for the detection of caries lesions. For more than a century it has been recognized that the full range of signs and symptoms of caries lesions includes early noncavitated lesions confined to the enamel [88, 211], sometimes designated incipient lesions. Despite this, there has been a longstanding tradition in dental caries epidemiology for recording dental caries only in case of obvious cavitation. The arguments for ignoring the earlier clinically detectable manifestations of caries lesion formation have typically involved concerns regarding the ease of use of the recording system and the reproducibility (reliability) of the recordings [103]. As an example, the World Health Organization (WHO) guides to oral health surveys continue to stress that the stages of caries that precede cavitation should not be recorded, as it is claimed that 'they cannot be reliably diagnosed' [209–213]. As is shown in Chapters 10 and 12, this claim is erroneous. Moreover, it is highly unfortunate as it prevents dental students and clinicians from understanding how the dental caries process can be controlled to avoid the progression of subclinical and early clinical lesions into overt cavities.

The lack of consensus on the methods and criteria for detection of caries lesions probably results from the idea that different purposes dictate different means. Epidemiological purposes are frequently perceived as requiring methods and criteria that work well with multiple examiners under field conditions where adequate light and means of drying teeth could pose difficulties. Similarly, clinical research studies carried out to test new diagnostic devices or therapeutic agents may call for a set of criteria designed specifically to reflect the anticipated effect of the therapeutic agent or the mode of action of the diagnostic device. The level of disease in the population could also be a determinant of the caries lesion detection systems used. In low-caries populations, such as many contemporary European populations, it has increasingly been considered important to record the early, pre-cavitated stages of caries. Not only do such lesions constitute the vast majority of the caries lesions observed [86, 127], there is now also scientific evidence that these lesions constitute the key to the control of dental caries (see Chapters 13 and 17). On the other hand, there are many places in this world where the caries experience remains so high, and the access to treatment so low, that a need is felt to supplement the recording of cavitated lesions by recordings of the consequences of untreated decay (cavities) to adequately reflect the disease burden in the population. This can be achieved by recording the number of severely decayed teeth with either visible pulpal involvement, ulceration caused by dislocated tooth fragments, fistulas or abscesses (the PUFA index) [141] (see also Chapter 3, Figs 3.57, 3.58, and 3.59).

Validity and reliability of caries lesion detection systems

The ideal criteria for caries lesion detection are typically described as being valid and reliable and characterized by clarity, objectivity, and acceptability. *Validity* refers to the ability of the caries lesion detection system to measure what it purports to measure [115]. Three types of validity are relevant for caries lesion detection methods and criteria: content, construct, and criterion validity (Box 4.2).

Reliability of measurements refers to the degree of stability or consistency of the results obtained when measurements are repeated under consistent conditions. Inter-examiner reliability expresses the degree of agreement between different examiners who examine the same subjects independently of each other, while the *intra-examiner* reliability expresses the degree of agreement within an examiner at two time points sufficiently close to ensure that the caries situation has not changed, and sufficiently apart to ensure that the examiner is unable to remember their first recordings. Inter- and intra-examiner agreement is typically expressed as the percentage sites or teeth for which there was agreement between the duplicate recordings or as the chance-adjusted percentage agreement [2], the κ value [42].

While it is easy to describe the ideal caries lesion detection system in terms of perfect validity and reliability, the real world is full of imperfections. There is no global definition of the construct of 'a caries lesion', and there is no universally acceptable 'gold standard' for caries lesion presence or caries lesion behavior. Validity is therefore neither present nor absent, but a relative phenomenon. Similarly, inter- and intra-examiner reliability is never perfect, but ranges between no agreement and complete agreement, typically never reaching either endpoint. We therefore consider it more fruitful to seek other approaches to the definition of what should count as caries and how caries lesions should be classified.

It is our view that the *management* of the caries problem is the centerpiece. From the dental patient's perspective there can be little doubt that the best caries lesion detection system is the one that leads to the best health outcome for the patient; that is, the one that best reflects the optimal management options for different types of caries lesions [8, 10, 86, 157]. This means that the best caries lesion detection systems can be identified through randomized controlled clinical trials as the caries lesion detection system that results in the best health outcomes for the patients included in the trial. *We see no reason why epidemiological studies or studies carried out for clinical research purposes should be carried out using caries lesion detection systems that do not reflect all manageable caries lesions.*

Most caries epidemiological studies are based on caries recordings made using a visual–tactile caries detection method. Ismail [87] reviewed the scientific literature and

Type of validity	Question addressed (Q) and examples (E) of compromised validity
Content	Q: Does the method lead to the detection of all facets of the construct 'a caries lesion'? E: If important facets such as the early lesions are excluded, content validity is compromised
Construct	Q: Does the method actually measure the construct 'a caries lesion'? E: If the method includes noncarious lesions, such as dental fluorosis lesions, construct validity is compromised
Criterion – concurrent	Q: Do the lesions detected by the method corroborate a 'gold standard' (true) measure of lesions? E: If clinically detected 'enamel lesions' are seen histologically to penetrate into dentin, the concurrent criterion validity is compromised
Criterion – predictive	Q: Do the lesions detected by the method predict the known behavior/fate of such lesions? E: If active caries lesions are detected that have not progressed when reassessed at a later stage, predictive criterion validity may be compromised

Box 4.2 Types of validity relevant to the 'ideal' caries lesion detection system

identified no less than 29 unique visual–tactile caries lesion detection systems that had been published between 1966 and 2001. These 29 caries lesion detection systems varied considerably in terms of the criteria used to detect and classify caries lesions and in terms of their use of explorers and drying or cleaning of teeth prior to the examination. This review showed variable content validity of the caries lesion detection systems [87, 103], since many criteria systems measure only a single – typically the cavitated – stage of caries lesion formation. It was also noted that the construct validity was compromised for some of the systems, as they did not provide guidance on how to distinguish actual caries lesions from other dental hard tissue lesions of noncarious origin [87]. An interesting observation in this review was the apparent gulf between caries lesion detection systems developed in Europe and those developed in the USA, as there has been a trend for European systems since the 1960s to include early signs of caries, whereas criteria developed in the USA have remained focused on measuring cavitated stages only.

Grading the 'severity' of caries lesions

Since the publication of the WHO's *A guide to oral health epidemiological investigations* [211] it has been a tradition in caries epidemiology to range the clinically detected caries lesions along a D_1–D_4 continuum of severity, where D is short for 'decayed.' The D_1 designation is typically used to indicate lesions described as *incipient* or *enamel lesion with intact surface* or *noncavitated*, while the D_4 designation indicates a cavitated lesion with pulpal involvement. However, the interpretation of results presented in the D_1–D_4 framework depends on the underlining caries lesion detection system used, as the comparability is limited across detection systems [87]. Therefore, even though the D_3 level is typically interpreted as signifying the presence of a cavity, this is not necessarily the case as noncavitated lesions judged to involve dentin are sometimes also regarded as D_3 lesions [63]. Table 4.1 shows the types of caries lesions detected by some of the more commonly used visual–tactile caries lesion detection systems. From these caries lesion labels it is not entirely clear how lesions detected in one system would be classified by another system, and the more precise descriptions found in the original publications of each type of lesion are not necessarily helpful either. Similarly, it is not immediately clear if different types of caries lesions scored according to these systems would call for different treatments. *It is therefore important to stress that comparability across caries lesion detection systems may be limited, even when results are expressed in a D_1–D_4 framework of lesion severity.* This means that diligence should be exercised when comparing results obtained in different populations using different caries lesion detection systems and different examiners [1].

Expressing the extent of dental caries: the DMF count

A fully dentate adult person has 32 permanent teeth, representing 148 surfaces, while the young child has 20 primary teeth, representing 88 surfaces. In caries epidemiology it is necessary to summarize the caries recordings for each subject, to express the extent of caries – 'the caries experience' – for each person. A method to achieve a subject-level measure of caries experience, the DMF index, was suggested in 1937 [105]. The DMF-value for each subject is obtained by counting the number of decayed (D/d), missing due to caries (M/m), filled (F/f) teeth (T/t) or surfaces (S/s), resulting in a DMFT (or dmft) or DMFS (or dmfs) count for each subject examined. Use of capital letters indicates counts based on permanent teeth, whereas use of lower case indicates counts based on primary teeth. Occasionally, the letter 'e' is used instead of 'm' to indicate a primary tooth extracted due to dental caries.

The DMF/dmf index is widely used in caries epidemiology owing to its simplicity, versatility and amenability to

Table 4.1 Descriptions of the types of caries lesions detected using some of the major caries lesion detection systems currently in use.

WHO 1979 [211]	WHO basic methods [212]	NIDRC/NHANES [4, 45]	BASCD [5]	Nyvad et al. [19, 128]	ICDAS [89, 90]
Initial caries	Decayed	Incipient lesions	Arrested dentinal decay	Inactive lesion, surface intact	First visual change in enamel
Enamel caries		Frank lesions	Caries in dentine	Inactive lesion, surface discontinuity	Distinct visual change in enamel
Dentine caries			Decay with pulpal involvement	Inactive lesion, cavitated	Localized enamel breakdown because of caries with no visible dentin or underlying shadow
Pulpal involvement				Active lesion, surface intact	Underlying dark shadow from dentin with or without localized enamel breakdown
				Active lesion, surface discontinuity	Distinct cavity with visible dentin
				Active lesion, cavitated	Extensive distinct cavity with visible dentin

General

- The philosophical basis for giving equal weights to untreated caries (D), restorations (F), and missing (M) teeth or surfaces is questionable.
- The number of teeth/surfaces at risk to DMF/dmf is not known. DMF counts, therefore, have little meaning unless age is stated.
- DMF/dmf data are of little use for estimating treatment needs.

M component

- Teeth may be missing for reasons other than caries (e.g., periodontal diseases, orthodontics, trauma). Information on the reasons may be difficult to elicit.
- Tooth extractions are heavily influenced by the dentist's view on treatment options and the patient's willingness/ability to pay for treatment.
- Traditionally, a missing tooth will count as four or five surfaces in the DMFS/dmfs, depending on tooth type. However, it is quite unlikely that all tooth surfaces have been carious, whereby some overestimation of caries experience may be anticipated in the M component contribution.

F component

- The presence of a restoration in a surface may reflect restorative treatment principles ('extension for prevention', 'preventive restorations') rather than dental caries.
- Sealants may be placed for preventive or cosmetic reasons, in which case they do not signify caries (restorations); or they could be placed as a treatment for early, noncavitated active caries lesions, in which case they should be counted as caries related.
- Sealants, composite, and resin restorations can be hard to detect, and this may lead to underestimation.

D component

- The criteria used in the detection and classifications of caries lesions are crucial for the DMF/dmf counts. DMF/dmf counts, therefore, cannot be compared without reference to the caries lesion detection criteria used.

Box 4.3 Some important limitations to the DMF index.

statistical analysis. However, the interpretation of the DMF/dmf as a measure of caries experience is limited by a number of factors [26, 30, 179] (Box 4.3). In high-income countries where access to dental treatment is widespread, the DMF counts tend to reflect a high level of restorative treatment, and the F component dominates, whereas in low-income countries with limited access to dental care the d/D component, measuring untreated caries, dominates the dmf/DMF counts. Therefore, the dmf/DMF counts are occasionally supplemented with estimates of the Care Index, which is calculated by dividing the number of f/F teeth by the total dmf/DMF count, and expressed as a percentage.

Summarizing the caries experience in groups of interest

The dmf/DMF counts are attributes of single individuals/patients, and as such they are not of particular interest in caries epidemiology, where the central task is to quantify the occurrence of dental caries in populations, rather than in individuals. The central caries occurrence measures (Box 4.4) are the *prevalence* (the proportion of people in the population who have caries at the specified time point) and the *extent* (the mean number of teeth affected by caries of a given *severity*). The population average dmf/DMF counts are often provided with the subscripts '1' or '3' to express the caries lesion *severity* threshold used when assessing the extent. Hence, the label D$_1$MFT signifies that all teeth with incipient caries lesions or worse have been counted, whereas the D$_3$MFS label signifies that only surfaces with cavitated caries lesions contribute to the count. The mean dmf/DMF count and the associated standard deviation provide an excellent description of the distribution of dmf/DMF counts in the population when the counts follow an approximately normal (Gaussian) distribution. In such circumstances, the entire distribution can be calculated based on only two parameters: the mean value and the standard deviation.

Some have expressed concern over the use of mean dmf/DMF counts because the population distribution of dmf/DMF counts is increasingly becoming skewed [57, 181]. The Significant Caries Index (SiC-index) [23, 145] has therefore been devised to alleviate the perceived problem that the mean dmf/DMF 'does not accurately reflect this skewed distribution leading to the incorrect conclusion that the caries situation for the whole population is controlled, while in reality, several individuals still have caries' [205]. The SiC Index value is the mean dmf/DMF count for the third of the population with the highest dmf/DMF counts. The WHO has endorsed the SiC-Index, and this statistic is reported along with the dmf/DMF counts in the WHO dental data bank [205].

Others have attempted to give weight to dental health and function rather than to the traditional disease-focused caries experience measure, the DMFT. This has been achieved by counting the number of filled and sound teeth, the FS-T index value [179]. Although a few studies are at variance [120], the FS-T count of sound and functional teeth has generally been reported to be more effective than the DMFT in reflecting the variation

Occurrence measures

Prevalence	The number of individuals who have caries at a specified point in time divided by the total number of individuals in the study population at the same point in time. This proportion is typically expressed as a percentage (%) and time is often not explicitly stated.
Extent	The number of teeth or surfaces with caries. This count can be summarized in different ways. The two most commonly used approaches include the arithmetic calculation of the mean count (e.g., mean DMFT) and the graphical presentation of the actual distribution of the counts in the study population. The arithmetic method works very well when the distribution of counts is approximately normal (Gaussian), whereas the graphical method is ideal for illustrating the increasingly skewed distributions of the DMF counts in the population.
Severity	Refers to the severity of the lesions that have been counted when estimating the prevalence and extent of caries. Adding a suffix to the D of the DMF is used to show this. D_1 indicates that early/incipient enamel lesions have been included, whereas D_3 indicates that only cavitated/dentinal lesions have been considered.

Incidence measures

Incidence proportion	The number of surfaces with new lesions during a given period divided by the number of surfaces at risk at the beginning of the period. This measure, which is dimensionless, assumes complete follow-up of all surfaces over the observation period.
Incidence rate	The number of surfaces with new lesions during a given period divided by the total surface-time at risk to development of new lesions. This measure, which has the dimension $time^{-1}$, is the ideal method, but also complicated since information is needed on the exact time of lesion development (transition from sound to carious).

Box 4.4 Central measures of disease frequency of relevance to dental caries.

in oral health status within and between populations [16, 80, 132, 142, 143].

The FS-T thus overcomes the problems of the DMFT that the M component does not necessarily reflect caries experience, just as the D and the F components contribute with the same weight to the count (Box 4.3). The FS-T index is therefore gaining popularity as a measure of the dental health status in populations [80], just as increasing emphasis is placed on counting the number of sound and untreated teeth [22, 204].

Finally, simple caries extent measures have been devised [68] based on the observation of a 'natural' ordering of the teeth and surfaces according to their susceptibility to caries. The original Grainger hierarchy partitions the dentition into five caries susceptibility or 'severity' zones. Subjects whose caries lesions are confined to the pit and fissure surfaces of posterior teeth are placed in zone 1 because they are most susceptible to caries lesion development, whereas subjects with caries in proximal surfaces of mandibular anterior teeth are placed in zone 5 because these teeth and surfaces are the least susceptible to caries. The exact nature of the hierarchy has been modified on a number of occasions [71, 94, 103, 158], and one such modification is still used to group Danish children into one of four 'severity zones' [46].

Interpretation of caries data

Although the dmf/DMF count has been seriously criticized over the years [30, 104] (Box 4.3) it remains a useful tool for the characterization of dental caries in populations. This is due to the fact that caries data – at the population level, not necessarily at the individual level – follow certain universal patterns of occurrence that can be used as working rules guiding the interpretation of the data [177, 178].

The *first rule* dictates that there is a relationship between the current population caries level and the population caries level at a later age. This phenomenon is called 'tracking of the dental caries experience', and is illustrated in Figure 4.1, which shows how the mean caries experience (dmf/DMF) follows distinct trend lines. 'Tracking' implies that the caries level at one age predicts the caries level at a later age. Each cohort has a particular trajectory of caries experience, which is distinct from the trajectories of the neighboring cohorts. This tracking phenomenon has been noted in many studies [28, 136, 137], and applies to groups as well as individuals [28].

The *second rule* holds that as the mean caries experience (dmf/DMF) decreases, the percentage of 'caries-free' individuals increases [4, 5, 12, 46, 109] and the caries distribution contracts [5, 12, 18, 174]. Figure 4.2 is based on data from the Danish public dental health service for children for the period 1988–2012 and illustrates the rule that the higher the mean dmf/DMF the lower is the proportion of 'caries-free' individuals. The linear relationship is the same for 5- and 7-year-olds in the primary dentition, whereas the linear relationships between the mean dmf/DMF counts and the percentage of 'caries-free' children are different for each of the ages 7, 12, and 15 years. This is due to the differences in the number of permanent teeth at risk to caries in these age groups. Figure 4.3 shows an example of how the caries distribution contracts as the mean DMF count decreases. Clearly, the major differences are seen at the lower end of the range of DMF counts, but even the fraction of individuals at the high-end tail of the distribution of DMF counts becomes smaller.

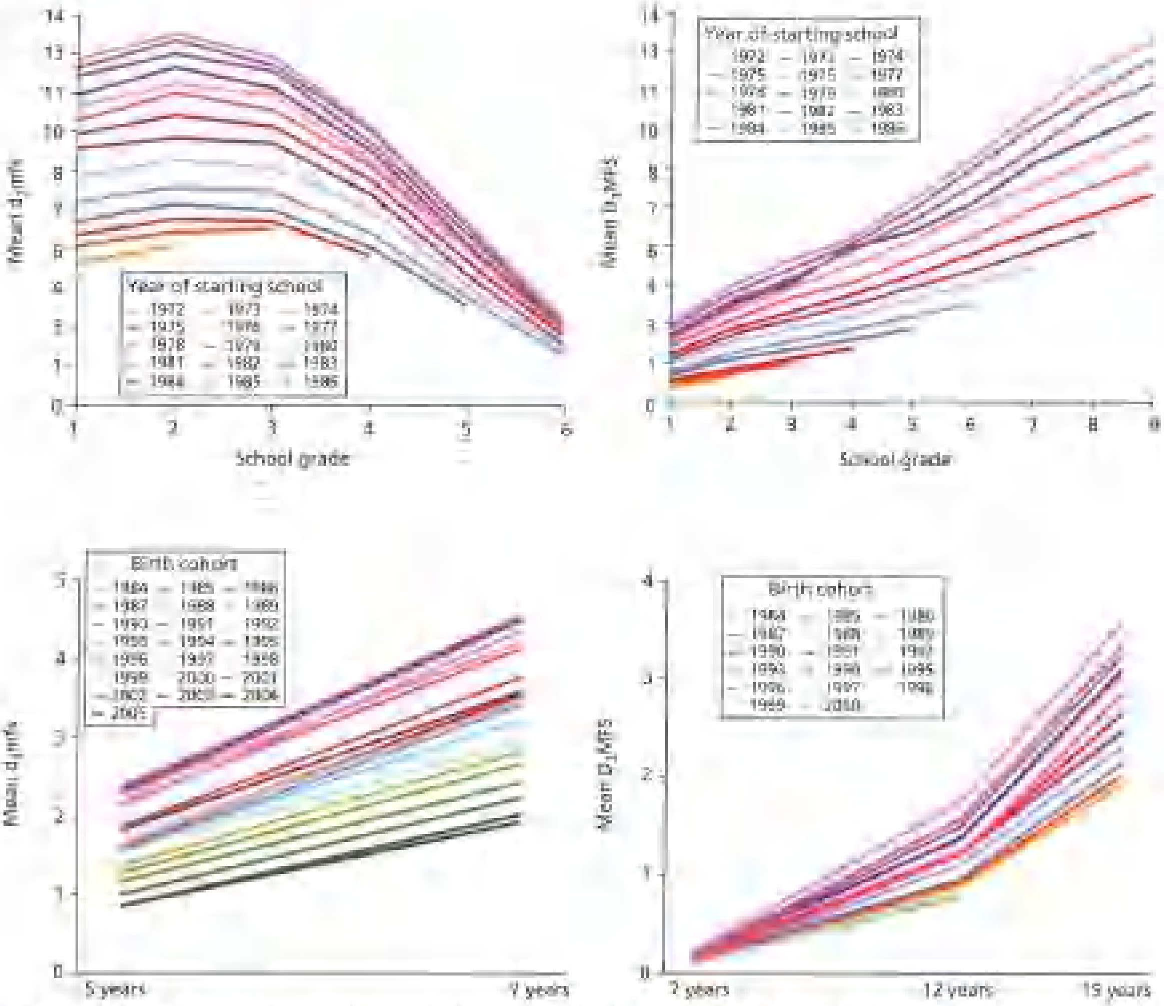


Figure 4.3 *The mean dmf/DMF counts in a cohort follow trend lines. Upper left panel:* Mean $d_1$mfs counts according to school grade for cohorts of Danish children starting school between 1972 and 1985. *Upper right panel:* Mean D_1MFS according to school grade for cohorts of Danish children starting school between 1972 and 1985. *Lower left panel:* Tracking of the mean $d_1$mfs counts between ages 5 and 7 years for the Danish birth cohorts 1984–2005. *Lower right panel:* Tracking of the mean D_1MFS counts between ages 7 and 15 years for the Danish birth cohorts 1984–2000. Data from the Danish Health and Medicines Authority.

The *third rule* is that there is a specific mathematical relationship between the mean dmfs/DMFS and the mean dmft/DMFT [89, 90, 109]. Figure 4.4 shows this relationship for the primary dentition among 5- and 7-year-olds, and for the permanent dentition among 7-, 12-, and 15-year-old Danish children as recorded in the Danish public dental health service over the period 1988–2012. Essentially, these graphs show that it would not be necessary for epidemiological purposes to record dental caries at the surface level since the dmfs/DMFS could be calculated from the dmft/DMFT.

The *fourth rule* is that as the mean caries experience (dmf/DMF) declines in the population the progression rate of caries through enamel decreases. This is illustrated by the ratio of the $d_3$mfs/D_3MFS to the $d_1$mfs/D_1MFS (Figure 4.5). These curves clearly show that the proportion of d_1/D_1 lesions (i.e., noncavitated caries lesions) increases as the $d_3$mfs/D_3MFS count decreases. A declining caries experience clearly means that the time needed for d_1/D_1 lesions to become d_3/D_3 lesions is increasing.

Finally, there is a hierarchy of caries susceptibility by tooth type and type of site [13, 27, 33, 37, 71, 121, 125, 126, 130, 136–138, 158] such that first and second molars are the most caries-susceptible teeth, followed by the premolars, while the lower anterior teeth are the least susceptible. The most caries-susceptible surfaces are the pit and fissured surfaces, followed by the approximal surfaces, whereas the smooth surfaces are the least caries-susceptible surfaces.

The rules outlined above are extremely useful, not only for the interpretation of caries data from a given population, but also, and perhaps more importantly, for the use of epidemiological data to plan the types of health-care services needed to achieve better oral health outcomes for the population [178]. A particular mean DMFT for a given age group can be

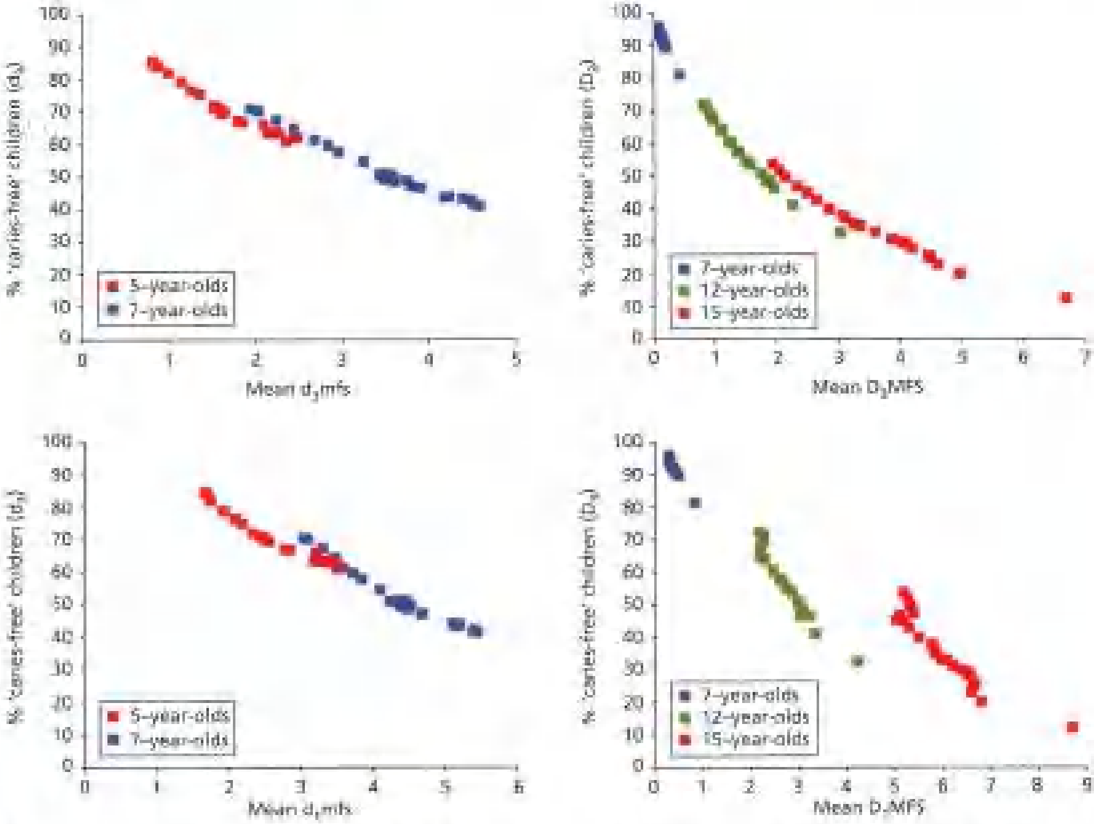


Figure 4.2 There is a close relationship between the mean dmf/DMF count and the percentage of 'caries-free' children in a population. The two upper panels show the relationship between the $d_3$mfs/D_3MFS and the percentage 'caries-free' (d_3/D_3-threshold) children, and the two lower panels show that the relationship also holds for the $d_1$mfs/D_1MFS percentage 'caries-free' (d_1/D_1-threshold) children. Data points originate in data from the Danish public dental health service for the years 1988–2012.

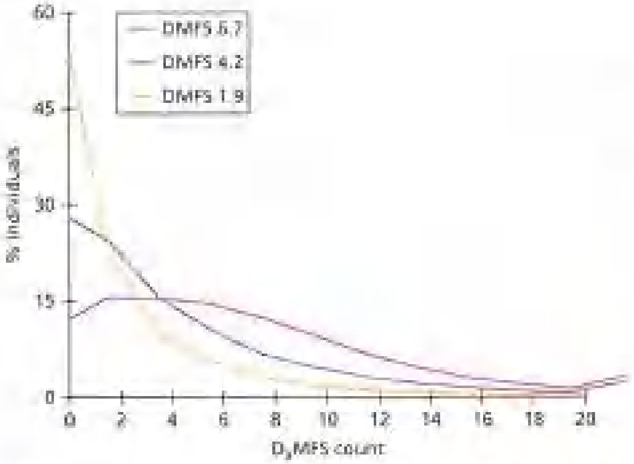


Figure 4.3 The frequency distribution of individuals according their individual D_3MFS counts contracts as the mean D_3MFS for the population decreases. Data from the Danish public dental health service for 15-year-olds in the years 1988, 1993, and 2012.

used to predict the mean DMFT for this group at a later age, just as it can be translated into a mean DMFS and a caries distribution pattern within the population and within the mouth. The caries distribution pattern concerns both the distribution of DMF counts in the population and the distribution of caries lesions in the dentition (the caries susceptibility pattern). Finally, the mean DMF provides information on the rate of caries lesion progression in the population.

Who? The distribution of caries in populations

Variation and inequality in the distribution of caries

The caries experience varies within a population. Where caries levels are generally high, the prevalence of a dmf/DMF >0 is typically close to 100% and the distribution of the individual dmf/DMF counts approaches a normal (Gaussian) distribution. This implies that the individual

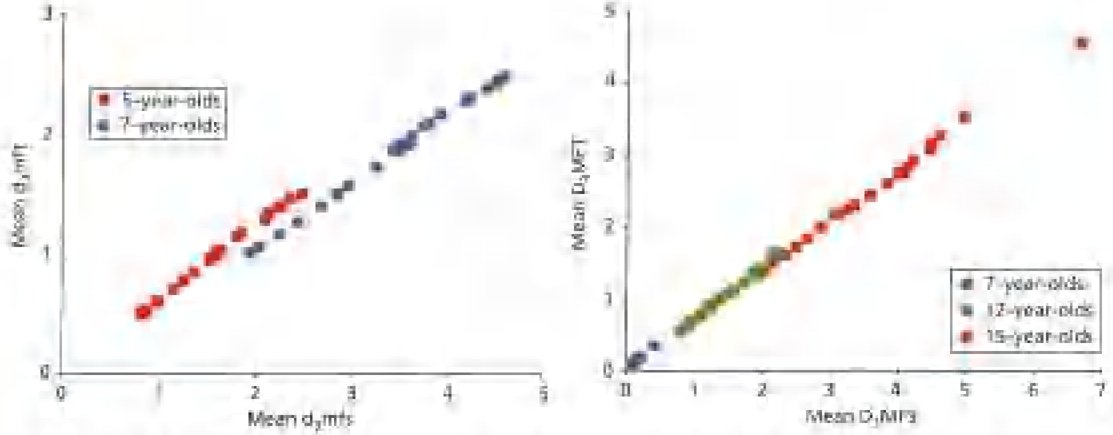


Figure 4.4 The relationship between the mean dmfs/DMFS and the mean dmft/DMFT. Data from the Danish public dental health service for the years 1988–2012.

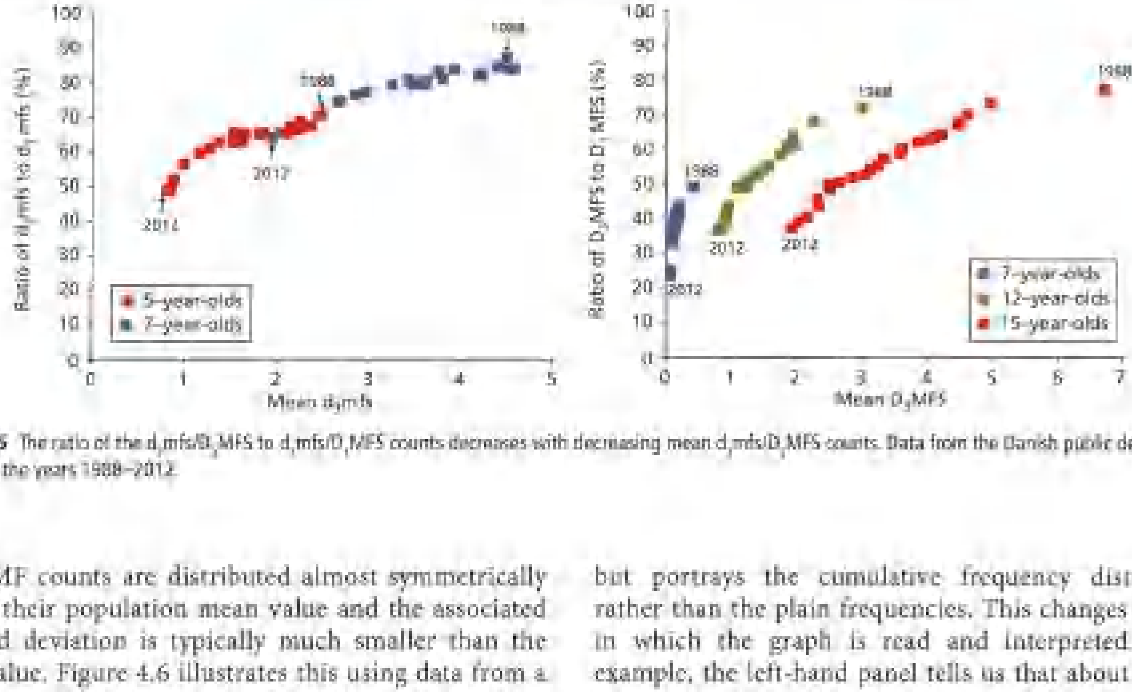


Figure 4.5 The ratio of the d$_3$mfs/D$_3$MFS to d$_1$mfs/D$_1$MFS counts decreases with decreasing mean d$_1$mfs/D$_1$MFS counts. Data from the Danish public dental health service for the years 1988–2012.

dmf/DMF counts are distributed almost symmetrically around their population mean value and the associated standard deviation is typically much smaller than the mean value. Figure 4.6 illustrates this using data from a population that had relatively high caries levels about two decades ago [9, 127, 128]. The left-hand panel shows the distribution of D$_1$MFS counts among 12-year-olds and the D$_1$MFS counts in the same children 3 years later, when they had reached the age of 15 years. It is seen that very few children had a D$_1$MFS count of zero, and the peak of the distribution occurs around 10 D$_1$MFS for 12-year-olds and around 20 D$_1$MFS when the children had reached the age of 15. The mean D$_1$MFS counts for the two ages were somewhat higher – 15.0 at the age of 12 years and 23.8 at the age of 15 years – which illustrates the sensitivity of the mean value to deviations from symmetry of the distribution. The right-hand panel of Fig. 4.6 illustrates the same data as the left-hand panel, but portrays the cumulative frequency distribution rather than the plain frequencies. This changes the way in which the graph is read and interpreted. As an example, the left-hand panel tells us that about 4.8% of the 15-year-olds had a D$_1$MFS of exactly 21, whereas the right-hand panel tells us that 50% of the 15-year-olds had a D$_1$MFS count of 21 or more, and 10% had a D$_1$MFS count of 40 or more. Both panels of Fig. 4.6 illustrate the tendency for positive skewness (i.e., a long right-hand tail of the distribution), and this will inflate the mean D$_1$MFS value relative to what is a typical D$_1$MFS observation in this population.

As previously mentioned, a decline in the population mean caries experience results in a contraction of the distribution of DMF counts. In 1980, the mean D$_1$MFS among 15-year-old Danes was around 12.9, while it had dropped to about 4.8 by 1995 [160]. The corresponding distributions of the D$_1$MFS counts detailed in the left-hand panel of Fig. 4.7

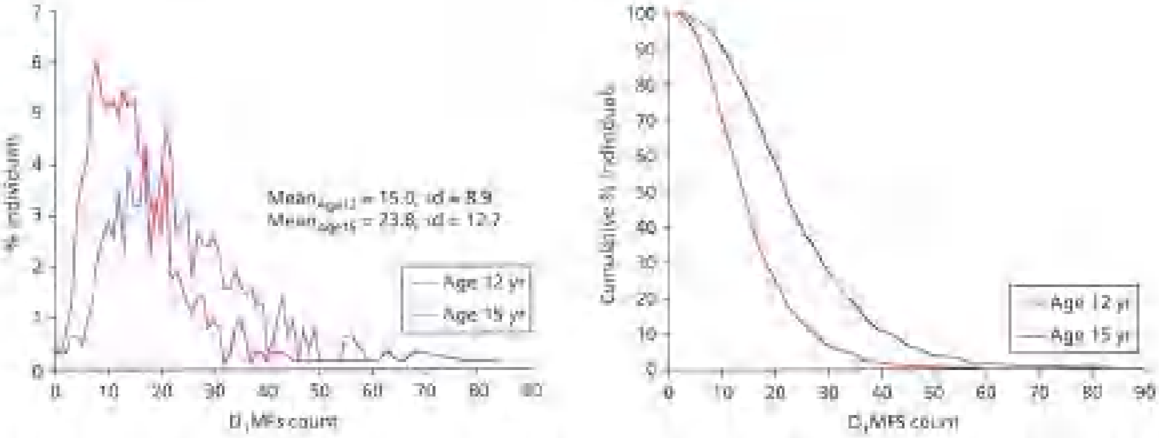


Figure 4.6 The distribution of individual D$_1$MFS counts among 12-year-old Lithuanian children, and the distribution for the same children 3 years later, when they had reached the age of 15 years. The left panel shows the simple frequency distribution of the D$_1$MFS counts, whereas the right panel shows the cumulative frequency distribution of these counts. Based on data from [9, 127, 128].

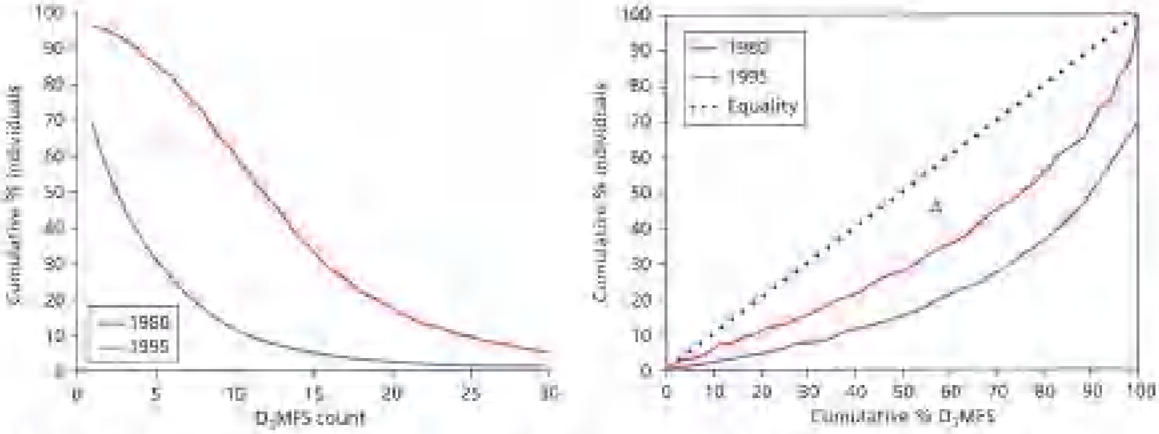


Figure 4.7 The cumulative frequency distribution of individual D$_3$MFS counts among 15-year-old Danes in 1980 and 1995 (left-hand panel), and the corresponding Lorenz curves (right-hand panel) illustrating the degree of inequality of the distribution of the caries burden in the population. Dividing the area (A) between the Lorenz curve for the year 1980 and the line indicating perfect equality by the total area under the perfect equality line gives the Gini coefficient. Data from [160].

show that the decline has led to more pronounced positive skewness in the distribution, and the right-hand tail of the distribution has become more obvious, although a reduction in the occurrence of very high D$_3$MFS counts can be discerned. This phenomenon explains the frequent observation that the inequality in the distribution of caries increases when there is an overall caries decline in the population [6, 19, 118, 160]. In a situation of equality, 10% of the population accounts for 10% of the total number of caries lesions, 20% of the population for 20% of the caries burden, and so forth; this generates the diagonal dotted line in the right-hand panel of Fig. 4.7. The area (A) between the actual distribution of the caries burden (the Lorenz curve [124]) and the line indicating perfect equality is a measure of the degree of inequality in the distribution of caries. This is often expressed as a fraction of the total area under the perfect equality line, the Gini coefficient, which takes the value zero in the case of perfect equality and one in the case of the most extreme inequality. The latter would occur if, hypothetically, caries had been eradicated to the extent that only a single individual remained in the population who had some caries experience. Although this may seem paradoxical in a situation where close to 100% in the population are caries free and, therefore, equal in some sense, it should be appreciated that the Gini coefficient measures the degree of polarization of the caries occurrence. When caries declines, it is evident that individuals, who in previous cohorts had a low to moderate caries experience, are the 'easy pickings,' whereas it is considerably more difficult to influence individuals at the far right-hand tail of the distribution. This is illustrated by the vertical distance between the two cumulative frequency distribution curves in the left-hand panel of Fig. 4.7, which was 55% at 5 D_1MFS and 15% at 20 D_3MFS.

Variation in the distribution of caries is a prerequisite for evaluation of possible determinants of the occurrence of caries. Most epidemiological studies seek to assess possible determinants of caries occurrence within populations, but it should be appreciated that the variation is greatly increased when a between-population view is taken. In order to do so one must necessarily be able to account for the major determinants of within-population variation.

Age and gender

It is a universal observation that the mean dmf/DMF counts in a population increase with age [55, 83, 84, 125, 130, 170] (Fig. 4.1), indicating that new lesions may continue to form across all ages. In the primary dentition this increase continues until tooth exfoliation 'turns the tide' around the age of 8–9 years (Fig. 4.1, top left panel). There was a time when caries was considered a childhood disease because most of the caries-susceptible surfaces were affected already by adolescence. However, this misunderstanding of the natural history of caries arose from the insensitivity of the DMF count to capture new caries attacks in already affected surfaces. Nowadays, most individuals reach adulthood with a relatively low caries experience and it is therefore possible to illustrate that caries is indeed a lifelong phenomenon. As Fig. 4.8 and Fig. 4.9 show, the caries experience is higher the older the age group. Moreover, with advancing age, an increasing number of root surfaces become exposed to the oral environment owing to a gradual recession of the gingival margin, and root caries therefore becomes a manifestation of caries among middle-aged and older people [55, 67, 75, 125, 129, 204] (Fig. 4.9 and Fig. 4.10).

As regards gender, it is frequently found that girls and women have higher dmf/DMF counts than do boys and men [15, 65, 93, 99, 110, 207] (Fig. 4.11). This difference may be discernible from an early age and has been ascribed to a comparatively longer exposure time to the oral environment for girls [33], owing to the generally earlier tooth eruption among girls [34, 147]. However, more recent analyses [117, 148] suggest that girls may have a genuinely higher caries incidence rate (Fig. 4.12) and that this is more closely related to chronological age than to the posteruptive age of the teeth [148]. Moreover, the higher dmf/DMF count among women is typically due to a higher number of filled or missing teeth and surfaces, whereas men tend to have a higher number of untreated caries lesions. This suggests that the higher dmf/DMF counts among women may also be attributable to a greater dental treatment experience, which is supported by the observation that women tend to visit the dentist more often than men [35, 146].

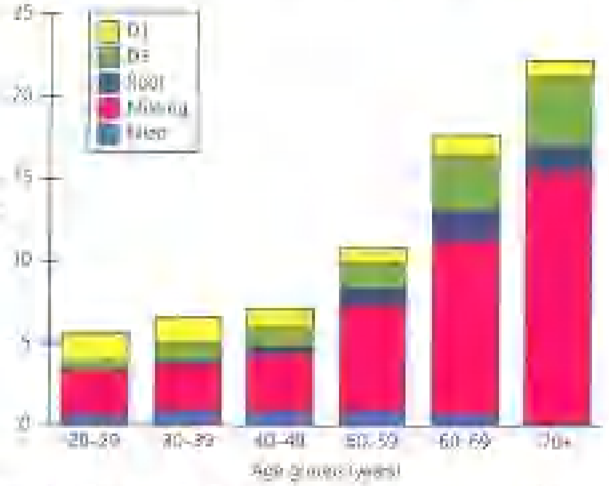


Figure 4.9 The mean DMFT and its components among adult and elderly Chinese examined 1984–1985. Data from [125].

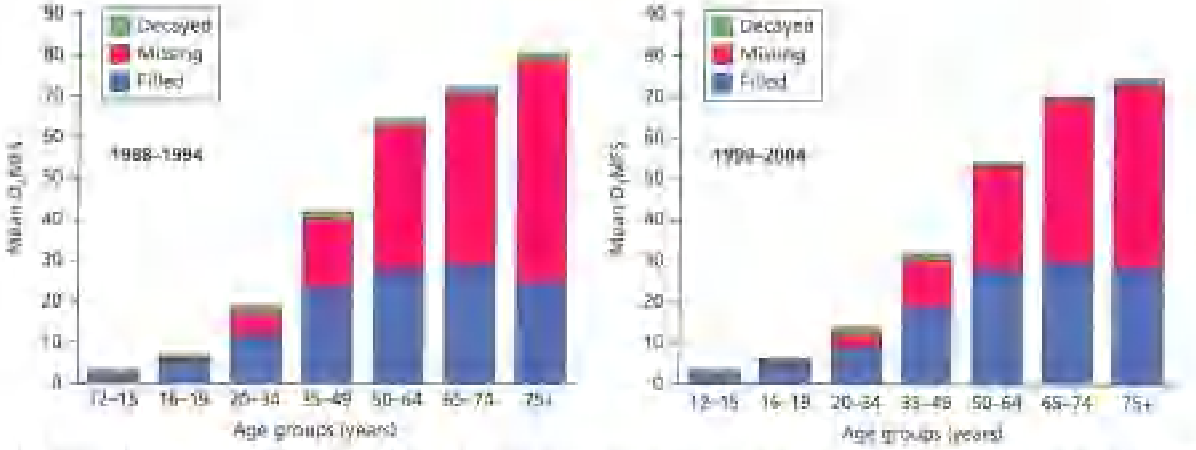


Figure 4.8 The mean D_1MFS among US adolescents, adults, and elderly in two national surveys, one in 1988–1994 and one in 1999–2004. Data from [55].

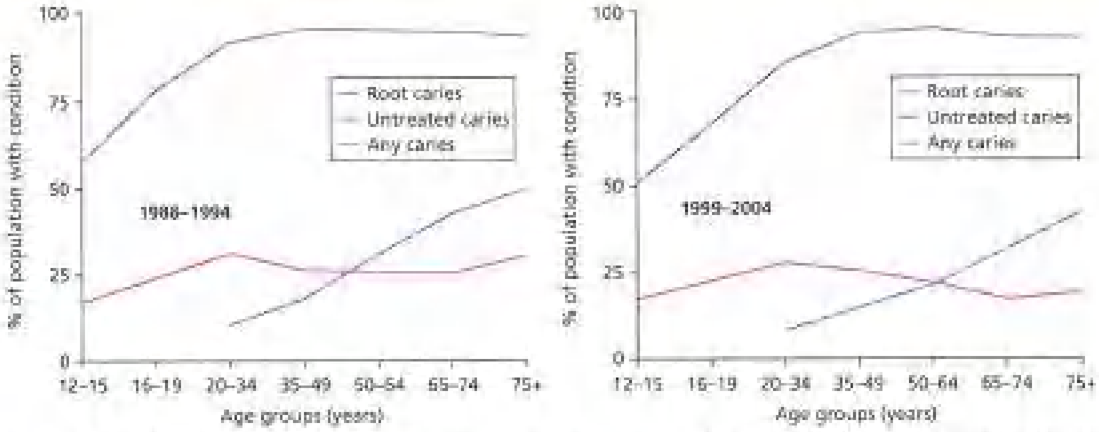


Figure 4.10 The prevalence of any caries (D_1 level), untreated caries (D_1), and root caries among US adolescents, adults, and elderly in two national surveys, one in 1988–1994 and one in 1999–2004. Data from [55].

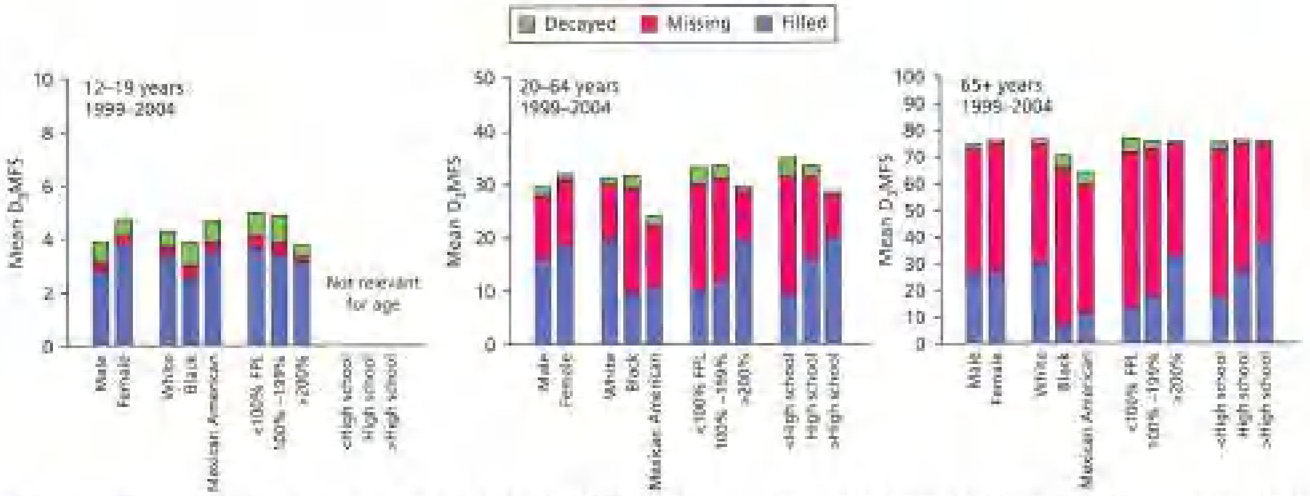


Figure 4.11 The mean D_1MFS according to selected socio-demographic factors for the age groups 12–19 years, 20–64 years, and ≥65 years as recorded in 1999–2004. Data from [55].

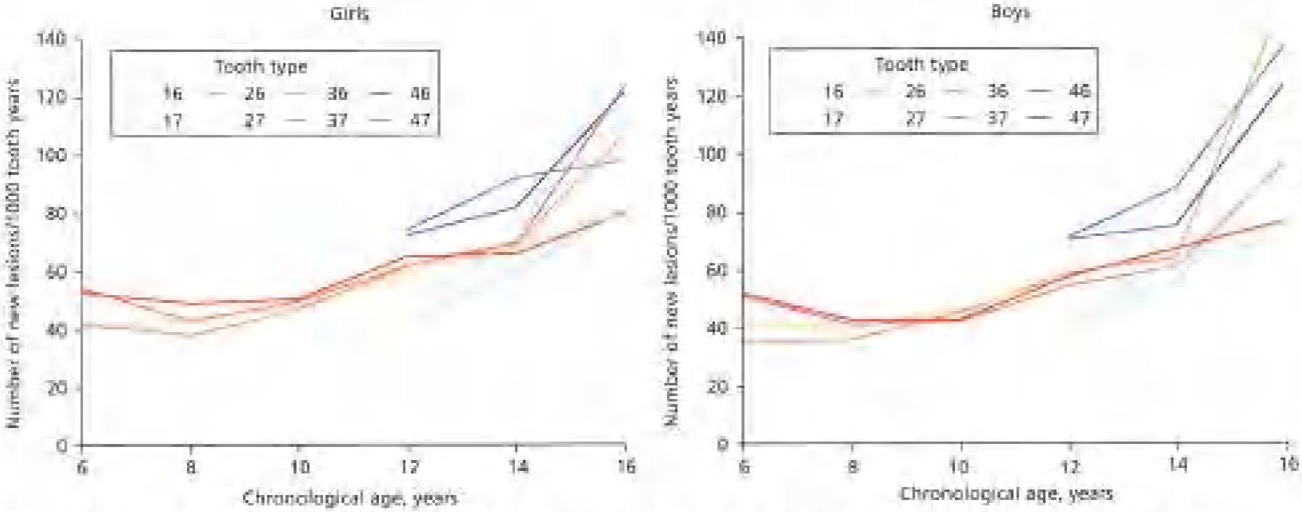


Figure 4.12 The tooth-specific caries incidence rates (new lesions/1000 tooth-years at risk) for Danish boys and girls born 1980. Data from [148]

Race/ethnicity: genes or social class?

It is routine in some multiracial and multiethnic countries, most notably the USA [15, 54, 55, 139, 207], to classify individuals according to race when describing the population variation in disease occurrence. For decades it has been a common finding that whites have overall higher DMF counts than African-Americans, although the latter have more untreated caries and fewer fillings [98, 144, 207], and African-Americans have been observed to have a higher caries incidence than whites [66]. The traditional definition of race refers to physical characteristics [115] such as skin color, eye color, hair color, and facial features and has often been given a biological, inheritance interpretation [114]. The racial disparities seen in many health outcomes, including dental caries, have therefore often been given a biological interpretation, and 'race' is often used in epidemiology as a surrogate for unmeasured genetic factors [96]. The concept of ethnicity was suggested as an alternative basis for classification to reduce the biological connotations of race [95] in favor of emphasis on broad 'cultural' factors, such as nationality, culture, ancestry, language, and beliefs. However, the distinction between the two remains blurred, and they are often collapsed into a single dimension of 'race/ethnicity' [55, 95]. Moreover, there is increasing recognition that 'race' is a social construct more than anything else [91] and that 'racial' differences in the caries occurrence are largely attributable to the material circumstances of peoples' lives in terms of income, education, employment status, and access to care [161]. *There is no evidence to support inheritance as a factor explaining the disparity in caries occurrence or incidence between different racial or ethnic groups.* On the contrary, there is ample evidence that the root causes of 'racial' differences in observed oral and general health outcomes are found in an unsavory combination of lower socioeconomic status [165] and racism [206], whether this is institutionalized through differential access to goods, services and opportunities, whether personally mediated through prejudice and discrimination, or whether internalized through acceptance of less ability and minor worth by the members of the stigmatized race [93]. An example of prejudice from dentistry is the observation that the patient's race per se may influence the dentist's decision to extract or retain a decayed tooth [32]. It is worth mentioning that in other multiracial and multiethnic countries, such as the UK and Canada, there seems to be no need to institutionalize 'racial' differences by using race as a classification variable when monitoring the oral health conditions of the population. Instead, more relevant classification variables are sought, which portray the socioeconomic and contextual root causes of the disparity in caries occurrence [22, 51, 62, 183, 202–204]. Figure 4.11 shows that such information is indeed also available for the US population and that there is a clear relationship between poverty status or educational attainment and the caries experience (12–19- and 20–64-year-olds) or the composition of the caries experience in terms of filled and missing surfaces (20–64- and ≥65-year-olds).

The last decade has witnessed a resurgence of the idea that caries has a genetic background [64, 175, 199, 214]. The idea of inheritance playing a role for the caries occurrence probably dates back to the 1930s and 1940s [106] when the familial basis for 'caries immunity' and 'caries susceptibility' were key ideas in caries epidemiology. Familial patterns of caries occurrence have also been noted at later dates [162, 176], but more weight was quite rightly placed on the shared environment in the families than on genetic inheritance when observations were interpreted. Genetics do not explain why the caries status of spouses correlates [108] and seems to 'merge' despite being dissimilar during childhood [167]. Similarly, genetics do not explain why the caries status of the offspring correlates more closely with the caries status of the mother than with that of the father [162]. Families share dietary practices and oral hygiene behaviors, and these two factors are sufficiently strong determinants of the caries outcome to explain why the notion of caries 'running in families' has arisen. However, the era of genomics has provided scientists with new tools, and the pursuit of a genetic basis for caries susceptibility would seem to be more a question of applying exciting new techniques than of providing solutions to tangible problems of importance for the control of dental caries in populations.

It remains an indisputable fact that the occurrence of caries in a population is related to measures of socioeconomic status. It is a common finding in medium- and high-income countries that those with higher income, better educations, better jobs, and upscale area residence, or combinations thereof, have less caries and better oral health than those who are less fortunate [17, 19, 20, 44, 49, 50, 56, 57, 61, 65, 118, 126, 134, 135, 149, 151, 154, 195]. However, the relationship between caries levels and measures of socioeconomic status can be the reverse in low-income countries. As an example, the mean dmf/DMF counts increase with increasing income in low-income country Vietnam, and decrease with increasing income in high-income country Australia [49]. Similar observations were made in the USA in the 1940s, where marked differences were discernible in the composition of the DMF count in spite of the fact that the overall DMF counts did not vary much between socioeconomic groups [107]. Lower socioeconomic groups had higher counts for the D and the M components and lower counts for the F component than did higher socioeconomic groups. By the 1960s, white children in higher socioeconomic strata had higher DMF counts than white children in lower socioeconomic strata, whereas the reverse was characteristic for African-American children [99]. In white children, there was a strong correlation between increasing socioeconomic status and an increasing number of fillings.

which caused the total DMF to increase with increasing socioeconomic status. A similar socioeconomic gradient in the number of fillings was not seen for African-American children, and their DMF counts therefore decreased with increasing socioeconomic status. These observations highlight the huge influence of treatment accessibility and experience on the observed caries experience.

In epidemiologic research, measures of socioeconomic status are often used as attributes of single individuals [122]. This use of socioeconomic status, as determined by measures of people's income, education, or occupation, is intended as a broad condensation of their knowledge, attitudes, values, and beliefs, which are thought to be key determinants of their 'lifestyles,' and hence their health-related behaviors. Attempts have been made to 'improve' the socioeconomic status concept by adding more determinants beyond those of income, education, and occupation, such as car ownership and type of housing. However, the fundamental problem is that the above interpretation of the associations between poorer health outcomes and lower socioeconomic status relies on the rational choice model, which assumes that people are rational, aware, self-creating agents of their own health who behave in the pursuit of self-interest [38]. Much public health education is based on this rational choice model in which individual behavior is understood as a psychological property of individuals influenced by consciously chosen goals [38]. However, there is an increasing understanding – also in caries epidemiology – that the social influences on health and disease occurrence are much more pervasive and profound than indicated by individual socioeconomic attributes, and embrace a host of contextual factors that are not under the influence of single individuals (Fig. 4.13). People's health is greatly influenced by social factors that cannot be reduced to individual attributes. These factors include the circumstances in which people are born, grow, live, work, and age, and their structural drivers in terms of inequitable distribution of power, money, and resources [43]. Low-income people are concentrated in low-income areas, where access to stores with fresh and nutritious foods is limited but fast-food options abound; where housing conditions and sanitation are poor; where health-care availability and accessibility are low; where psychosocial stress is considerable; where social support is limited; and where collective social norms and peer pressure

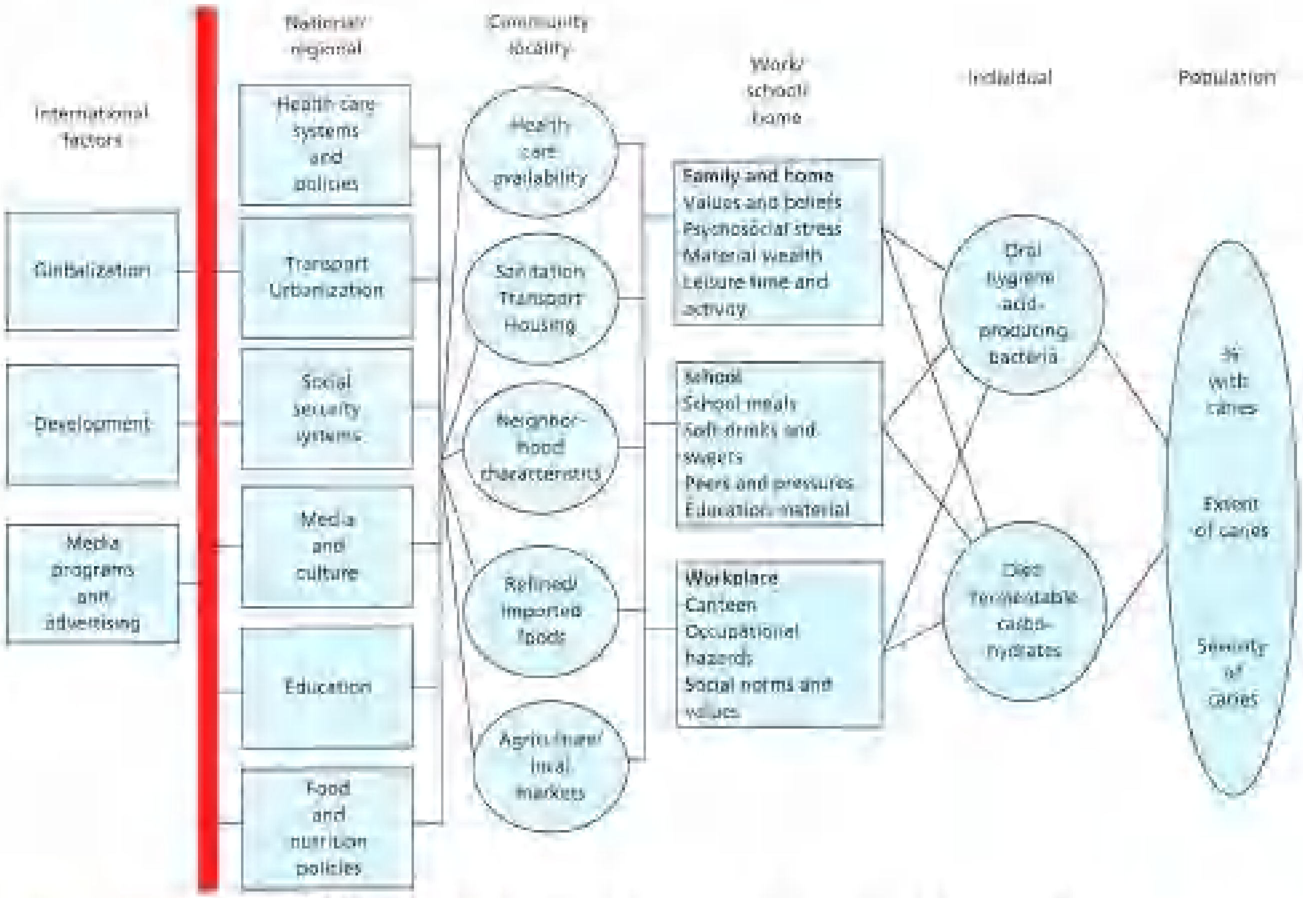


Figure 4.13 A comprehensive model of the global, national, and local structural drivers of the circumstances in which people are born, grow, live, work, and age, which in turn determine the biological processes that lead to dental caries in individuals and in populations. Modified from [111].

determine individual behavior. The influence of such contextual factors is also evident for dental health. A study of low-income African-American families [167] has shown that people with a capacity for resilience to poverty (i.e., people who score positively on at least four of five markers: live in a well-kept house, have a social network, are regular church attendants, have no depression, and are nonsmokers) have much higher odds of retaining at least 20 natural teeth, just as their children have a lower caries incidence than those who are less resilient. Lack of social support [195] has been found to be associated with having more caries when controlling for socioeconomic factors, just as neighborhood disadvantage is associated with poorer oral health independently of individual socioeconomic characteristics [69, 168, 186, 194]. Interestingly, low-income adults benefit from living in affluent areas, and wealthier adults do not lose their oral health advantage when living in poor neighborhoods [168].

The social gradient

It has been a common perception that the socioeconomic influence on the distribution of oral disease is confined to the extremes in society. The frequent contrasting of deprived or poor population groups against the remaining population – the rich against the poor – has left the impression that there is some absolute level of deprivation or poverty, beyond which there is no social or socioeconomic influence on oral health outcomes. However, this is a misconception. Both oral and general health outcomes are socially patterned along the entire social hierarchy [60, 164, 166, 169, 201], leading to a social gradient. A social gradient implies that those in the higher social ranks are better off than those immediately below them in a stepwise and consistent manner [53, 166, 201]. Figure 4.14 illustrates the social gradient according to job classification in the occurrence of edentulousness among English adults aged ≥50 years [192], and similar observations have been made among Japanese men [142]. Social gradients are discernible even in high-income countries [77] and among children and adolescents [123, 187], which goes to show the pervasiveness of the effect of *relative* social position on oral health outcome.

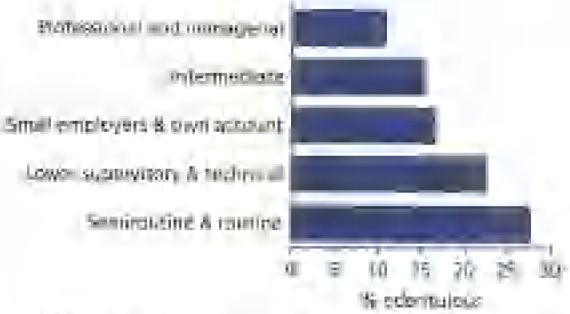


Figure 4.14 The social gradient in oral health illustrated by the almost linear relationship between occupational classification and the prevalence of edentulousness. Data from [192].

Where? The geography of caries

There is a marked variation in the occurrence of caries between the countries of the world [25, 150, 152] (Fig. 4.15). The WHO Collaborating Centre for Education, Training and Research in Oral Health has established a Country/Area Profile Project (CAPP) database that presents epidemiological information on oral disease occurrence for different countries and areas around the world for the indicator age group of 12-year-olds. The information fed into this database typically originates in locally initiated 'pathfinder' surveys carried out in accordance with the methodology described in the WHO manuals on the basic methods in oral health surveys [209, 210, 212, 213]. These manuals provide some detail on the methods to be used, including recording methods, diagnostic criteria, examiner calibration, selection of study sites, sampling, and indicator age groups. Although this ensures some degree of standardization of the methodology used, and hence comparability between studies, the sample sizes underpinning the estimates reported to the database are often quite small. As variation may be considerable, even within countries with overall very low levels of dental caries (Fig. 4.16), it is hardly surprising that the estimates provided by the CAPP database must be viewed as crude estimates associated with a possibly sizeable degree of imprecision. Nevertheless, some broad generalizations can be made regarding the occurrence of caries among 12-year-olds in different parts of the world. The highest caries levels are generally seen in the Latin American countries and in the European region [24], whereas the lowest caries levels are reported for the African and Southeast Asian countries [24]. However, as Fig. 4.15 shows, the relatively high overall caries levels among European 12-year-olds are chiefly due to high caries levels in the eastern European countries. Most western European countries have low levels of caries among 12-year-olds, although they are not as low as observed for many African and Southeast Asian countries. The low overall caries levels among African and Southeast Asian countries, particularly Tanzania, Ghana, Nigeria, Eritrea, Sudan, Egypt, Kenya, Nepal, and China (Fig. 4.15), are contrasted by occasionally rather high caries levels; for example, in Gabon, India, and the Philippines. Among the Middle Eastern countries, Saudi Arabia stands out as having the highest caries levels observed in the 2000s among 12-year-olds.

Adult dental caries is also monitored for the indicator age group of 35–44 years. The data for DMFT among 35–44-year-olds show that the highest caries levels are found in the highly industrialized countries in Europe, North America and Australia, just as most Latin American countries have

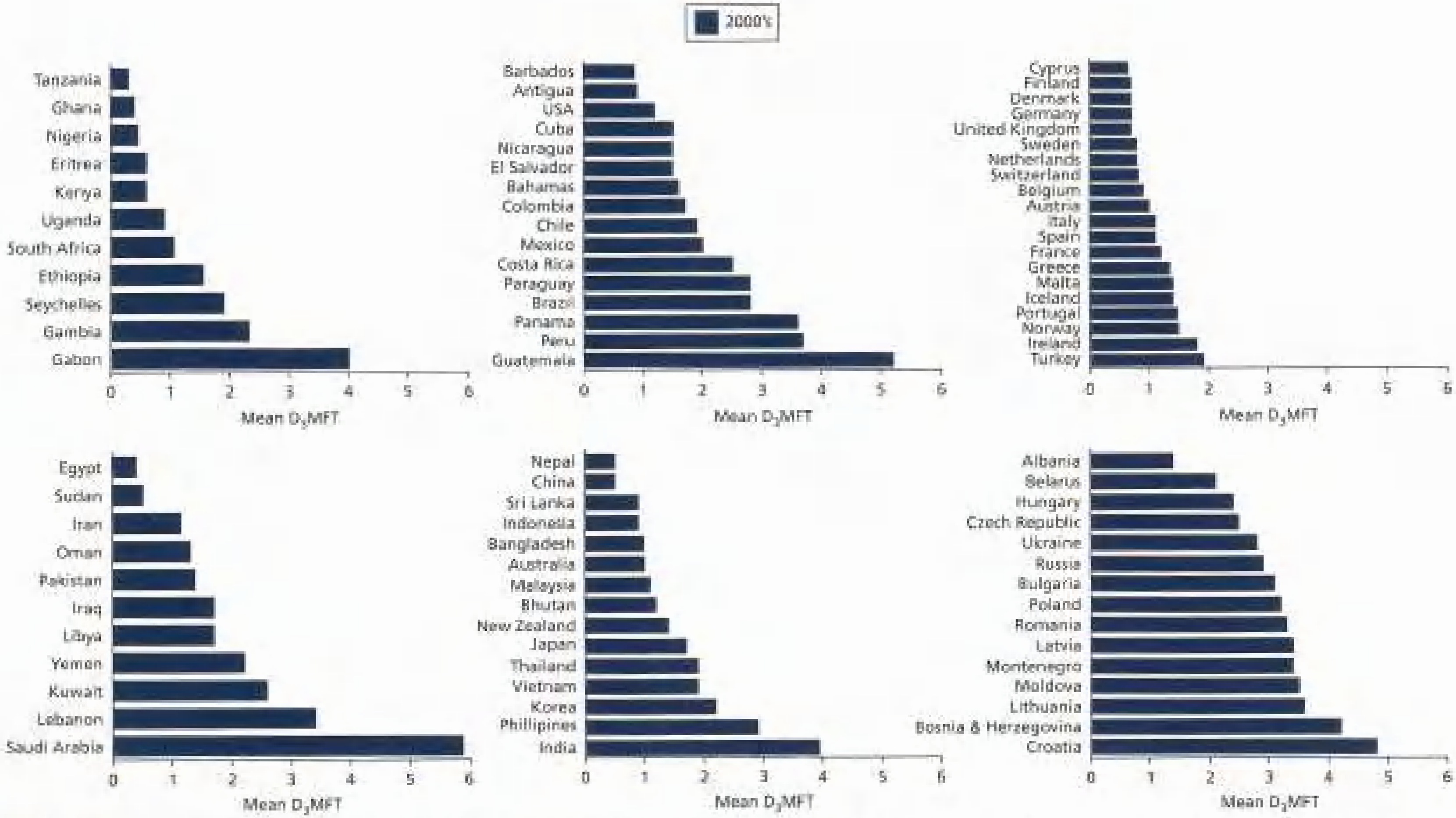


Figure 4.15 The mean D_3MFT counts for 12-year-olds in different countries as reported to the WHO Oral Health Country/Area Profile Programme Database (http://www.mah.se/capp/) in the 2000s.

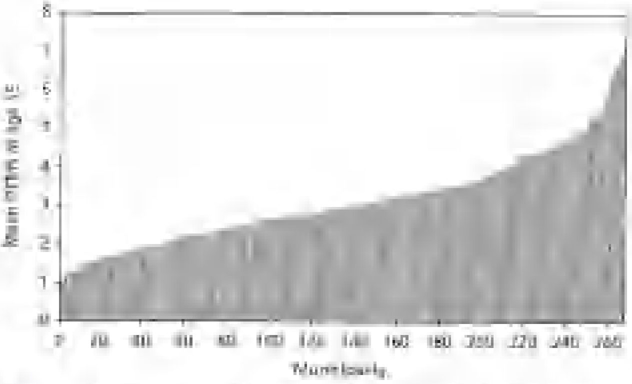


Figure 4.16 The variation among the 267 Danish municipalities in the mean D_3MFS counts for 15-year-olds in year 2003. Note the eightfold difference between the municipality with the lowest mean D_3MFS (~1) and that with the highest mean D_3MFS (~8). Data courtesy of Dr Jens Heidmann.

very high caries levels among adults. In contrast, the developing African and Southeast Asian countries, excepting the Philippines where caries flourishes, have very low caries levels [152] among 35–44-year-olds.

The determinants of the variation across countries in the levels of caries are the same living conditions that govern the within-population variation in caries occurrence, and in most other health outcomes, that is, the broad social and environmental circumstances in which people are born, grow, live, work, and age [151, 152]. These influence a number of more proximal socio-behavioral determinants, including nutrition and dietary practices, oral and general hygiene, and oral and general health-care coverage [25, 81, 151, 152].

When? Trends in caries

As already alluded to, dental caries is declining in most countries around the world (Fig. 4.17). This decline has been thoroughly documented for the highly industrialized countries [7, 29, 35, 47, 48, 52, 55, 74, 83, 85, 92, 97, 134, 135, 153, 159, 173, 182, 191, 197], for eastern European countries [3, 112, 113, 184, 198], for Latin American and Caribbean countries [14, 21, 36, 41, 146, 180], and for African countries [39, 40]. Even already low-caries African countries, for which a caries increase might have been expected, have witnessed a predominantly downward trend [39] or relative stability of the caries levels [41].

The majority of studies from which the caries decline is inferred have been carried out among children and adolescents. While concerns have been raised that the caries decline among children and adolescents may merely represent a delay in the development of caries [58], there is little doubt that the caries decline is also manifest in younger adult and middle-aged population groups [55, 58, 78, 85, 171, 196]. Trends among older age groups are compounded by the simultaneous trend for increasing tooth retention and reduced edentulism [83, 85, 171], which leads to the observation of higher mean DMFT counts among the older age groups of later birth cohorts than seen in earlier generations. Figure 4.18 shows how the caries decline has trickled in among younger and middle aged Swedish adults, while the greater tooth retention and the reduced frequency of edentulism has resulted in higher mean D_1FS counts among the 60-, 70-, and 80-year-olds in the two most recent surveys [83].

Claims are regularly made that caries is now on the increase again [11]. Indeed, reports exist that seem to indicate a trend for a caries increase [72, 82], particularly among young children. However, in many of these reports, the time points that are compared are not far apart. As shown in Fig. 4.19, which is based on national Danish data, it is indeed possible, and particularly so for young children, to observe short-term trends for 'caries increases' that are superimposed on the long-term trend for a caries decline. Another illustration of this phenomenon is the claim made over a decade ago for a reversal of the caries decline among Norwegian children [72] that was later refuted [73].

Why? The causes of caries

Around 1950, ecological studies by Toverud demonstrated that the caries decline in Norwegian children during World War 2 and the subsequent increase in the post-war years were almost mirror images of the changes in the food supply, including the average per capita sugar consumption [188–190]. The observations were soon supported by experimental proof of a causal link through the Vipeholm study [70], which was a 5-year longitudinal study of the caries increments among groups of mentally disabled and institutionalized people who were experimentally fed various highly artificial cariogenic diets. Some of these diets involved the between-meal consumption of up to 24 large toffees per day! The results of the Vipeholm study suggested that the key parameters for caries development were the frequency of sugar consumption and the stickiness of the sugar-containing food items. Until the 1960s dental caries was largely considered a dietary disease with a hereditary caries susceptibility component [165]. However, animal experimental work by Keyes [100], which had been intended to explore the genetic heritability basis for the perceived individual 'susceptibility' to caries development [185], instead spurred a considerable interest in dental plaque, and the strictly biological causes of caries had been identified. Since then, caries etiological research has remained focused on this triangle of diet/sugar, plaque/bacteria, and host/tooth, although the emphasis on each has varied over time. As an example, more recent research indicates that the sugar–caries associations are much weaker in contemporary populations than were the case in the middle of the 20th century

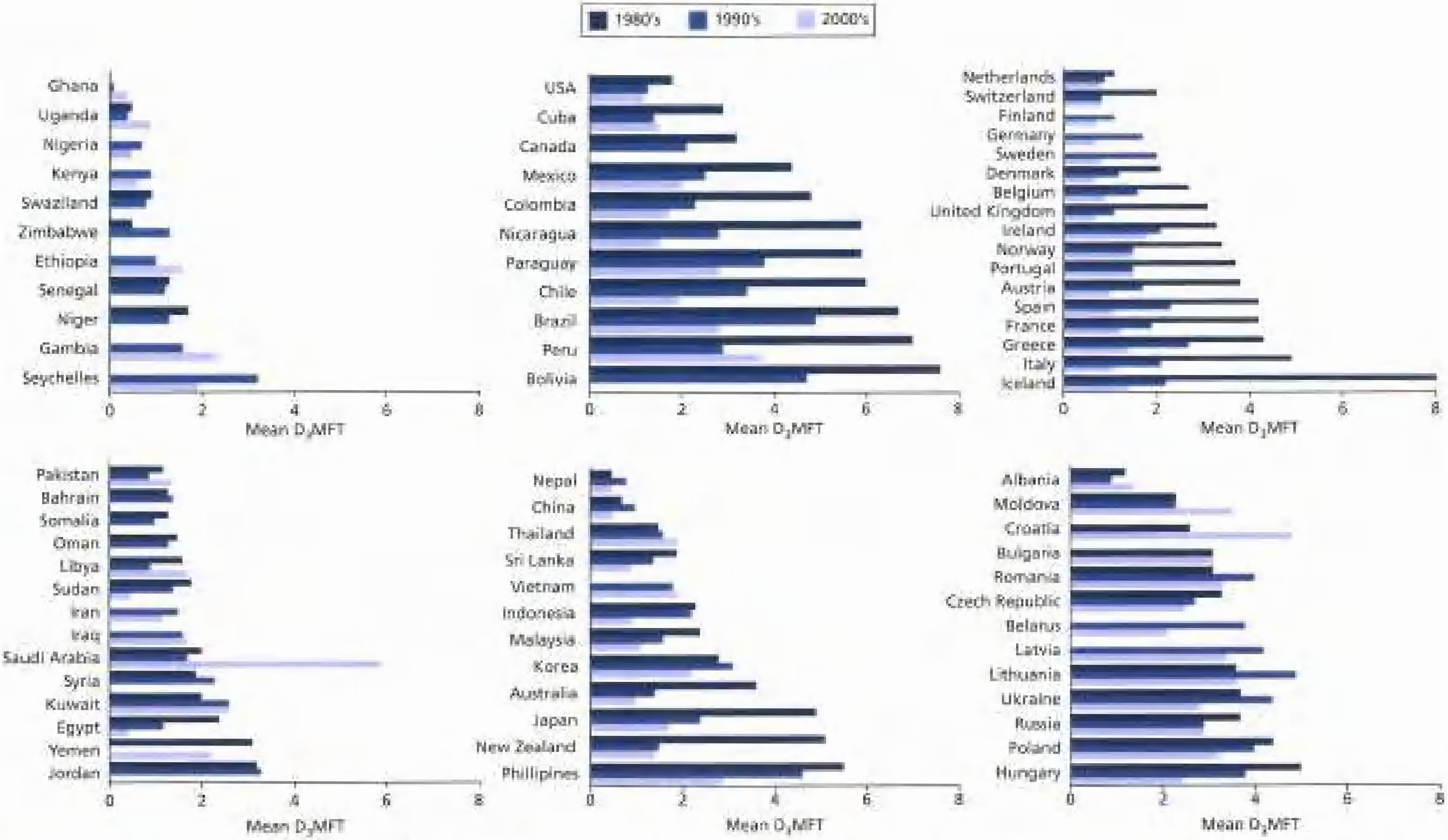


Figure 4.17 The mean D_3MFT counts for 12-year-olds in different countries as reported to the WHO Oral Health Country/Area Profile Programme Database (http://www.mah.se/capp/) during the 1980s, 1990s and 2000s.

[31, 140, 208], and dietary research has been toned down in favor of biofilm research, and most recently also in favor of genetic caries 'susceptibility' research [64, 175, 199, 214].

Proximal, strictly biological causes

From a biological standpoint the causes of dental caries are clear: microbial agents in the biofilm formed on tooth surface produce acids in response to being fed with fermentable carbohydrates from the diet. When these episodes of acid production are sufficiently intense the result is a net mineral loss that marks the incipient caries lesion on the tooth surface. This causal model basically comprises three components – the tooth, the dental plaque, and the diet – and is known as the Keyes triad [101] (Fig. 4.20). Later, this strictly biological model for caries causation was expanded to include more biological factors, such as salivary flow, buffer capacity, and sugar clearance rates [59], and a few socio-behavioral factors at the periphery of the model (Fig. 4.21). These socio-behavioral factors were not considered genuine causes of caries because they were perceived to derive their association with the disease only because of being associated with the strictly biological determinants, the perceived 'real' causes of caries [59]. Importantly, time was added to the model, to indicate the necessity for a drift in the process involving multiple episodes of de- and remineralization. Another interpretation of the time factor in the model is that it serves as a black box of unobserved

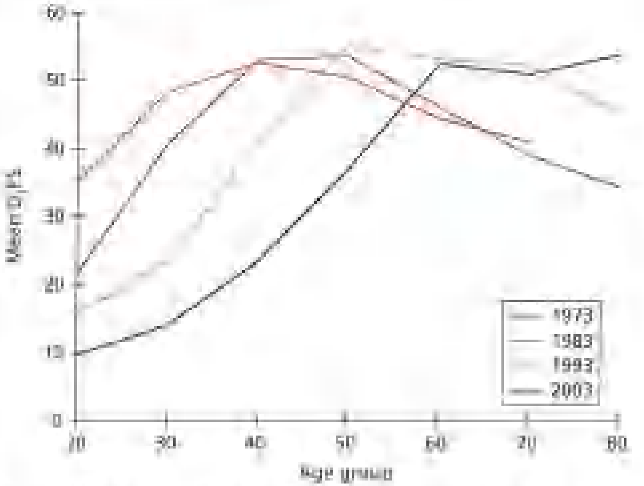


Figure 4.18 The mean D_3FS counts recorded among Swedish adults aged 20, 30, 40, 50, 60, 70, and 80 years in each of four surveys carried out in 1973, 1983, 1993, and 2003. Data from [83].

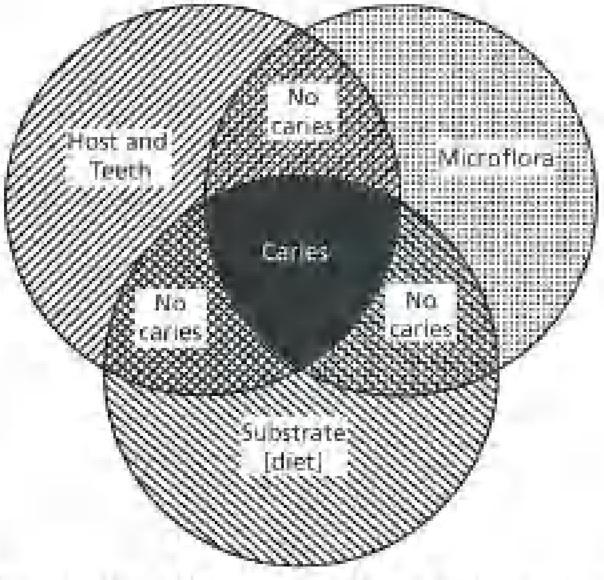


Figure 4.20 Keyes' triad. Three overlapping circles indicate that concomitancy in factors in host, microflora, and substrate is necessary for caries activity [101]. Reproduced with permission of John Wiley & Sons.

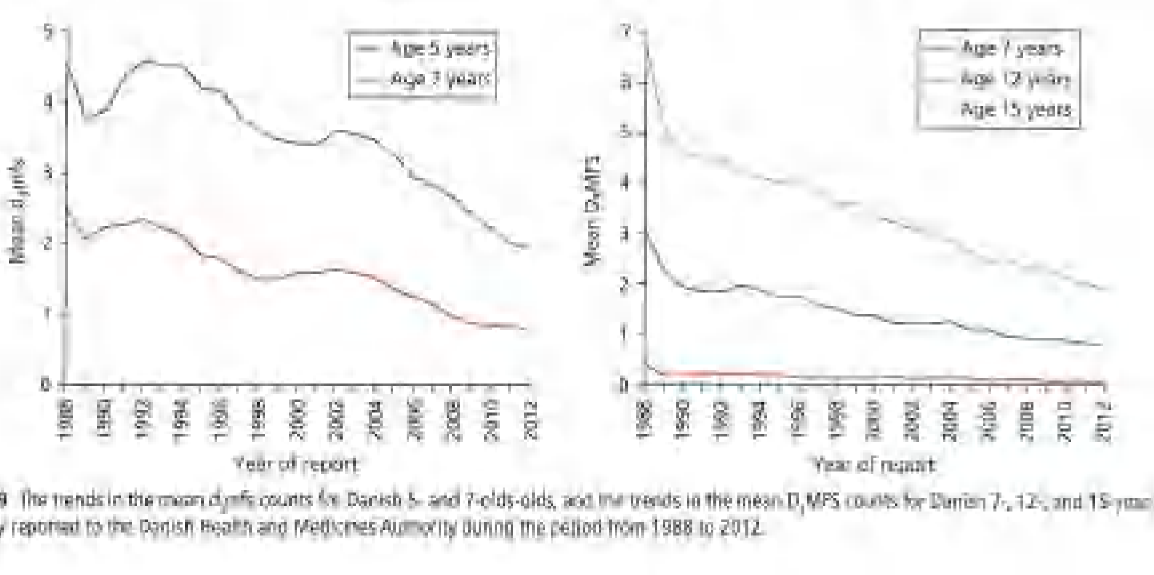


Figure 4.19 The trends in the mean d_3mfs counts for Danish 5- and 7-year-olds, and the trends in the mean D_3MFS counts for Danish 7-, 12-, and 15-year-olds, as compulsorily reported to the Danish Health and Medicines Authority during the period from 1988 to 2012.

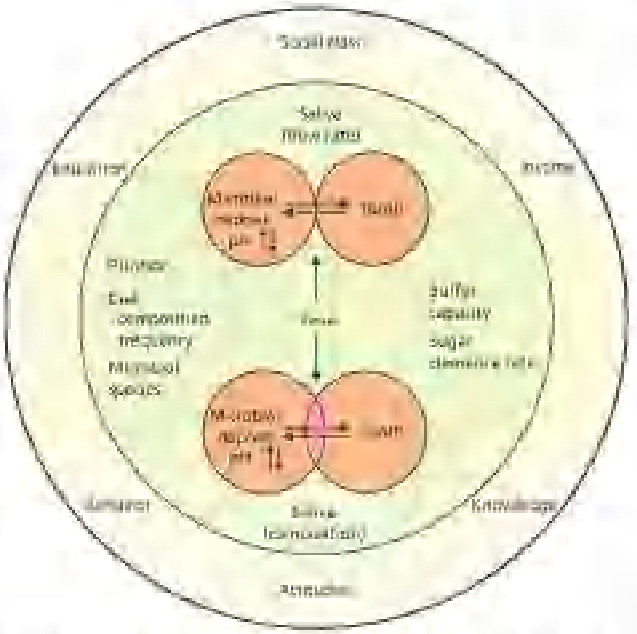


Figure 4.21 The Fejerskov and Manji model for caries causation. Adapted from [59]. Reproduced with permission of the University of North Carolina School of Dentistry.

or disregarded causes. In any case, this narrow biological view of caries causation has resulted in a host of literature discussing the relative role of the strictly biological causal factors in a downstream perspective that goes from the dental plaque to its specific microbial components, from the diet to its different carbohydrate elements, from the oral fluids surrounding the teeth to their constituent components, and from the tooth surface itself to the enamel trace elements and crystal structure (see also Chapters 6–8).

However, this strictly biological understanding of the causes of caries on a tooth surface is insufficient for the understanding of the occurrence of caries in individuals and in populations [76, 79]. It is true that there is a host of experimental evidence from human studies supporting the influence of abstention from oral hygiene procedures and frequent sucrose exposures on the development of caries, such as the Vipeholm study [70], just as there is a host of experimental evidence on the effect of careful oral hygiene and fluoride toothpastes or rinses on the remineralization of experimentally induced caries lesions (see Chapters 13 and 14). Although these experimental studies may 'prove the principles,' they remain experimental (i.e., entirely controlled by scientists), and the results only outline the most proximal biological mechanisms underpinning the formation of a caries lesion in a tooth surface. These studies do not explain why some people have worse oral hygiene or a higher consumption of 'cariogenic' foods than other people do, just as they provide no indication that the experimental interventions (such as abstention from oral hygiene procedures and frequent sucrose doses) are relevant anywhere beyond the realms of the experimental situation. Even so, it is precisely the results of these experimental studies that form the basis for the caries controlling measures used by clinicians in the treatment of individual patients (dietary counseling, oral hygiene instructions, and fluoride toothpastes). Many clinicians, however, will also testify to the considerable problems they encounter when attempting to make their caries-prone patients behave in ways that the dentist based on this experimental evidence considers to be in the patient's 'own best interest,' such as cleaning their teeth regularly using fluoride toothpaste and avoiding unhealthy dietary practices. This occurs precisely because the strictly biological causal model for caries is grossly insufficient for the explanation of caries in individuals and in populations.

Looking to the upstream causes of caries

The limitations of the strictly biological model of caries causation lie in the inability to explain why some people get a lot of caries while others do not and in the inability to explain why caries levels are high in some populations and low in others [76, 79]. To understand that we must address the causes of the causes; that is, we must explain why biofilms may rest on the teeth for days, weeks and years; why there are frequent and extensive pH drops in that biofilm; and why there is no fluoride in the oral fluids. This is akin to asking why some people neglect or forget about their oral hygiene, why they eat cheap and fast meals that are high in fat and sugar, and why they do not get round to buying and using appropriate toothpastes on a regular basis. At this point, a number of behavioral rational choice models are typically invoked to tell us that it is chiefly a lack of knowledge and skills that form people's attitudes and lead them into undesirable behaviors. Not only does this thinking inappropriately blame the victims of extensive caries [36, 200], it also disregards the fact that individual behaviors, such as those related to hygiene and diet, are socially determined and that the broader social contexts into which people are born and grow, work, and age determine the opportunities and constraints that shape these individual behaviors [38] (Fig. 4.11). While it is not in the hands of dental clinicians to deal with these major structural drivers of the occurrence of caries, whether in individuals or in populations, clinicians should be aware that individual behaviors are embedded in the patients' broader social contexts, and that these circumstances may provide constraints that cannot be remedied by oral hygiene instructions and dietary counseling.

References

1. Agbaje JO, Lesaffre E, Declerck D. Assessment of caries experience in epidemiological surveys: a review. *Community Dent Health* 2012; **29**: 14–19.
2. Agbaje JO, Mutsvari T, Lesaffre E, Declerck D. Measurement, analysis and interpretation of examiner reliability in caries experience surveys: some methodological thoughts. *Clin Oral Investig* 2012; **16**: 117–27.
3. Aleksejuniene J, Holst D, Balciuniene I. Factors influencing the caries decline in Lithuanian adolescents – trends in the period 1993–2003. *Eur J Oral Sci* 2004;**112**: 3–7.
4. Antunes JL, Narvai PC, Nugent ZJ. Measuring inequalities in the distribution of dental caries. *Community Dent Oral Epidemiol* 2004; **32**: 41–8.
5. Armfield JM, Spencer AJ. Quarter of a century of change: caries experience in Australian children, 1977–2002. *Aust Dent J* 2008; **53**: 151–9.
6. Armfield JM, Spencer AJ, Slade GD. Changing inequalities in the distribution of caries associated with improving child oral health in Australia. *J Public Health Dent* 2009; **69**: 125–34.
7. Athanassouli I, Mamai-Homata E, Panagopoulos H, Koletsi-Kounari H, Apostolopoulos A. Dental caries changes between 1982 and 1991 in children aged 6–12 in Athens, Greece. *Caries Res* 1994; **28**: 378–82.
8. Baelum V. What is an appropriate caries diagnosis? *Acta Odontol Scand* 2010; **68**: 65–79.
9. Baelum V, Machiulskiene V, Nyvad B, Richards A, Vaeth M. Application of survival analysis to carious lesion transitions in intervention trials. *Community Dent Oral Epidemiol* 2003; **31**: 252–60.
10. Baelum V, Heidmann J, Nyvad B. Dental caries paradigms in diagnosis and diagnostic research. *Eur J Oral Sci* 2006; **114**: 263–77.
11. Bagramian RA, Garcia-Godoy F, Volpe AR. The global increase in dental caries. A pending public health crisis. *Am J Dent* 2009; **22**: 3–8.
12. Batchelor P, Sheiham A. The limitations of a 'high-risk' approach for the prevention of dental caries. *Community Dent Oral Epidemiol* 2002; **30**: 302–12.
13. Batchelor PA, Sheiham A. Grouping of tooth surfaces by susceptibility to caries: a study in 5–16 year-old children. *BMC Oral Health* 2004; **4**: 2.
14. Beltrán-Aguilar ED, Estupiñán-Day S, Báez R. Analysis of prevalence and trends of dental caries in the Americas between the 1970s and 1990s. *Int Dent J* 1999; **49**: 322–9.
15. Beltrán-Aguilar ED, Barker LK, Canto MT, Dye BA, Gooch BF, Griffin SO, Hyman J, Jaramillo F, Kingman A, Nowjack-Raymer R, Selwitz RH, Wu T. Surveillance for dental caries, dental sealants, tooth retention, edentulism, and enamel fluorosis – United States 1988–1994 and 1999–2002. *MMWR Morb Mortal Wkly Rep* 2005; 54 (SS-3): 1–43.
16. Benigeri M, Payette M, Brodeur JM. Comparison between the DMF indices and two alternative composite indicators of dental health. *Community Dent Oral Epidemiol* 1998; **26**: 303–9.
17. Bernabé E, Hobdell MH. Is income inequality related to childhood dental caries in rich countries? *J Am Dent Assoc* 2010; **141**: 143–9.
18. Bjarnason S, Finnbogason SY, Holbrook P, Köhler B. Caries experience in Icelandic 12-year-old urban children between 1984 and 1991. *Community Dent Oral Epidemiol* 1993; **21**: 195–7.
19. Blair YI, McMahon AD, Macpherson LM. Comparison and relative utility of inequality measurements: as applied to Scotland's child dental health. *PLoS One* 2013; **8**: e58593.
20. Bonanato K, Pordeus IA, Moura-Leite FR, Ramos-Jorge ML, Vale MP, Paiva SM. Oral disease and social class in a random sample of five-year-old preschool children in a Brazilian city. *Oral Health Prev Dent* 2010; **8**: 125–32.
21. Bönecker M, Cleaton-Jones P. Trends in dental caries in Latin American and Caribbean 5–6- and 11–13-year-old children: a systematic review. *Community Dent Oral Epidemiol* 2003; **31**: 152–7.
22. Bower E, Gulliford M, Steele J, Newton T. Area deprivation and oral health in Scottish adults: a multilevel study. *Community Dent Oral Epidemiol* 2007; **35**: 118–29.
23. Bratthall D. Introducing the Significant Caries Index together with a proposal for a new global oral health goal for 12-year-olds. *Int Dent J* 2000; **50**: 378–84.
24. Bratthall D. Estimation of global DMFT for 12-year-olds in 2004. *Int Dent J* 2005; **55**: 370–2.
25. Bratthall D, Petersen PE, Stjernswärd JR, Brown LJ. Oral and craniofacial diseases and disorders. In: Jamison DT, Breman JG, Measham AR, Alleyne G, Claeson M, Evans DB, Jha P, Mills A, Musgrove P, eds. *Disease control priorities in developing countries*, 2nd ed. Washington, DC: World Bank, 2006.
26. Broadbent JM, Thomson WM. For debate: problems with the DMF index pertinent to dental caries data analysis. *Community Dent Oral Epidemiol* 2005; **33**: 400–9.
27. Broadbent JM, Thomson WM, Poulton R. Progression of dental caries and tooth loss between the third and fourth decades of life: a birth cohort study. *Caries Res* 2006; **40**: 459–65.
28. Broadbent JM, Thomson WM, Poulton R. Trajectory patterns of dental caries experience in the permanent dentition to the fourth decade of life. *J Dent Res* 2008; **87**: 69–72.
29. Brown LJ, Wall TP, Lazar V. Trends in caries among adults 18 to 45 years old. *J Am Dent Assoc* 2002; **133**: 827–34.
30. Burt BA. How useful are cross-sectional data from surveys of dental caries? *Community Dent Oral Epidemiol* 1997; **25**: 36–41.
31. Burt BA, Pai S. Sugar consumption and caries risk: a systematic review. *J Dent Educ* 2001; **65**: 1017–23.
32. Cabral ED, Caldas Jr AF, Cabral HAM. Influence of the patient's race on the dentist's decision to extract or retain a decayed tooth. *Community Dent Oral Epidemiol* 2005; **33**: 461–6.
33. Carlos JP, Gittelsohn AM. Longitudinal studies of the natural history of caries. II. A life-table study of caries incidence in the permanent teeth. *Arch Oral Biol* 1965; **10**: 739–51.
34. Carlos JP, Gittelsohn AM. Longitudinal studies of the natural history of caries. I. Eruption patterns of the permanent teeth. *J Dent Res* 1965; **44**: 509–16.
35. Carvalho JC, D'Hoore W, Van Nieuwenhuysen JP. Caries decline in the primary dentition of Belgian children over 15 years. *Community Dent Oral Epidemiol* 2004; **32**: 277–82.
36. Carvalho JC, Figueiredo MJ, Vieira EO, Mestrinho HD. Caries trends in Brazilian non-privileged preschool children in 1996 and 2006. *Caries Res* 2009; **43**: 2–9.
37. Chestnutt IG, Schäfer F, Jacobson AP, Stephen KW. Incremental susceptibility of individual tooth surfaces to dental caries in Scottish adolescents. *Community Dent Oral Epidemiol* 1996; **24**: 11–16.
38. Chin NP, Monroe A, Fiscella K. Social determinants of (un)healthy behaviors. *Educ Health* 2000; **13**: 317–28.
39. Cleaton-Jones P, Fatti P. Dental caries trends in Africa. *Community Dent Oral Epidemiol* 1999; **27**: 316–20.
40. Cleaton-Jones P, Fatti P. Dental caries in children in South Africa and Swaziland: a systematic review 1919–2007. *Int Dent J* 2009; **59**: 363–8.
41. Cleaton-Jones P, Fatti P, Bönecker M. Dental caries trends in 5- to 6-year-old and 11- to 13-year-old children in three UNICEF designated regions – Sub Saharan Africa, Middle East and North Africa, Latin America and Caribbean: 1970–2004. *Int Dent J* 2006; **56**: 294–300.
42. Cohen J. A coefficient of agreement for nominal scales. *Educ Psychol Meas* 1960; **20**: 37–46.
43. Commission on Social Determinants of Health. *Closing the gap in a generation. Health equity through action on the social determinants of health.* Final report of the Commission on Social Determinants of Health. Geneva: World Health Organization, 2008: 1–256.
44. Costa SM, Martins CC, Bonfim Mde L, Zina LG, Paiva SM, Pordeus IA, Abreu MH. A systematic review of socioeconomic indicators and dental caries in adults. *Int J Environ Res Public Health* 2012; **9**: 3540–74.
45. Cypriano S, Hoffmann RH, de Sousa Mda L, Wada RS. Dental caries experience in 12-year-old schoolchildren in southeastern Brazil. *J Appl Oral Sci* 2008; **16**: 286–92.
46. Danish Health and Medicines Authority (Sundhedsstyrelsen). *Indberetning på børne- og ungdomstandplejeområdet.* Copenhagen: Danish Health and Medicines Authority (Sundhedsstyrelsen), [illegible].
47. Davies MJ, Spencer AJ, Slade GD. Trends in dental caries experience of school children in Australia – 1977 to 1993. *Aust Dent J* 1997; **42**: 389–94.
48. De Liefde B. The decline of caries in New Zealand over the past 40 years. *NZ Dent J* 1998; **94**: 109–13.
49. Do LG. Distribution of caries in children: variations between and within populations. *J Dent Res* 2012; **91**: 536–43.

50. Do LG, Spencer AJ, Slade GD, Ha DH, Roberts-Thomson KF, Liu P. Trend of income-related inequality of child oral health in Australia. *J Dent Res* 2010; **89**: 959–64.
51. Donaldson AN, Everitt B, Newton T, Steele J, Sherriff M, Bower E. The effects of social class and dental attendance on oral health. *J Dent Res* 2008; **87**: 60–4.
52. Downer MC. Time trends in caries experience of children in England and Wales. *Caries Res* 1992; **26**: 466–72.
53. Drury TF, Garcia I, Adesanya M. Socioeconomic disparities in adult oral health in the United States. *Ann N Y Acad Sci* 1999; **896**: 322–4.
54. Dye BA, Thornton-Evans G. Trends in oral health by poverty status as measured by Healthy People 2010 objectives. *Public Health Rep* 2010; **125**: 817–30.
55. Dye BA, Tan S, Smith V, Lewis BG, Barker LK, Thornton-Evans G, Eke PI, Beltran-Aguilar ED, Horowitz AM, Li CH. *Trends in oral health status: United States, 1988–1994 and 1999–2004*. Vital Health Statistics, Series 11, Number 248. Hyattsville, MD: U.S. Department of Health and Human Services, 2007: 1–92.
56. Edelstein BL. The dental caries pandemic and disparities problem. *BMC Oral Health* 2006; **6** (Suppl 1): S2.
57. Edelstein BL, Douglass CW. Dispelling the myth that 50 percent of U.S. schoolchildren have never had a cavity. *Public Health Rep* 1995; **110**: 522–30; discussion 1, 531–3.
58. Eriksen HM. Has caries merely been postponed? *Acta Odontol Scand* 1998; **56**: 173–5.
59. Fejerskov O, Manji F. Reactor paper. Risk assessment in dental caries. In: Bader JD, ed. *Risk assessment in dentistry*. Chapel Hill, NC: University of North Carolina Dental Ecology, 1990: 215–7.
60. Finlayson TL, Williams DR, Siefert K, Jackson JS, Nowjack-Raymer R. Oral health disparities and psychosocial correlates of self-rated oral health in the National Survey of American Life. *Am J Public Health* 2010; **100** (Suppl 1): S246–55.
61. Flinck A, Källestål C, Holm AK, Allebeck P, Wall S. Distribution of caries in 12-year-old children in Sweden. Social and oral health-related behavioural patterns. *Community Dent Health* 1999; **16**: 160–5.
62. Fuller E, Steele J, Watt R, Nuttall N. 1: Oral health and function – a report from the Adult Dental Health Survey 2009. In: O'Sullivan I, Lader D, eds. *Adult dental health survey 2009*. NHS Information Centre, 2011: 1–42.
63. Fyffe HE, Deery C, Nugent ZJ, Nuttall NM, Pitts NB. Effect of diagnostic threshold on the validity and reliability of epidemiological caries diagnosis using the Dundee Selectable Threshold Method for caries diagnosis (DSTM). *Community Dent Oral Epidemiol* 2000; **28**: 42–51.
64. Gasse B, Grabar S, Lafont AG, Quinquis L, Opsahl Vital S, Davit-Béal T, Moulis E, Chabadel O, Hennequin M, Courson F, Droz D, Vaysse F, Laboux O, Tassery H, Al-Hashimi N, Boillot A, Carel JC, Treluyer JM, Jeanpierre M, Beldjord C, Sire JY, Chaussain C. Common SNPs of AmelogeninX (AMELX) and dental caries susceptibility. *J Dent Res* 2013; **92**: 418–24.
65. Gatou T, Koletsi Kounari H, Mamai-Homata E. Dental caries prevalence and treatment needs of 5- to 12-year-old children in relation to area-based income and immigrant background in Greece. *Int Dent J* 2011; **61**: 144–51.
66. Gilbert GH, Foerster U, Dolan TA, Duncan RP, Ringelberg ML. Twenty-four month coronal caries incidence: the role of dental care and race. *Caries Res* 2000; **34**: 367–79.
67. Gökalp S, Doğan BG. Root caries in 35–44 and 65–74 year olds in Turkey. *Community Dent Health* 2012; **29**: 233–8.
68. Grainger RM. Epidemiological data. In: Chilton NW, ed. *Design and analysis in oral and dental research*. Philadelphia: Lippincott, 1967: 371–32.
69. Guarnizo-Herreño CC, Wehby GL. Explaining racial/ethnic disparities in children's dental health: a decomposition analysis. *Am J Public Health* 2012; **102**: 859–66.
70. Gustafsson BE, Quensel CE, Lanke LS, Lundqvist C, Grahnén H, Bonow BE, Krasse B. The Vipeholm dental caries study; the effect of different levels of carbohydrate intake on caries activity in 436 individuals observed for five years. *Acta Odontol Scand* 1954; **11**: 232–64.
71. Hannigan A, O'Mullane DM, Barry D, Schäfer F, Roberts AJ. A caries susceptibility classification of tooth surfaces by survival time. *Caries Res* 2000; **34**: 103–8.
72. Haugejorden O, Birkeland JM. Evidence for reversal of the caries decline among Norwegian children. *Int J Paediatr Dent* 2002; **12**: 306–15.
73. Haugejorden O, Birkeland JM. Analysis of the ups and downs of caries experience among Norwegian children aged five years between 1997 and 2003. *Acta Odontol Scand* 2005; **63**: 115–22.
74. Haugejorden O, Birkeland JM. Ecological time-trend analysis of caries experience at 12 years of age and caries incidence from age 12 to 18 years: Norway 1985–2004. *Acta Odontol Scand* 2006; **64**: 368–75.
75. Heegaard KM, Holm-Pedersen P, Bardow A, Hvidtfeldt UA, Grønbaek M, Avlund K. The Copenhagen Oral Health Senior Cohort: design, population and dental health. *Gerodontology* 2011; **28**: 165–76.
76. Holst D. Causes and prevention of dental caries: a perspective on cases and incidence. *Oral Health Prev Dent* 2005; **3**: 9–14.
77. Holst D. Oral health equality during 30 years in Norway. *Community Dent Oral Epidemiol* 2008; **36**: 326–34.
78. Holst D, Schuller AA. Oral health changes in an adult Norwegian population: a cohort analytical approach. *Community Dent Oral Epidemiol* 2000; **28**: 102–11.
79. Holst D, Schuller AA, Aleksejuniené J, Eriksen HM. Caries in populations – a theoretical, causal approach. *Eur J Oral Sci* 2001; **109**: 143–8.
80. Holtfreter B, Berg MH, Kocher T, Schiffner U, Hoffmann T, Micheelis W. Change in FS-T index in adults in the German national oral health surveys between 1989 and 2005. *Community Dent Oral Epidemiol* 2013; **41**: 251–60.
81. Hosseinpoor AR, Itani L, Petersen PE. Socio-economic inequality in oral healthcare coverage: results from the World Health Survey. *J Dent Res* 2012; **91**: 275–81.
82. Hu D, Luo G. Trends of caries prevalence and experience in children in Chengdu City, West China, 1982–1990. *Community Dent Oral Epidemiol* 1992; **20**: 308–9.
83. Hugoson A, Koch G. Thirty year trends in the prevalence and distribution of dental caries in Swedish adults (1973–2003). *Swed Dent J* 2008; **32**: 57–67.
84. Hugoson A, Koch G, Slotte C, Bergendal T, Thorstensson B, Thorstensson H. Caries prevalence and distribution in 20–80-year-olds in Jönköping, Sweden, in 1973, 1983, and 1993. *Community Dent Oral Epidemiol* 2000; **28**: 90–6.
85. Hugoson A, Koch G, Helkimo AN, Lundin SA. Caries prevalence and distribution in individuals aged 3–20 years in Jönköping, Sweden, over a 30-year period (1973–2003). *Int J Paediatr Dent* 2008; **18**: 18–26.
86. Ismail AI. Clinical diagnosis of precavitated carious lesions. *Community Dent Oral Epidemiol* 1997; **25**: 13–23.
87. Ismail AI. Visual and visuo-tactile detection of dental caries. *J Dent Res* 2004; **83** (Spec Iss C): C56–C66.
88. Ismail AI, Hasson H, Sohn W. *Dental caries in the second millennium*. Washington, DC: NIH Consensus Development Conference on Dental Caries Diagnosis and Management 2001.
89. Järvinen S. Epidemiologic characteristics of dental caries: relation of DMFS to DMFT. *Community Dent Oral Epidemiol* 1983; **11**: 363–6.
90. Järvinen S. Epidemiologic characteristics of dental caries: relation of DMFT and DMFS to proportion of children with DMF teeth. *Community Dent Oral Epidemiol* 1985; **13**: 235–7.
91. Jones CP. Invited commentary: "Race," racism, and the practice of epidemiology. *Am J Epidemiol* 2001; **154**: 299–304.
92. Kalsbeek H, Truin GJ, van Rossum GMJM, van Rijkom HM, Poorterman JHG, Verrips GH. Trends in caries prevalence in Dutch adults between 1983 and 1995. *Caries Res* 1998; **32**: 160–5.
93. Kaste LM, Selwitz RH, Oldakowski RJ, Brunelle JA, Winn DM, Brown LJ. Coronal caries in the primary and permanent dentition of children and adolescents 1–17 years of age: United States, 1988–1991. *J Dent Res* 1996; **75** Spec No: 631–41.
94. Katz RV, Meskin LH. Testing the internal and external validity of a simplified dental caries index on an adult population. *Community Dent Oral Epidemiol* 1976; **4**: 227–31.
95. Kaufman JS, Cooper RS. Commentary: Considerations for use of racial/ethnic classification in etiologic research. *Am J Epidemiol* 2001; **154**: 291–8.
96. Kaufman JS, Cooper RS. Race in epidemiology: new tools, old problems. *Ann Epidemiol* 2008; **18**: 119–23.

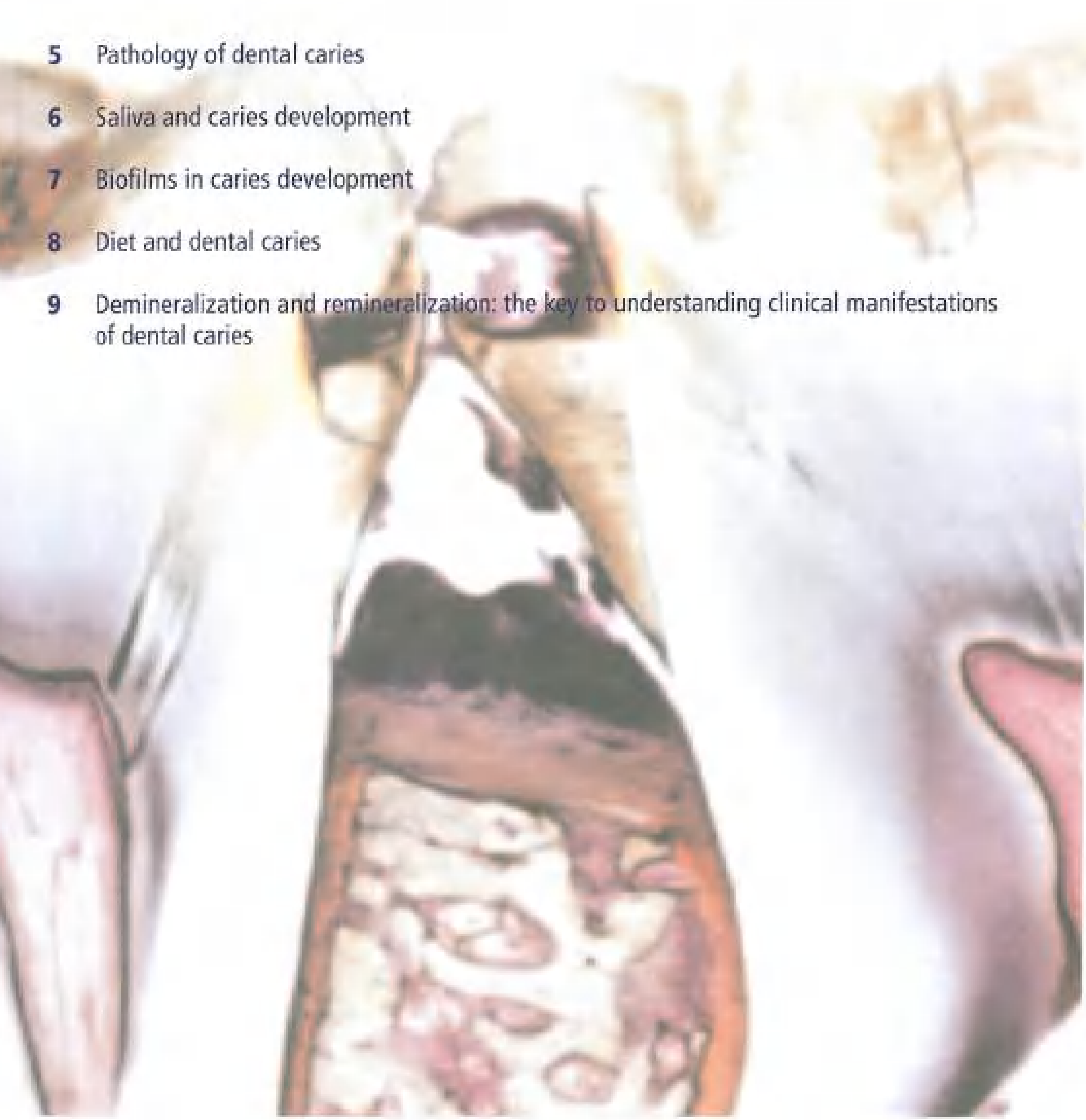
97. Kawashita Y, Kitamura M, Saito T. Monitoring time-related trends in dental caries in permanent teeth in Japanese national surveys. *Int Dent J* 2012; 62: 100–5.
98. Kelly JE, Harvey CR. *Basic data on dental examination findings of persons 1–74 years. United States, 1971–1974*. Hyattsville, MD: US Department of Health, Education, and Welfare; 1979.
99. Kelly JE, Scanlon JV. *Decayed, missing, and filled teeth among children. United States*. Rockville, MD: US Department of Health, Education, and Welfare; 1971.
100. Keyes PH. The infectious and transmissible nature of experimental dental caries. Findings and implications. *Arch Oral Biol* 1960; 1: 304–20.
101. Keyes PH. Recent advances in dental caries research. Bacteriology. Bacteriological findings and biological implications. *Int Dent J* 1962; 12: 443–64.
102. Kingman A. A method of utilizing the subjects' initial caries experience to increase efficiency in caries clinical trials. *Community Dent Oral Epidemiol* 1979; 7: 87–90.
103. Kingman A. Acceptance criteria for clinical caries models. In: Stookey GK, ed. *Proceedings of the 7th Indiana Conference Clinical Models Workshop: Remin–Demin, Precavitation, Caries*. Indianapolis, IN; 2005: 79–98.
104. Kingman A, Selwitz RH. Proposed methods for improving the efficiency of the DMFS index in assessing initiation and progression of dental caries. *Community Dent Oral Epidemiol* 1997; 25: 60–8.
105. Klein H, Palmer CE. Dental caries in American Indian children. Public Health Bulletin no. 239 ed. Washington, DC: US Treasury Department Public Health Service; 1937: 1–54.
106. Klein H, Palmer CE. Studies on dental caries. V. Familial resemblance in the caries experience of siblings. *Public Health Rep* 1938; 53: 1353–64.
107. Klein H, Palmer CE. Community economic status and the dental problem of school children. *Public Health Rep* 1940; 55: 187–205.
108. Klein H, Shimizu T. The family and dental disease. I. DMF experience among husbands and wives. *J Am Dent Assoc* 1945; 32: 945–55.
109. Knutson JW. Epidemiological trend patterns of dental caries prevalence data. *J Am Dent Assoc* 1958; 57: 821–9.
110. Krustrup U, Petersen PE. Dental caries prevalence among adults in Denmark – the impact of socio-demographic factors and use of oral health services. *Community Dent Health* 2007; 24: 225–32.
111. Kumanyika S, Jeffery RW, Morabia A, Ritenbaugh C, Antipatis VJ. Obesity prevention: the case for action. *Int J Obes* 2002; 26: 425–36.
112. Künzel W. Trends in caries experience of 12-year-old children in east European countries. *Int J Paediatr Dent* 1996; 6: 221–6.
113. Künzel W, Fischer T, Lorenz R, Brühmann S. Decline of caries prevalence after the cessation of water fluoridation in the former East Germany. *Community Dent Oral Epidemiol* 2000; 28: 382–9.
114. Last JM, ed. *A dictionary of epidemiology*. Oxford: Oxford University Press; 1995.
115. Last JM. *A dictionary of epidemiology*. Oxford: Oxford University Press; 2001.
116. Lauris JR, da Silva Bastos R, de Magalhaes Bastos JR. Decline in dental caries among 12-year-old children in Brazil, 1980–2005. *Int Dent J* 2012; 62: 308–14.
117. Leroy R, Bogaerts K, Lesaffre E, Declerck D. Multivariate survival analysis for the identification of factors associated with cavity formation in permanent first molars. *Eur J Oral Sci* 2005; 113: 145–52.
118. Levin KA, Davies CA, Topping GV, Assaf AV, Pitts NB. Inequalities in dental caries of 5-year-old children in Scotland, 1993–2003. *Eur J Public Health* 2009; 19: 337–42.
119. Levin KA, Davies CA, Douglas GV, Pitts NB. Urban–rural differences in dental caries of 5-year old children in Scotland. *Soc Sci Med* 2010; 71: 2020–7.
120. Lewis JM. Improving dental health status indicators for evaluation. *Community Dent Oral Epidemiol* 1996; 24: 32–6.
121. Lith A, Lindstrand C, Gröndahl HG. Caries development in a young population managed by a restrictive attitude to radiography and operative intervention: II. A study at the surface level. *Dentomaxillofac Radiol* 2002; 31: 232–9.
122. Locker D. Deprivation and oral health: a review. *Community Dent Oral Epidemiol* 2000; 28: 161–9.
123. López R, Fernández O, Baelum V. Social gradients in periodontal diseases among adolescents. *Community Dent Oral Epidemiol* 2006; 34: 184–96.
124. Lorenz MO. Methods of measuring the concentration of wealth. *Am Stat Assoc* 1905; 9: 209–19.
125. Luan WM, Baelum V, Chen X, Fejerskov O. Dental caries in adult and elderly Chinese. *J Dent Res* 1989; 68: 1771–6.
126. Macek MD, Beltrán-Aguilar ED, Lockwood SA, Malvitz DM. Updated comparison of the caries susceptibility of various morphological types of permanent teeth. *J Public Health Dent* 2003; 63: 174–82.
127. Machiulskiene V, Nyvad B, Baelum V. Prevalence and severity of dental caries in 12-year-old children in Kaunas, Lithuania 1995. *Caries Res* 1998; 32: 175–80.
128. Machiulskiene V, Richards A, Nyvad B, Baelum V. Prospective study of the effect of post-brushing rinsing behaviour on dental caries. *Caries Res* 2002; 36: 301–7.
129. Mamai-Homata E, Topitsoglou V, Oulis C, Margaritis V, Polychronopoulou A. Risk indicators of coronal and root caries in Greek middle aged adults and senior citizens. *BMC Public Health* 2012; 12: 484.
130. Manji F, Fejerskov O, Baelum V. Pattern of dental caries in an adult rural population. *Caries Res* 1989; 23: 55–62.
131. Mantonanaki M, Koletsi-Kounari H, Mamai-Homata E, Papaioannou W. Prevalence of dental caries in 5-year-old Greek children and the use of dental services: evaluation of socioeconomic, behavioural factors and living conditions. *Int Dent J* 2013; 63: 72–9.
132. Marcenes WS, Sheiham A. Composite indicators of dental health: functioning teeth and the number of sound-equivalent teeth (T-Health). *Community Dent Oral Epidemiol* 1993; 21: 374–8.
133. Marmot M, Bell R. Social determinants and dental health. *Adv Dent Res* 2011; 23: 201–6.
134. Marthaler TM. Changes in dental caries 1953–2003. *Caries Res* 2004; 38: 173–81.
135. Marthaler T, Menghini G, Steiner M. Use of the Significant Caries Index in quantifying the changes in caries in Switzerland from 1964 to 2000. *Community Dent Oral Epidemiol* 2005; 33: 159–66.
136. Massler M, Pindborg JJ, Mohammed C. A compilation of epidemiologic studies in dental caries. *Am J Public Health Nations Health* 1954; 44: 1357–62.
137. McDonald SP, Sheiham A. The distribution of caries on different tooth surfaces at varying levels of caries – a compilation of data from 18 previous studies. *Community Dent Health* 1992; 9: 39–48.
138. Mejàre I, Källestål C, Stenlund H. Incidence and progression of approximal caries from 11 to 22 years of age in Sweden: a prospective radiographic study. *Caries Res* 1999; 33: 93–100.
139. Miller AJ, Brunelle JA, Carlos JP, Brown LJ, Löe H. *Oral health of United States adults. The national survey of oral health in U.S. employed adults and seniors: 1985–1986. National findings*. Washington, DC: US Department of Health and Human Services; 1987.
140. Mølgaard C, Andersen NL, Barkholt V, Grunnet N, Hartmann K, Nyvad B, Pedersen BK, Raben A, Rosenberg LC, Sørensen S. The impact of sugar on health. *Ugeskr Laeger* 2003; 165: 4207–10 (in Danish).
141. Monse B, Heinrich-Weltzien R, Benzian H, Holmgren C, van Palenstein Helderman W. PUFA – an index of clinical consequences of untreated dental caries. *Community Dent Oral Epidemiol* 2010; 38: 77–82.
142. Morita I, Nakagaki H, Yoshii S, Tsuboi S, Hayashizaki J, Mizuno K, Sheiham A. Is there a gradient by job classification in dental status in Japanese men? *Eur J Oral Sci* 2007; 115: 275–9.
143. Namal N, Vehid S, Sheiham A. Ranking countries by dental status using the DMFT and FS-T indices. *Int Dent J* 2005; 55: 373–6.
144. National Center for Health Statistics (US). *Decayed, missing, and filled teeth in adults. United States 1960–1962*. Rockville, MD: US Department of Health, Education, and Welfare; 1967.
145. Nishi M, Stjernswärd J, Carlsson P, Bratthall D. Caries experience of some countries and areas expressed by the Significant Caries Index. *Community Dent Oral Epidemiol* 2002; 30: 296–301.
146. Okunseri C, Okunseri E, Garcia RI, Visotcky A, Szabo A. Predictors of dental care use: findings from the national longitudinal study of adolescent health. *J Adolesc Health* 2013; 53: 663–70.
147. Parner ET, Heidmann JM, Væth M, Poulsen S. A longitudinal study of time trends in the eruption of permanent teeth in Danish children. *Arch Oral Biol* 2001; 46: 425–31.

148. Parner ET, Heidmann JM, Væth M, Poulsen S. Surface-specific caries incidence in permanent molars in Danish children. *Eur J Oral Sci* 2007; 115: 491–6.
149. Perera I, Ekanayake L. Social gradient in dental caries among adolescents in Sri Lanka. *Caries Res* 2008; 42: 105–11.
150. Petersen PE. The World Oral Health Report 2003: continuous improvement of oral health in the 21st century – the approach of the WHO Global Oral Health Programme. *Community Dent Oral Epidemiol* 2003; 31: 3–23.
151. Petersen PE. Sociobehavioural risk factors in dental caries – international perspectives. *Community Dent Oral Epidemiol* 2005; 33: 274–9.
152. Petersen PE, Bourgeois D, Ogawa H, Estupinan-Day S, Ndiaye C. The global burden of oral diseases and risks to oral health. *Bull World Health Org* 2005; 83: 661–9.
153. Pieper K, Schulte AG. The decline in dental caries among 12-year-old children in Germany between 1994 and 2000. *Community Dent Health* 2004; 21: 199–206.
154. Piovesan C, Mendes FM, Antunes JL, Ardenghi TM. Inequalities in the distribution of dental caries among 12-year-old Brazilian schoolchildren. *Braz Oral Res* 2011; 25: 69–75.
155. Pitts NB. Discovering dental public health: from Fisher to the future. *Community Dent Health* 1993; 10: 113–8.
156. Pitts NB. Diagnostic tools and measurements – impact on appropriate care. *Community Dent Oral Epidemiol* 1997; 25: 24–35.
157. Pitts NB, Longbottom C. Preventive care advised (PCA)/operative care advised (OCA) – categorising caries by the management option. *Community Dent Oral Epidemiol* 1995; 23: 55–9.
158. Poulsen S, Horowitz HS. An evaluation of a hierarchical method of describing the pattern of dental caries attack. *Community Dent Oral Epidemiol* 1974; 2: 7–11.
159. Poulsen S, Pedersen MM. Dental caries in Danish children: 1988–2001. *Eur J Paediatr Dent* 2002; 4: 195–8.
160. Poulsen S, Heidmann J, Vaeth M. Lorenz curves and their use in describing the distribution of 'the total burden' of dental caries in a population. *Community Dent Health* 2001; 18: 68–71.
161. Reid BC, Hyman JJ, Macek MD. Race/ethnicity and untreated dental caries: the impact of material and behavioral factors. *Community Dent Oral Epidemiol* 2004; 32: 329–36.
162. Ringelberg ML, Matonski GM, Kimball AW. Dental caries – experience in three generations of families. *J Public Health Dent* 1974; 34: 174–80.
163. Rose G. *The strategy of preventive medicine*. Oxford: Oxford University Press, 1992.
164. Sabbah W, Tsakos G, Chandola T, Sheiham A, Watt RG. Social gradients in oral and general health. *J Dent Res* 2007; 86: 992–6.
165. Sabbah W, Tsakos G, Sheiham A, Watt RG. The effects of income and education on ethnic differences in oral health: a study in US adults. *J Epidemiol Community Health* 2009; 63: 516–20.
166. Sanders AE, Slade GD, Turrell G, Spencer AJ, Marcenes W. The shape of the socioeconomic–oral health gradient: implications for theoretical explanations. *Community Dent Oral Epidemiol* 2006; 34: 310–9.
167. Sanders AE, Lim S, Sohn W. Resilience to urban poverty: theoretical and empirical considerations for population health. *Am J Public Health* 2008; 98: 1101–6.
168. Sanders AE, Turrell G, Slade GD. Affluent neighborhoods reduce excess risk of tooth loss among the poor. *J Dent Res* 2008; 87: 969–73.
169. Sanders AE, Slade GD, John MT, Steele JG, Suominen-Taipale AL, Lahti S, Nuttall NM, Allen PF. A cross-national comparison of income gradients in oral health quality of life in four welfare states: application of the Korpi and Palme typology. *J Epidemiol Community Health* 2009; 63: 569–74.
170. Schiffner U, Hoffmann T, Kerschbaum T, Micheelis W. Oral health in German children, adolescents, adults and senior citizens in 2005. *Community Dent Health* 2009; 26: 18–22.
171. Schuller AA, Holst D. Changes in the oral health status of adults from Trøndelag, Norway, 1973–1983–1994. *Community Dent Oral Epidemiol* 1998; 26: 201–8.
172. Schuller AA, Holst D. Oral status indicators DMFT and FS-T: reflections on index selection. *Eur J Oral Sci* 2001; 109: 155–9.
173. Schützhold S, Holtfreter B, Hoffmann T, Kocher T, Micheelis W. Trends in dental health of 35- to 44-year-olds in West and East Germany after reunification. *J Public Health Dent* 2013; 73: 65–73.
174. Seppä L, Kärkkäinen S, Hausen H. Caries trends 1992–1998 in two low-fluoride Finnish towns formerly with and without fluoridation. *Caries Res* 2000; 34: 462–8.
175. Shaffer JR, Feingold E, Wang X, Lee M, Tcuenco K, Weeks DE, Weyant RJ, Crout R, McNeil DW, Marazita ML. GWAS of dental caries patterns in the permanent dentition. *J Dent Res* 2013; 92: 38–44.
176. Shearer DM, Thomson WM, Caspi A, Moffitt TE, Broadbent JM, Poulton R. Family history and oral health: findings from the Dunedin Study. *Community Dent Oral Epidemiol* 2012; 40: 105–15.
177. Sheiham A. Impact of dental treatment on the incidence of dental caries in children and adults. *Community Dent Oral Epidemiol* 1997; 25: 104–12.
178. Sheiham A, Sabbah W. Using universal patterns of caries for planning and evaluating dental care. *Caries Res* 2010; 44: 141–50.
179. Sheiham A, Maizels J, Maizels A. New composite indicators of dental health. *Community Dent Health* 1987; 4: 407–14.
180. Souza ML, Bastos JL, Peres MA. Trends in dental caries rates in 12- and 13-year-old schoolchildren from Florianópolis (Brazil) between 1971 and 2005. *Oral Health Prev Dent* 2008; 6: 187–92.
181. Spencer AJ. Skewed distributions – new outcome measures. *Community Dent Oral Epidemiol* 1997; 25: 52–9.
182. Stecksén-Blicks C, Sunnegårdh K, Borssén E. Caries experience and background factors in 4-year-old children: time trends 1967–2002. *Caries Res* 2004; 38: 149–55.
183. Steele JG, Treasure ET, O'Sullivan I, Morris J, Murray JJ. Adult Dental Health Survey 2009: transformations in British oral health 1968–2009. *Br Dent J* 2012; 213: 523–7.
184. Szöke J, Petersen PE. Evidence for dental caries decline among children in an East European country (Hungary). *Community Dent Oral Epidemiol* 2000; 28: 155–60.
185. Tanzer JM. Dental caries is a transmissible infectious disease: the Keyes and Fitzgerald revolution. *J Dent Res* 1995; 74: 1536–42.
186. Thomson WM, Mackay TD. Child dental caries patterns described using a combination of area-based and household-based socio-economic status measures. *Community Dent Health* 2004; 21: 285–90.
187. Thomson WM, Poulton R, Milne BJ, Caspi A, Broughton JR, Ayers KM. Socioeconomic inequalities in oral health in childhood and adulthood in a birth cohort. *Community Dent Oral Epidemiol* 2004; 32: 345–53.
188. Toverud G. Dental caries in Norwegian children during and after the last World War: a preliminary report. *Proc R Soc Med* 1949; 42: 249–58.
189. Toverud G. The influence of war and post-war conditions on the teeth of Norwegian school children. II. Caries in the permanent teeth of children aged 7–8 and 12–13 years. *Milbank Mem Fund Q* 1957; 35: 127–96.
190. Toverud G. The influence of war and post-war conditions on the teeth of Norwegian school children. III. Discussion of food supply and dental condition in Norway and other European countries. *Milbank Mem Fund Q* 1957; 35: 373–459.
191. Truin GJ, König KG, Bronkhorst EM, Frankenmolen F, Mulder J, van't Hof MA. Time trends in caries experience of 6- and 12-year-old children of different socioeconomic status in The Hague. *Caries Res* 1998; 32: 1–4.
192. Tsakos G, Demakakos P, Breeze E, Watt RG. Social gradients in oral health in older adults: findings from the English longitudinal survey of aging. *Am J Public Health* 2011; 101: 1892–9.
193. Tsakos G, Sabbah W, Chandola T, Newton T, Kawachi I, Aida J, Sheiham A, Marmot MG, Watt RG. Social relationships and oral health among adults aged 60 years or older. *Psychosom Med* 2013; 75: 178–86.
194. Turrell G, Sanders AE, Slade GD, Spencer AJ, Marcenes W. The independent contribution of neighborhood disadvantage and individual-level socioeconomic position to self-reported oral health: a multilevel analysis. *Community Dent Oral Epidemiol* 2007; 35: 195–206.
195. Vadiakas G, Oulis CJ, Tsinidou K, Mamai-Homata E, Polychronopoulou A. Socio-behavioural factors influencing oral health of 12 and 15 year old Greek adolescents. A national pathfinder survey. *Eur Arch Paediatr Dent* 2011; 12: 139–45.

196. Vilstrup L, Christensen LB, Hede B, Kristensen SF. Tandsundhed for brugere af praksistandplejen i 2000–2008. *Tandlaegebladet* 2010; **114**: 704–12.
197. Virtanen JI. Changes and trends in attack distributions and progression of dental caries in three age cohorts in Finland. *J Epidemiol Biostat* 2001; **6**: 325–9.
198. Vrbic V. Reasons for the caries decline in Slovenia. *Community Dent Oral Epidemiol* 2000; **28**: 126–32.
199. Wang X, Shaffer JR, Zeng Z, Begum F, Vieira AR, Noel J, Anjomshoaa I, Cuenco KT, Lee MK, Beck J, Boerwinkle E, Cornelis MC, Hu FB, Crosslin DR, Laurie CC, Nelson SC, Doheny KF, Pugh EW, Polk DE, Weyant RJ, Crout R, McNeil DW, Weeks DE, Feingold E, Marazita ML. Genome-wide association scan of dental caries in the permanent dentition. *BMC Oral Health* 2012; **12**: 57.
200. Watt RG. From victim blaming to upstream action: tackling the social determinants of oral health inequalities. *Community Dent Oral Epidemiol* 2007; **35**: 1–11.
201. Watt RG. Social determinants of oral health inequalities: implications for action. *Community Dent Oral Epidemiol* 2012; **40** (Suppl 2): 44–8.
202. Watt RG, Steele JG, Treasure ET, White DA, Pitts NB, Murray JJ. Adult Dental Health Survey 2009: implications of findings for clinical practice and oral health policy. *Br Dent J* 2013; **214**: 71–5.
203. White D, Pitts N, Steele J, Sadler K, Chadwick B. 2: Disease and related disorders – a report from the Adult Dental Health Survey 2009. In: O'Sullivan I, Lader D, eds. *Adult dental health survey 2009*. NHS Information Centre, 2011: 1–55.
204. White DA, Tsakos G, Pitts NB, Fuller E, Douglas GV, Murray JJ, Steele JG. Adult Dental Health Survey 2009: common oral health conditions and their impact on the population. *Br Dent J* 2012; **213**: 567–72.
205. WHO Country/Area Profile Project (CAPP). *Significant Caries Index*. http://www.mah.se/CAPP/Methods-and-Indices/for-Caries-prevalence/Significant-Caries-Index/. Accessed October 10, 2014.
206. Williams DR. Race, socioeconomic status, and health. The added effects of racism and discrimination. *Ann N Y Acad Sci* 1999; **896**: 173–88.
207. Winn DM, Brunelle JA, Selwitz RH, Kaste LM, Oldakowski RJ, Kingman A, Brown LJ. Coronal and root caries in the dentition of adults in the United States, 1988–1991. *J Dent Res* 1996; **75**: 642–51.
208. Woodward M, Walker AR. Sugar consumption and dental caries: evidence from 90 countries. *Br Dent J* 1994; **176**: 297–302.
209. World Health Organization. *Oral health surveys. Basic methods*. Geneva: World Health Organization, 1971.
210. World Health Organization. *Oral health surveys. Basic methods*. Geneva: World Health Organization, 1977.
211. World Health Organization. *A guide to oral health epidemiological investigations*. Geneva: World Health Organization, 1979: 1–43.
212. World Health Organization. *Oral health surveys. Basic methods*. Geneva: World Health Organization, 1987.
213. World Health Organization. *Oral health surveys. Basic methods*. Geneva: World Health Organization, 1997.
214. Zeng Z, Shaffer JR, Wang X, Feingold E, Weeks DE, Lee M, Cuenco KT, Wendell SK, Weyant RJ, Crout R, McNeil DW, Marazita ML. Genome-wide association studies of pit-and-fissure- and smooth-surface caries in permanent dentition. *J Dent Res* 2013; **92**: 432–7.

Part II

The caries lesion and its biological determinants



5

Pathology of dental caries

O. Fejerskov

Introduction

Dental caries is the localized destruction of the tooth caused by the metabolic events taking place in the oral biofilm. The disease can affect enamel, dentin, and cementum. The demineralization progresses very slowly in most individuals. The gradual demineralization of the tissues involved is kept active when there is a disturbance in the physiological equilibrium in the biofilm or dental plaque (see Chapter 9) covering the affected site. The disease is seldom self-limiting unless the dental plaque covering the site is regularly disturbed mechanically and/or the metabolism in the biofilm is interfered with. In the absence of this intervention, dental caries progresses rather slowly until the tooth is destroyed. The localized destruction of the hard tissues, often referred to as the *lesion*, is the *sign* or *symptom* of the metabolic disturbance in biofilm equilibrium.

The lesions can be arranged on a scale ranging from initial loss of mineral at the ultrastructural/nanoscale level to total tooth destruction (Fig. 5.1). Even though many scientists consider caries initiation and progression to be a result of multiple interrelated factors, it is a prerequisite for caries destruction to develop that oral bacteria form a biofilm (dental plaque) on the tooth surface. However, teeth may be covered by dental biofilm without visible signs of

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

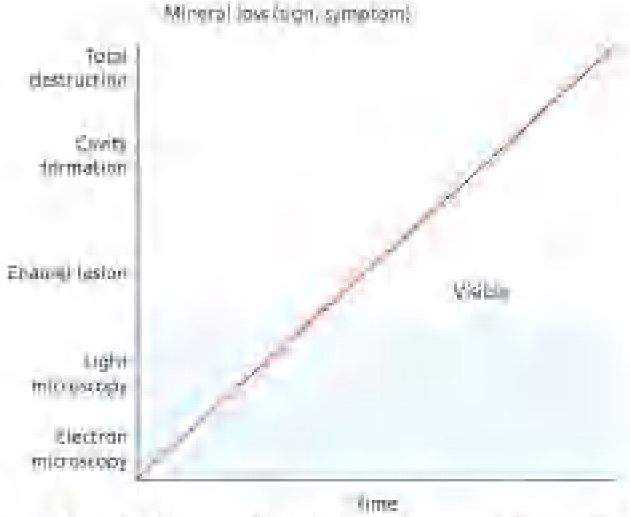


Figure 5.1 Principal progress of mineral loss in relation to time. The slope of the line may vary depending on the caries challenge, and time may vary from weeks to months and years. The blue zone indicates that the mineral loss is not visible.

caries; therefore, we can conclude that, *while microbial deposits are necessary, they are not sufficient to cause caries.* As described in Chapter 2 the metabolic events in the biofilm result in multiple fluctuations in pH in the plaque fluid. Thus, the tooth surface minerals will constantly be in a dynamic equilibrium with the oral fluids. Changes in pH, buffer capacity of the biofilm, and degree of saturation of minerals in the fluid phase will influence this equilibrium over time.

Schematically, this is presented in Fig. 5.2. As pH fluctuates (the upper line) within minutes, hours, days, and months, dissolution and redeposition of minerals occur (for details on chemical reactions, see Chapter 9). The three curves illustrate three different theoretical scenarios in terms of net loss or gain of minerals at the tooth surface. When (and if) the net loss of mineral reach a certain level (indicated by the dotted horizontal line) the increased pore volume (see later this chapter) results in a clinically visible white, opaque change of the affected enamel: 'a lesion.' Each of the lines represents what may happen at a given tooth surface. If averaged they give straight lines of different inclination reflecting, arbitrarily, the rate of lesion progression at the given surface.

In order to provide relevant information for diagnosis and treatment of the disease, chapters on pathology of dental caries conventionally focus on clinical, histological, and ultrastructural changes characterizing different stages of tissue destruction. Since any caries lesion is *a result of past and present metabolic activities in microbial plaque*, we prefer to combine information on intraoral plaque accumulation with corresponding tissue reactions. We have chosen this approach for two reasons. First, because diagnosis and treatment decisions cannot be made on the basis of clinical signs only, but require appreciation of the local environment (the oral cavity of the patient) in its broader sense. Second, because examination of the interplay between dental plaque and the tooth gives important information that is useful for an understanding of intraoral mechanisms for caries initiation, progression, and arrest. The ultimate objective of this chapter is to provide the scientific basis for a rational clinical examination as presented in Chapters 10, 11, and 12.

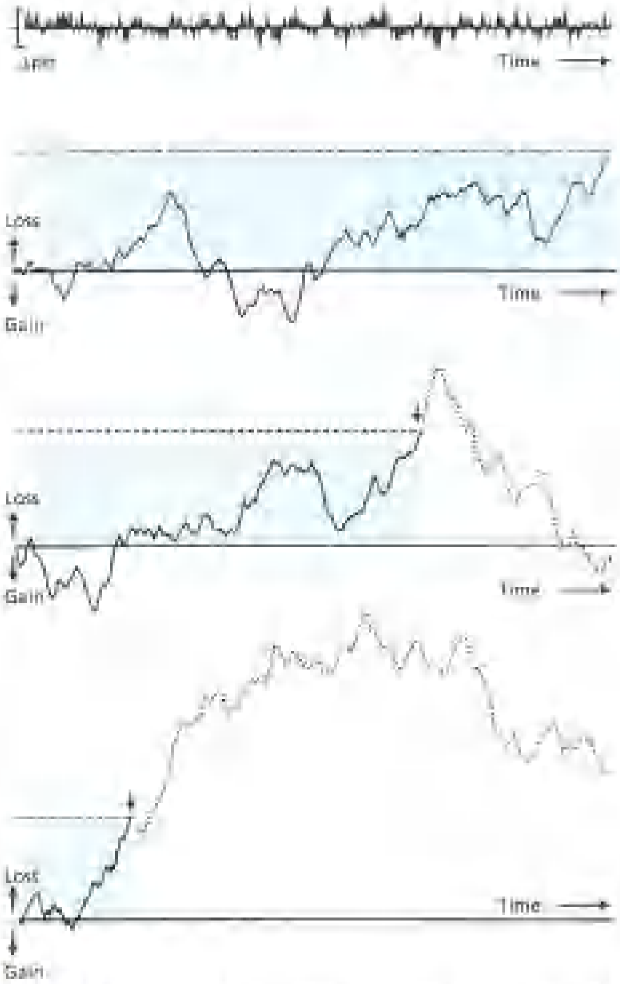


Figure 5.2 Schematic illustration of micro-events at a surface over time. The upper fluctuating line indicates pH fluctuations in a biofilm over time (minutes, hours, days). The three curves show three different examples of fluctuating mineral loss (up) or gain (down) in enamel as a result of innumerable fluctuations in pH. The horizontal dotted lines indicate where loss of mineral may be seen clinically as a white spot. See text for details.

Although we are aware that dentists cannot use electron microscopes or sectioning techniques in their clinical examinations, we will be referring to these techniques widely in this chapter. Mind you, *what we see and perceive depends to a large extent on what we know.* Thus, a freshman looking into the mouth of a patient observes only two arches of teeth, but a trained dentist recognizes teeth of specific types, different kinds of treatment, and past diseases. We cannot give you experience, but we seek to give you biological information on which to base your observations.

This chapter will deal with:

- the basic structure and chemistry of enamel at time of eruption;
- how the enamel structure interacts with the oral environment – and discuss possible prerequisites for caries initiation, progression, and arrest.

On the basis of the fundamental structural characteristics of the white spot lesion, we will then deal with:

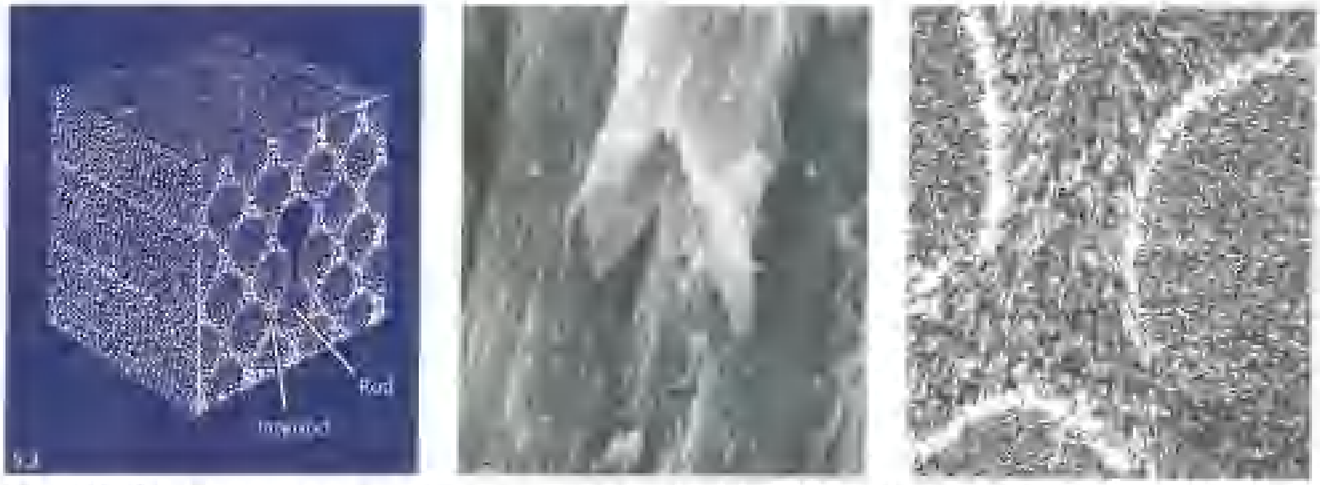
- caries lesion development on approximal and occlusal surfaces;
- the gradual lesion progression involving the pulpo-dentinal organ;
- root caries, in the final section.

Human dental enamel at time of eruption

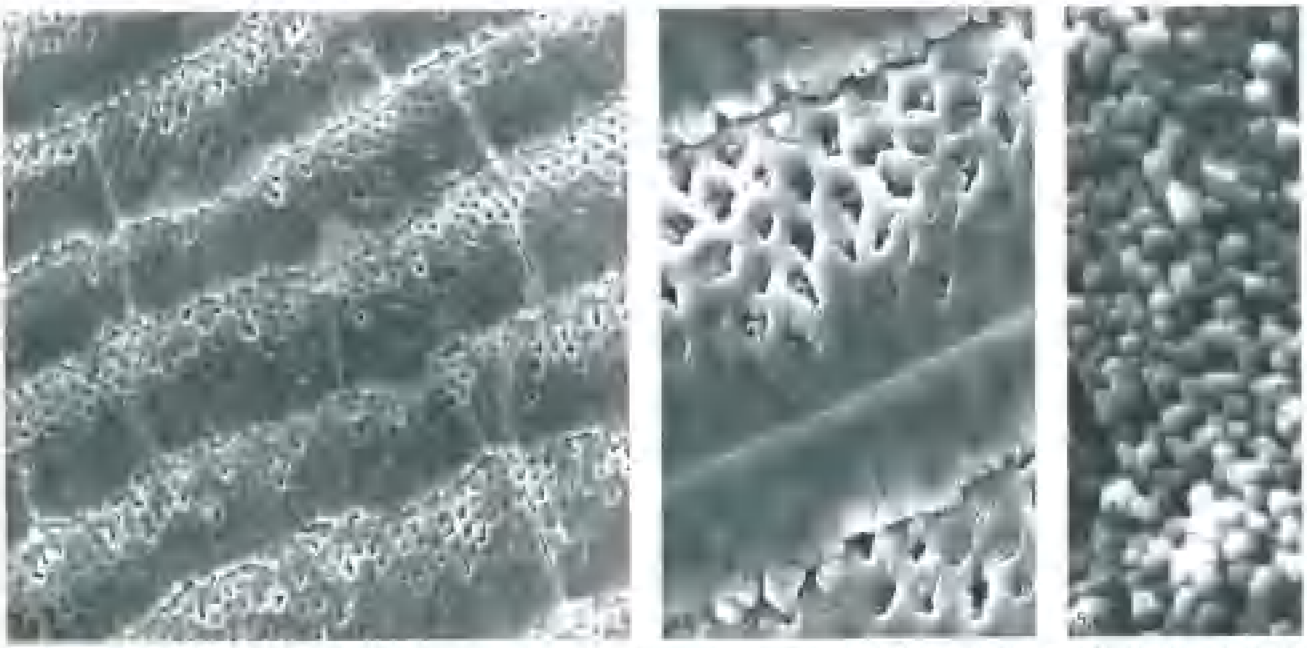
When a tooth erupts into the oral cavity the enamel is fully mineralized. At eruption the enamel has attained its final concentrations of 95% mineral and 5% water and organic matrix by weight. The corresponding figures on volume basis are 86% mineral, 2% organic material, and 12% water.

Normal, sound enamel consists of hydroxyapatite crystals so tightly packed that the enamel has a glass-like appearance; the enamel is translucent. The yellow-white color of teeth is therefore the result of dentin 'shining through' the translucent enamel cover. Thus, the thickness of the enamel in a particular area will affect color. Therefore, teeth have different colors incisally and cervically. The enamel crystals are not haphazardly packed, but are arranged in rod and interrod enamel, as schematically shown in Fig. 5.3. Based on this type of illustration, the rod/interrod pattern is commonly referred to as a *fish shape* comprised of the 'head' (rod) and the 'tail' (interrod) regions when seen in cross-sections. This figure can also be identified in fractured enamel examined in the scanning electron microscope (Fig. 5.4). Thus, in the rods, which extend though the entire thickness of the enamel, the long axes of crystals follow the rod direction; hence, in sections cut perpendicular to the long axis of rods the crystals are regular hexagonal in shape (see Chapter 9) and tightly packed (Fig. 5.5). The packing of crystals is slightly looser along the rod periphery than in the rod and interrod enamel as crystals in the interrod (tail) enamel gradually bend their long axes away from the long axes of the rods – compare Figs 5.3 and 5.5. This particular pattern of crystals can be explained by the way in which enamel matrix secretion and early mineralization take place [7] (Figs 5.6–5.11). Even though crystal packing is very tight at the electron microscopic level (Figs 5.8 and 5.9), each crystal is separated from its neighbors by tiny intercrystalline spaces; these are particularly abundant along the interface between rod and interrod enamel forming the periprismatic sheaths [8]. These spaces are not empty, but filled with water and organic material of developmental origin. The intercrystalline spaces together form a fine network of diffusion pathways which are often referred to as micropores, or simply pores, in the enamel. Their size can be estimated in a number of ways.

There is no doubt that the very outermost enamel is rather porous, as demonstrated by the openings of the striae of Retzius at the surface (Figs 5.6 and 5.7); the perikymata grooves indicate where the striae reach the surface and open to larger diffusion pathways. Similarly, the numerous pits of Tomes' processes are partly encircled by the openings of the



Figures 5.3–5.5 The principal orientation of crystals in human enamel. Figure 5.3 is a schematic drawing showing that in the rods the long axes of crystals run in parallel with the long axes of rods (head), but in the interrod regions (tail) the crystals gradually bend in the cervical direction. This creates in a cross section a fish-like figure consisting of a head and tail. Figure 5.4 shows this pattern in a fractured enamel surface examined by SEM. In Fig. 5.5 it is examined in a transmission electron microscope, where the section is cut perpendicular to the long axes of the rods. R, rod; IR, interrod.



Figures 5.6–5.8 Scanning electron micrographs showing an unerupted enamel surface at different levels of examination. Figure 5.6 shows an overview of perikymata and Tomes' processes pits, and this is shown in detail in Fig. 5.7. Figure 5.8 shows at high magnification the ends of rounded crystals separated by distinct intercrystalline spaces. The surface is examined after removal of organic films. Courtesy of IRL Press.

Figures 5.9–5.11 Human enamel examined by scanning electron microscopy and transmission electron microscopy after removal of the mineral content (Fig. 5.11) just prior to eruption. In Fig. 5.9 the surface crystals are seen from a fractured surface. In Fig. 5.10 the surface shows rod (R) endings surrounded by periprismatic, arch-shaped gaps representing the openings of the interface between rod and interrod enamel (IR). The mineralized surface is highly irregular, occasionally with holes into the enamel filled by developmental proteins (Fig. 5.11). These proteins also occupy the gaps surrounding partly the rods and are part of the diffusion pathways throughout the enamel. E: enamel space; DP: developmental protein.

arch-shaped spaces (where the periprismatic sheaths are located). These extend throughout the enamel and partly separate the rod (or prism) from the interrod enamel (Figs 5.7 and 5.10) [15, 27]. Moreover, a varying number of developmental defects, designated focal holes, small irregular fissures, and microholes less than 1 µm in diameter, are observed in the enamel. These features are filled with developmental proteins, extending as plugs into the enamel surface (Fig. 5.11).

Although these potential diffusion pathways may be seen in the SEM following chemical removal of proteins and dehydration, it is important to appreciate that under *in vivo* conditions all spaces within the enamel, irrespective of their size, will contain protein of developmental origin, lipid, and water. The presence of this organic component will naturally modify the diffusion processes into and out of enamel, as well as modify the reaction of the mineral phase to the environmental factors in the oral cavity. *It is therefore reasonable to consider dental enamel as a microporous solid composed of tightly packed crystals.* In the enamel and at the surface, however, there are variations in crystal packing related to different anatomical structures.

Once the enamel has erupted into the oral cavity, its surface constantly undergoes modification caused by chemical and physical traumas; therefore, it must be regarded as being in dynamic transformation at all times.

Because of the surface porosity, it has been suggested that the enamel undergoes a period of posteruptive maturation subsequent to eruption. Nobody has fully explained the nature of such a maturation, but it is thought that, during this period of time, mineral ions and fluoride in the oral environment diffuse passively into the surface enamel. Evidence for such a process is suggested by the fact that the fluoride concentration in surface enamel increases subsequent to eruption. However, from a chemical point of view it is difficult to appreciate how such a process is mediated as there does not seem to be a true driving force existing under natural (neutral) pH conditions (see chemical explanation in Chapter 9). It is a much more likely explanation that the posteruptive uptake of fluoride is entirely driven by the pH fluctuations in the biofilm [18]. So let us consider what may happen during the long-lasting eruption that might explain the phenomenon 'posteruptive maturation.'

Dental enamel is a highly mineralized acellular tissue in which calcium phosphate crystals comprise some 99% of the dry weight (see Chapter 9, Table 9.1). The crystals resemble the mineral hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, in the way that the calcium, phosphate and hydroxyl ions are arranged in a repeating pattern in the crystal lattice structure. Inclusions of carbonate, sodium, fluoride, and other ions make it an impure form of the mineral (see also Chapter 9). Apatite is commonly found in biological hard tissues such as enamel, dentin, cementum, and bone. Enamel apatite crystals are long and thin, approximately 50 nm wide in cross-section and more than 100 μm long in the c-axis, and are tightly packed in a repeating arrangement that forms the enamel prisms. Some individual crystals may run the full thickness of enamel and fuse with adjacent crystals at places along their length [12]. The space between the crystals is occupied by water (11% by volume) and organic material (2% by volume). Because of its very high mineral content and minimal acellular matrix, the color, hardness, and other physical properties of enamel are similar to those of hydroxyapatite. For example, the density of hydroxyapatite is 3.16 g/cm^3 and that of enamel is 2.95 g/cm^3. Hydroxyapatite is a colorless mineral, and enamel is also colorless; the slight yellowish color of tooth crowns, as already mentioned, is due to the color of dentin showing through. Although hydroxyapatite crystals are transparent, the fact that they have a refractive index (RI) of 1.64 while surrounded by water with an RI of 1.33 renders enamel translucent. If water is replaced by air then enamel appears opaque chalky white. Therefore, pores in the enamel can be assessed by changing the content of water and replacing it with air or liquids with different, known refractive indices and then examining sections of teeth by polarized light microscopy. Hydroxyapatite has a hardness of about 430 KHN (Knoop hardness number) and enamel 378 KHN; however, this not only reflects hydroxyapatite hardness but is also related to how strongly the individual crystals adhere to one another. Most importantly, the solubility of enamel apatite corresponds to the solubility of enamel as a tissue. See Chapter 9 concerning de- and remineralization of enamel, chemically and structurally.

Teeth, unlike mushrooms, do not erupt overnight! When a tooth gradually emerges, the partially erupted tooth does not participate in mastication. For this reason, such teeth offer more favorable conditions for bacterial accumulation (Fig. 5.12) than fully erupted teeth do [8–11, 22, 46]. Furthermore, microbial accumulation may be even further enhanced because children frequently avoid tooth brushing of erupting teeth as eruption is accompanied by gingival bleeding, and the area may be sore to touch. Erupting teeth are consequently exposed to microbial plaque for several months before functional occlusion is obtained. During this period of time, innumerable minute processes of mineral dissolution and redeposition occur at the enamel–plaque interface (see Fig. 5.2), and it is therefore not surprising that the enamel surface at the *subclinical* level exhibits a variety of microsurface destructions, as seen in Figs 5.13 and 5.14. These changes are not clinically visible but correspond to those observed after 1 week of exposure to cariogenic challenge of dental plaque in a clinical controlled experiment [43].

The changes represent *active and inactive enamel lesions at the subclinical level*. As the tooth approaches complete occlusion, shear forces from functional chewing will modify microbial accumulation, and hence cusps are often devoid of dental plaque.

Enamel surfaces free of microbial deposits once fully erupted are always covered by the proteinaceous pellicle. Beneath this coating, signs of minor attrition may be observed in the form of scratches. Furthermore, larger irregular defects may represent scars as a result of previous surface dissolution.

These macroscopically invisible changes can be understood as *inactive enamel lesions at the subclinical level*. On this basis it can be concluded that subclinical active lesions

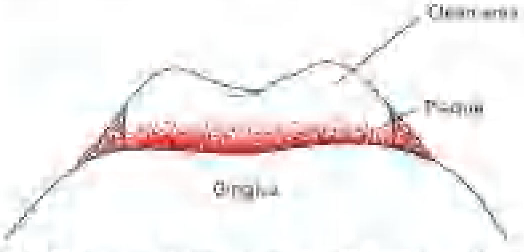


Figure 5.12 *Drawing illustrating partly erupted premolar with microbial accumulations predominantly located along the gingival margin.*

Figure 5.13 Enamel surface beneath the microbial plaque showing distinct signs of dissolution of rod (R) and interrod (IR) areas. These features are characteristic of active lesions at the subclinical level. Courtesy of INSERM.

Figure 5.14 Enamel surface from the 'clean' cuspal region showing marked wear, particularly corresponding to the interrod areas (IR). These features are characteristic of inactive lesions at the subclinical level. Courtesy of INSERM.

can be turned into inactive lesions when microbial accumulations are disturbed at regular intervals. This means that further progression of the lesion has ceased due to control of the unfavorable environmental conditions. We use the term 'disturbed' rather than 'removed' because it is not possible to remove all biofilm completely by brushing.

Since these changes from active to inactive lesions have taken place at the subclinical level, and hence are not recognized clinically, it is easy to understand that the factors which have promoted the transition (e.g., tooth brushing) have most commonly been regarded as *prevention* of caries. It might, however, be more appropriate to see the transition from active to inactive lesion, even at the subclinical level, as a result of *treatment or control* aiming at arrest of further lesion progression. The dynamic pH fluctuations as a result of the metabolism of the biofilm cannot be prevented – it is an ubiquitous, natural process. Its consequence, clinical lesion formation and progression, can be controlled however.

As the occlusal surfaces of posterior teeth approach full eruption, bacterial deposits are still relatively protected against removal forces in the deeper parts of the occlusal groove–fossa system corresponding to sites where visible signs of caries may occur [9, 22]. Hence, it is reasonable to conclude that visible signs of caries develop where bacterial deposits remain for the longest period of time, and a similar situation pertains to the approximal lesion.

Thus, establishment of the approximal contact leads to arrest of active subclinical caries in the facet areas, due to approximal wear and removal of bacterial deposits [44, 46]. Beneath the proximal facet, bacteria are still protected and, in conjunction with a gingival reaction, may be the focus from which later clinically detectable lesions may develop (compare the shape of lesions on Figs 3.11 and 3.15). It is important to appreciate that development of approximal caries implies the existence of a simultaneous gingivitis, since the interdental papilla normally fits snugly under the contact area of adjoining teeth. After this long explanation it should be understandable that probably the most important period for any tooth is from its eruption through the mucous membrane until it is in functional mastication.

At this stage three aspects are important to bear in mind:

- First, it will be understood that what we commonly refer to in the clinic as sound or normal enamel is really enamel that has been subjected to substantial chemical and minor mechanical modifications from the time of eruption.
- Second, what is referred to as posteruptive (secondary) maturation may more likely reflect the outcome of these chemical events, which have occurred at a subclinical level and have been described, perhaps incorrectly, as the period of passive mineral uptake.
- Third, in order to understand how fluoride may modify the caries lesion development and the rate of lesion progression, it should be remembered, therefore, that the entire enamel surface must be regarded as being in a dynamic equilibrium with its surrounding oral fluid at all times with innumerable fluctuations in pH (see Chapter 9 for details).

Enamel changes during early caries lesion development

There is no such thing as caries-susceptible sites, although this is a commonly used phrase. Carious lesions occur within the dentition in a very characteristic pattern both in the primary and permanent dentition, but this *does not* reflect differences in chemical composition of the enamel between parts of the dentition where caries lesions rarely or never develop compared with sites where lesions frequently appear [49]. Dental caries develops where microbial deposits are allowed to form biofilms that are not frequently removed or disturbed by mechanical wear (mastication, attrition, and abrasion from brushing, flossing, or toothsticks).

How rapidly may changes be recorded (microscopically and clinically) in enamel covered by dental plaque?

This section demonstrates what occurs in the mouth at any site if a 'protected area' is created at a part of the tooth surface [26], so that dental plaque is allowed to accumulate undisturbed by mechanical forces for days and weeks. G.V. Black did this experiment and reported it in his textbook of 1908 [7]. He was explaining to his colleagues that there is no such thing as inherently susceptible sites but that what matters is accumulation of plaque.

After 1 week no changes can be seen macroscopically even after a careful air-drying procedure. At the ultrastructural level, however, there are distinct signs of direct dissolution of the outer enamel surface (compare Figs 5.15 and 5.16). The intercrystalline spaces are wider, which is indicative of a partial dissolution of the crystal surfaces. Histological examination of sections of the enamel in polarized light shows a slight increase in enamel porosity, indicating an extremely modest loss of mineral to a depth of 20–100 μm from the outer surface.

The graph in Fig. 5.17 illustrates the principal distribution of porosity in enamel that has been subject to a cariogenic challenge for 9 weeks *in vivo*. The surface porosity has increased in accordance with the aforementioned enlargement of the intercrystalline spaces. In addition, the enamel immediately beneath the outer surface appears more porous than the surface itself.

After 14 days covered by undisturbed microbial plaque the enamel changes are clearly visible after air drying as whitish, opaque changes. A further increase in enamel porosity by preferential removal of mineral from the tissue deep in the outer surface has occurred. A subsurface lesion starts to form.

After 3 and 4 weeks the outermost surface exhibits dissolution of thin perikymata overlappings (Figs 5.18 and 5.19) and more marked dissolution corresponding to larger developmental irregularities, such as Tomes' processes pits and focal holes. It is important, however, that intercrystalline spaces of the entire involved enamel surface are enlarged and hence contribute to the overall increase in

Figure 5.15 Scanning electron micrograph of enamel surface prior to establishment of protected area by cementing orthodontic band. Note the rounding out of structural details by functional wear. Reproduced with permission of Karger Publishers.

Figure 5.16 Scanning electron micrographs of enamel surface after 1 week with local protection against mechanical wear and biofilm allowed to form. Note initial dissolution of the outer enamel surface beneath the undisturbed plaque. Reproduced with permission of Karger Publishers.

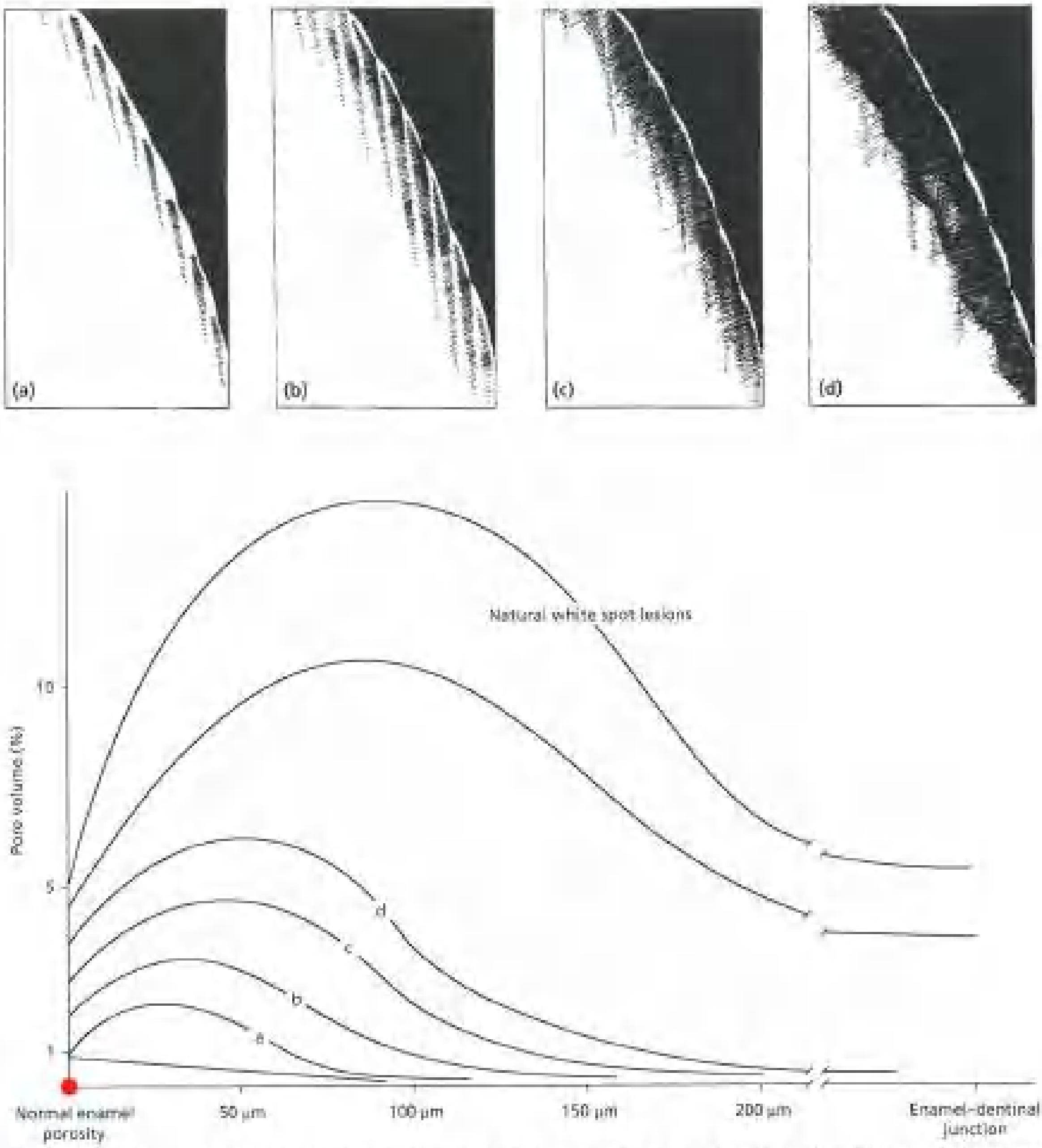


Figure 5.17 Diagram illustrating the distributions of enamel porosity at different stages of caries dissolution from the surface towards the enamel–dentinal junction. Parts (a) to (d) illustrate the gradual increase in pore volume after (a) 1 week to (d) 4 weeks of experimental caries *in vivo*. From [23].

porosity of the enamel. From this stage of lesion development, when the clinical changes can be readily seen without air drying, the more extensive loss of mineral beneath the outer surface is constantly increasing, as illustrated in Fig. 5.17.

Such experiments demonstrate that the surface partly dissolves from the very beginning of lesion formation with enlargement of intercrystalline diffusion pathways [20, 22, 24, 43–46].

Why does mineral loss predominantly occur underneath the enamel surface?

The precise mechanisms behind the relative 'protection' against further dissolution of the outer 10–50 μm of the enamel as removal of mineral from the subsurface region continues is understood from a physico-chemical point of view (see Chapter 9), but several other explanatory models have been proposed. For example, a protective

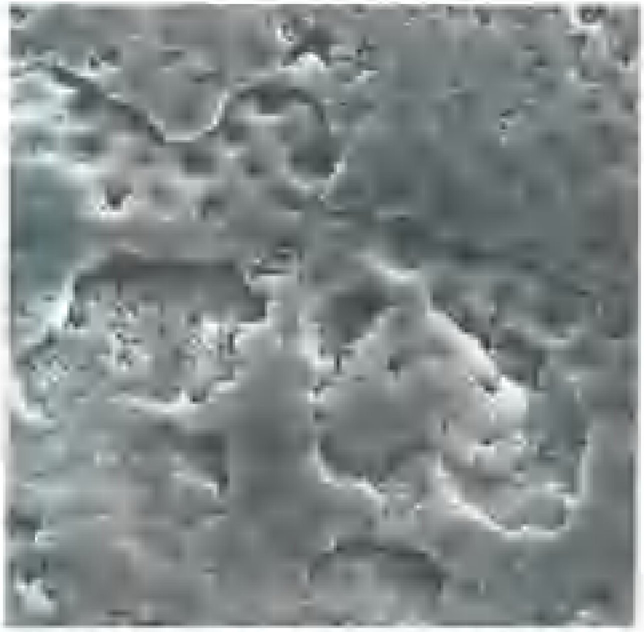


Figure 5.18 After 4 weeks of undisturbed biofilm the surface dissolution becomes more marked with loss of larger parts of perikymata overlappings. Reproduced with permission of Karger Publishers.

Figure 5.19 Detail of eroded perikymata overlappings with exposed underlying rod and interrod enamel at different stages of dissolution. Reproduced with permission of Karger Publishers.

role of salivary proline-rich proteins and other salivary inhibitors, such as statherin, during enamel demineralization has been suggested [21]. These inhibitors, which are particularly prevalent in the pellicle, have a dual function as they prevent spontaneous and selective precipitation of calcium phosphate or crystal growth of these salts directly onto the enamel surfaces, and they also tend to inhibit demineralization. Since the inhibitors are macromolecules, which cannot penetrate into the deeper parts of the enamel, their stabilizing role appears to be limited to the surface enamel.

The specific and inherent properties of the outer surface itself in terms of ultrastructural and chemical composition may play a role in the relative protection of the surface layer [49]. However, as will be described later in this chapter, even after visible cavity formation in the enamel there is still a tendency to form a better mineralized zone at the plaque–enamel interface relative to the interior part of the enamel. Finally, the fact that dental caries also develops as subsurface mineral loss in exposed root surfaces (see 'Histopathological features of root caries lesions' section) indicates a physico-chemical explanation common to all surfaces, irrespective of structure and chemical composition.

This observation, along with many experimental data, suggests that the relative protection of the outermost enamel, being in close proximity to the plaque fluid, is predominantly a result of the dynamic chemical processes taking place at the solid–solution interface, as described in Chapter 9. The fluoride concentration in the oral fluids will have a strong influence on maintenance and width of the surface zone (see explanation in Chapter 9 and Fig. 9.11).

An important question that arises at this stage is the development of carious lesions depends on structural and inherent factors of the tooth itself or whether lesion development is mainly dictated by environmental factors. Essentially, this question parallels the classical philosophical discussion of the relative role of genetic versus environmental factors. Carious lesions are a result of the interaction between the two mutually dependent factors: the enamel itself (the genetic factor) and the external environment (the environmental factors – where in fact part of the salivary composition may be genetically determined). Thus, in theory, both aspects eventually determine lesion development or caries resistance. Because the major concern in this context is linked to the treatment of the disease and its symptoms in individuals, the relative importance of the two factors ought to be considered. So far as dental caries is concerned, the most important factors are the environment, in terms of microorganisms adhering to the tooth and their products, and metabolism, which is highly influenced by nutrients (fermentable carbohydrates). From a practical point of view this insight is very useful, as our opportunities for influencing genetic factors in terms of tooth development and chemical composition of the tissues are negligible so far, in contrast to efforts directed towards affecting the environmental factors. This point of view also explains why the following sections highlight the role of local environmental conditions in enamel reactions.

How do such early lesions change when dental plaque is removed?

After 4 weeks an active enamel lesion, the white spot lesion, has a characteristic chalky surface as seen in Fig. 5.20a and c. This is partly because an increase in the internal enamel porosity due to demineralization causes a loss of translucency and this makes the enamel appear opaque. It is also partly caused by the direct surface erosion. The enamel loses its shiny appearance because the irregular surface generated by the erosion of the very outermost surface gives rise to a diffuse reflection of light.

Owing to the surface erosion it is also possible to make small scratches with a probe in the surface of active lesions. When such lesions created experimentally were re-exposed to the oral environment none of them continued to progress [26, 35]. After only 1 week they showed signs of clinical regression, that is, the whitish appearance had diminished (Fig. 5.20b and d). After 2 and 3 weeks where the surfaces were brushed, these surfaces had almost resumed the hardness as well as the shiny appearance of normal enamel. How can the clinical observation of arrest of lesion progression, and even regression, be interpreted?

Examination of the surfaces in relation to time after re-exposure to the oral environment showed a rapid and gradual increase in wear of the eroded surface. This indicates that mechanical brushing and removal of the cariogenic and acid-producing plaque is the dominating factor for lesion arrest *in vivo*. The clinical impression of the surface of the arrested lesion as 'shiny and hard' is therefore the result of abrasion or polishing of the dull, partly dissolved, surface of the active lesion (Figs 5.21, 5.22, 5.23, and 5.24). The mechanical removal of the outermost, partly dissolved, crystals ('polishing') results in exposure of more tightly packed crystals, explaining the clinical impression of resumed surface hardness. The polarized light examinations revealed that the porosity of the deeper parts of lesions was reduced after removal of the acid-producing plaque. The complete end of acid production at the surface results in a gradual return to neutral pH in the inner part of the lesion. For this reason there is an outward diffusion of protons. The reduced enamel porosity in the inner part of the lesion is therefore probably the result of a gradual return of enamel fluids to a stage of supersaturation with respect to apatites, causing a shift in equilibrium and reprecipitation of minerals in the sites of demineralization (see also Chapter 9). Detailed histological examination, however, particularly at the surface, suggests that the repair of the inner part of the lesion is not fully completed even 3 weeks after cessation of a cariogenic challenge [25].

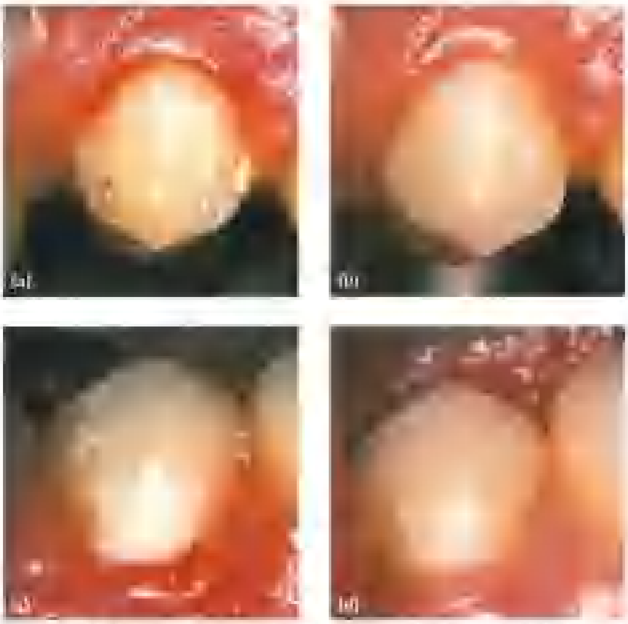
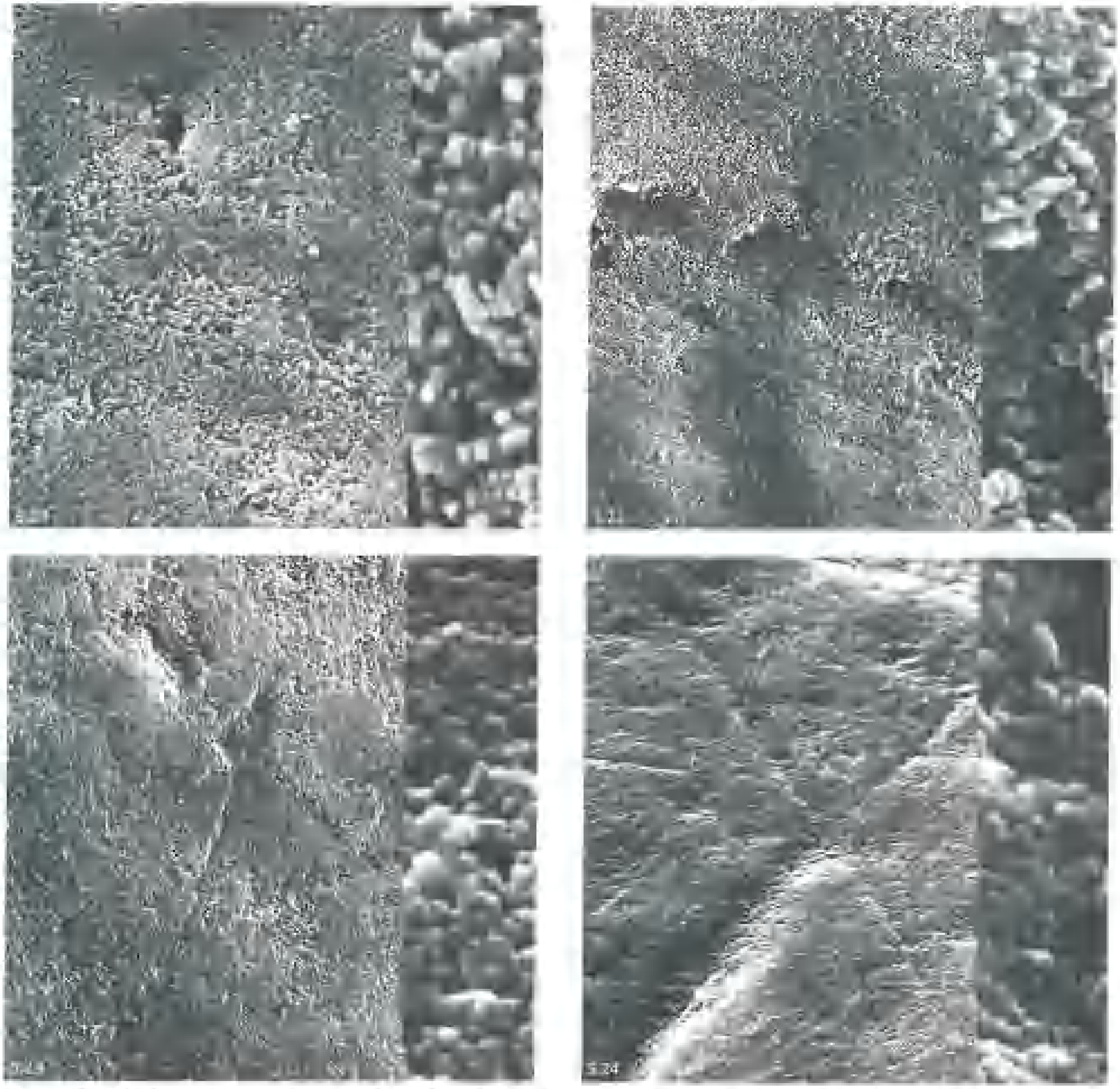


Figure 5.20 (a) Experimental tooth immediately after removal of the 4-week local protection by an orthodontic band. Note the typical appearance of an active enamel white spot lesion. (b) The same tooth 1 week after re-exposure to the oral environment. The inactive or arrested lesion appears less whitish due to wear and polishing of the external partly dissolved surface. (c) Experimental tooth immediately after cessation of 4 weeks of local protection. Note a typical opaque white, active enamel lesion. (d) The same tooth 2 weeks after re-exposure to wear in the oral environment. The arrested lesion is not readily visible in the clinic. Note the more shiny appearance of the surface. Reproduced with permission of Karger Publishers.

Frequently, orthodontic treatment with fixed appliances gives rise to side effects in terms of caries lesions around the brackets because the patients are not instructed in proper oral hygiene (Fig. 5.25). After removal of the appliance and professional plaque removal, further lesion progression ceases, and after 3 months (Fig. 5.26) the lesion shows features of a typical arrested lesion with a hard and shiny surface, but still with a maintained interior opacity [1, 2]. Scanning electron micrographs at low magnification of replica models clearly show that the transition from an active to an inactive stage is associated with wear as the mark made in the sound enamel has almost been worn away during a period of 3 months (Figs 5.27 and 5.28). The active lesion was a result of a prolonged period with partly undisturbed plaque accumulation, and the marked distinct border between sound enamel and the surface of the active lesion is therefore a clear indication of the degree of surface erosion during caries progression.

The approximal white spot lesion

The shape of the white spot lesion is determined by the distribution of the microbial deposits between the contact facet and the gingival margin, which results in a kidney-shaped appearance. On the proximal smooth surface there will typically be an interdental facet area partly surrounded by an opaque area extending in the cervical direction. The cervical border of the lesion is formed according to the shape of the gingival margin (Figs 3.11 and 3.12). It is often



Figures 5.21–5.24 Scanning electron-micrographs of enamel caries lesions after removal of local protection. Overview (left) and high-magnification detail (right). Figure 5.21 shows typical features of active enamel lesion with partial and complete dissolution of outermost crystals immediately after removal of 4 weeks' local protection. Courtesy of Scandinavian University Press. Figure 5.22 is after 1 week of exposure to the oral environment: multiple microscratches can be seen in the outermost partly dissolved crystal layer. Loosely bound crystals have been worn away (right). Courtesy of Scandinavian University Press. Figure 5.23 shows micro-wear after 2 weeks. Parts of the porous external micro-surface have been removed by wear. The exposed underlying crystals appear more tightly packed (right). Courtesy of Scandinavian University Press. Figure 5.24: After 3 weeks the surface appears smoother, with classical wear striation patterns owing to more complete removal of the eroded microsurface. The complete removal of loosely bound and partly dissolved crystals has exposed tightly packed crystals separated by a distinct network of intercrystalline spaces. Courtesy of Scandinavian University Press.

possible in such surfaces to see thin extensions of the opaque area, in buccal and lingual direction running in parallel with the gingival margin. Some of these lesions will be active and others inactive due to different efforts to control the microbial accumulations, for example with dental floss.

Surface features of the clinical white spot lesion

When examining the surface of an active white spot lesion (Fig. 5.29) characteristic changes can be observed on approximal surfaces, in principle corresponding to those described previously. The contact facet has a smooth appearance where

Figure 5.25 Clinical features immediately after removal of orthodontic appliances and cleaning. The orthodontic treatment had lasted for 2 years. Note the marked gingival reaction and the characteristic chalky surface appearance of the active enamel lesion.

Figure 5.26 After 3 months with careful oral hygiene the gingival tissues have recovered and the active lesion has been completely arrested. The white appearance of the lesion has diminished markedly due to polishing away of the eroded outermost enamel surface.

Figure 5.27 Scanning electron micrograph of replica of the active lesion. Note the distinct step between the eroded surface of the active lesion and the adjacent sound enamel (open arrows). A furrow has been made in the sound enamel area (arrows).

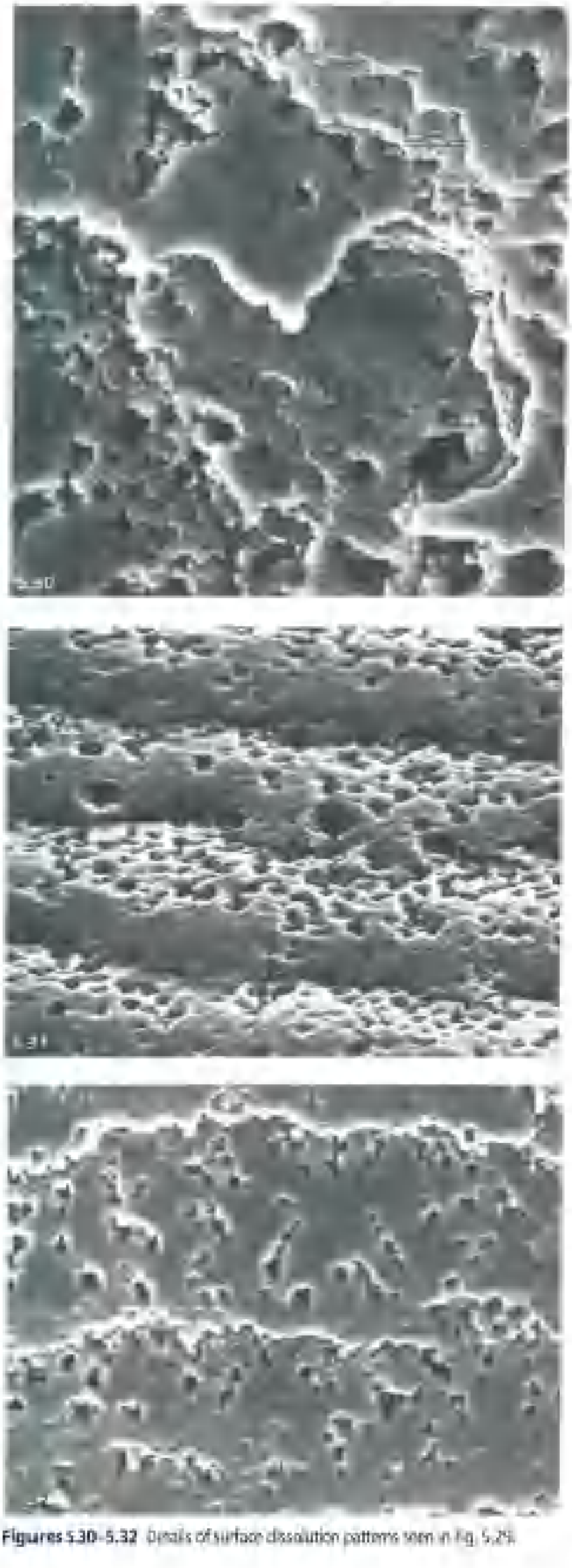
Figure 5.28 Scanning electron micrograph of replica of the arrested lesion. After 3 months, the furrow (arrow) has almost disappeared, and the step between the sound and arrested surface is slightly enhanced (open arrows). Courtesy of A. Thylstrup and J. Årtun.

Figure 5.29 Scanning electron micrograph of early surface dissolution cervical to contact facet (CF) in a natural, active enamel lesion. Courtesy of IRL Press.

the perikymata pattern has been abraded, but irregular fissures and other small defects can be observed along the periphery of the facet. Innumerable irregular holes are seen in the opaque surface enamel cervical to the facet; these are deepened and more irregular Tomes' processes pits and also an increased number of eroded focal holes. In other areas the deepened Tomes' processes pits appear to merge together, forming larger areas of irregular cracks or fissures (Figs 5.30, 5.31, and 5.32). The surface enamel exhibits distinct patterns of dissolution with widened intercrystalline spaces, and minor fractures of the perikymata edge are frequently found.

In other lesions these fractures may be so extensive that they involve two, three, or more perikymata whereby microcavities are formed. At the bottom of such microcavities, the classical honeycomb pattern of enamel rods is seen. The overlapping character of the enamel in these defects is evident with the opening of striae of Retzius corresponding to the bottom of each 'step.'

When examining inactive, arrested lesions, which still clinically appear as white spot lesions, some of these may



Figures 5.30–5.32 Details of surface dissolution patterns seen in Fig. 5.29.

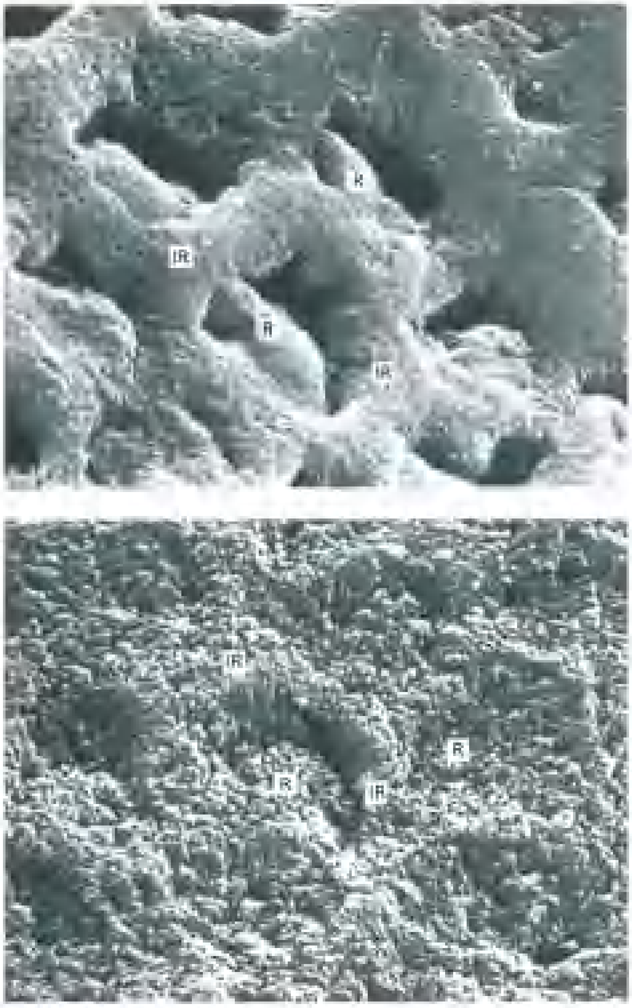
Figure 5.33 Scanning electron micrograph of part of an inactive enamel lesion with microcavity. At the bottom of the cavity, openings of striae of Retzius are seen. The rod pattern is clearly evident in the exposed enamel, in contrast to the abraded surface enamel.

also comprise microcavities (Fig. 5.33). The surface enamel surrounding such cavities exhibits marked abrasion with irregular scratches, but irregular deeper holes may be seen in between rows of Tomes' processes pits. The rod and interrod enamel in such areas, however, is also smooth (Fig. 5.34). In contrast, the enamel surface in sheltered areas, such as the bottom of the microcavities, appears densely granular (Fig. 5.35), indicative of merging ends of the individual crystals.

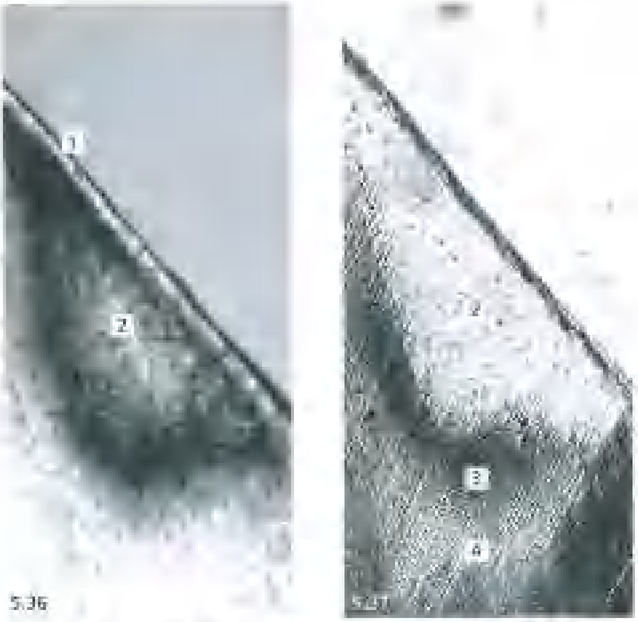
In conclusion, the early stages in enamel dissolution involve a distinct disintegration of the actual enamel surface, even leading to microcavities. It is also evident that approximal abrasion and attrition, caused by mechanical oral hygiene, significantly interfere with the surface features because the outermost enamel surface, only a few micrometers thick, is soft as a result of demineralization (erosion).

Histology of the white spot lesion

By sectioning the enamel perpendicular to the surface it is possible to produce 80–100 μm thick ground sections and examine these by microradiography and polarized light microscopy. When examining air-dried sections (air has RI = 1.0) in the polarized light microscope the porous lesion (area in the tissue where pore volume is exceeding 1%) appears as a wedge-shaped defect with the base at the enamel surface. When examining the same section with the intercrystalline spaces filled with water (RI = 1.33), areas where there is more than 5% pore volume in the tissue are observed mainly beneath the enamel surface, but still extending in a triangular shape into the tissue (Figs 5.36 and 5.37). In this way it is possible to distinguish between the apparently relatively intact surface zone, which varies in width from 20–50 μm, and the so-called body of the lesion where



Figures 5.34 and 5.35 Variations in surface features of rod (R) and interrod (IR) enamel in inactive lesions caused by variations in wear. Courtesy of IRL Press.



Figures 5.36 and 5.37 Ground section cut through the center of small enamel lesion examined in polarized light after imbibition in water (Fig. 5.36) and quinoline (Fig. 5.37): (1) surface zone; (2) body of the lesion; (3) dark zone; (4) translucent zone.

the pore volume exceeds 5%. The principal distribution of pore volume in an enamel lesion is illustrated in Fig. 5.38.

Two other histological zones are of interest in enamel caries lesions. These zones are only visible when the ground sections are examined imbibed in a clearing agent such as Canada balsam or quinoline. The latter in particular is very suitable since its RI is identical to that of enamel. When a ground section is examined in transmitted light after imbibition with quinoline, an apparently structureless translucent zone may be seen at the advancing front of the lesion (Fig. 5.37). This zone may vary from 5–100 μm in width and is located corresponding to that part of the lesion with a pore volume of slightly more than 1% when examined in dry air. Detailed microdensitometry studies of microradiograms have shown that there is a slight loss of mineral in this zone. The explanation for the translucent appearance of this zone with the enamel structures being less evident appears to be that initial dissolution of the enamel occurs mainly along the gaps between rod and the interrod enamel in the tissue. For this reason the quinoline is

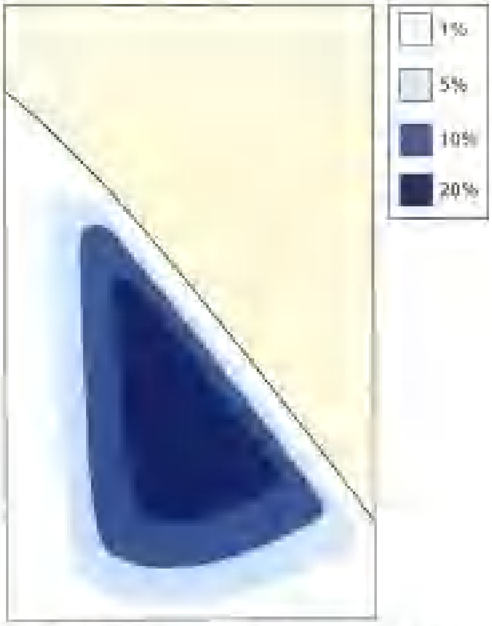


Figure 5.38 The principal pore volume distribution in the section examined Figs 5.36 and 5.37.

assumed to penetrate more easily into these enlarged pores, and as the medium has the same RI as that of the enamel crystals (RI = 1.62), the final result will look like a structureless zone.

The dark zone is a more constant feature of the advancing front of carious lesions than the translucent zone is. Thus, the dark zone occurs in 90–95% of lesions; and if the translucent zone is present, the dark zone is located between this and the body of the lesion (Fig. 5.37). Polarized light studies of the dark zone indicate a pore volume between 2 and 4%, and Silverstone has suggested that this zone possibly represents the results of a multitude of demineralization and reprecipitation processes [41]. The designation 'dark zone' originates from early studies showing that the zone appears dark brown in ground sections when examined in transmitted light after imbibition with quinoline. The dark appearance of the zone indicates that large quinoline molecules have not penetrated all micropores. The fact that quinoline is unable to penetrate the dark zone indicates that this contains very small pores in addition to the relatively larger ones that were present in the previous stage, the translucent zone. The occurrence of micropores impermeable to the large quinoline molecule are thought to be a result of precipitation of minerals in the sites of previous demineralization within the lesion, whereby parts of the large pores may be reduced by deposition of material (compare Fig. 9.3). Supporting this concept is the observation that *in vivo* caries lesions with a long history (i.e., slowly progressing or inactive lesions) frequently exhibit very wide dark zones.

Microradiographically, the increased pore volume as observed in the polarized light microscope is reflected as a loss of mineral deep to the relatively unaffected surface zone (Fig. 5.39). In principle, the loss of mineral is most pronounced corresponding to the body of the lesion, with a gradual decrease in loss toward the advancing front. However, the distribution of minerals within the enamel lesion varies greatly. Frequently, very thick surface zones are found. Similarly, deep within the body of the lesion a laminated appearance of the mineral distribution may be observed, indicative of periods with lesion arrest followed by new periods with active demineralization. This phenomenon is often particularly evident in the occlusal part of approximal lesions corresponding to where the interproximal attrition facet gradually develops (see also Chapter 9).

Within the enamel the spread of dissolution takes place particularly along the rod boundaries, as seen in the electron microscopes (Figs 5.40 and 5.41). At higher magnifications larger rhomboid irregular crystals, 'caries crystals,' may be found along these diffusion pathways (Chapter 9, Fig. 9.3). These crystals are interpreted as being a result of redeposition of minerals. In actively ongoing lesions, however, the apatite crystals exhibit various degrees of peripheral dissolution. But central dissolution along the c-axis of the crystals may also occur in the central lesion part (Chapter 9, Fig. 9.3).

Assuming a constant but high cariogenic challenge, there will be gradual subsurface dissolution of enamel, this being most pronounced deep to the enamel surface and spreading into the enamel following the rod directions. If, however, the cariogenic challenge varies as a result of, for instance, improved oral hygiene, topical fluoride application, and so on, such phases of remission and recurrence may result in a much more irregular pattern of mineral distribution within the lesion.

Progression of the enamel lesion

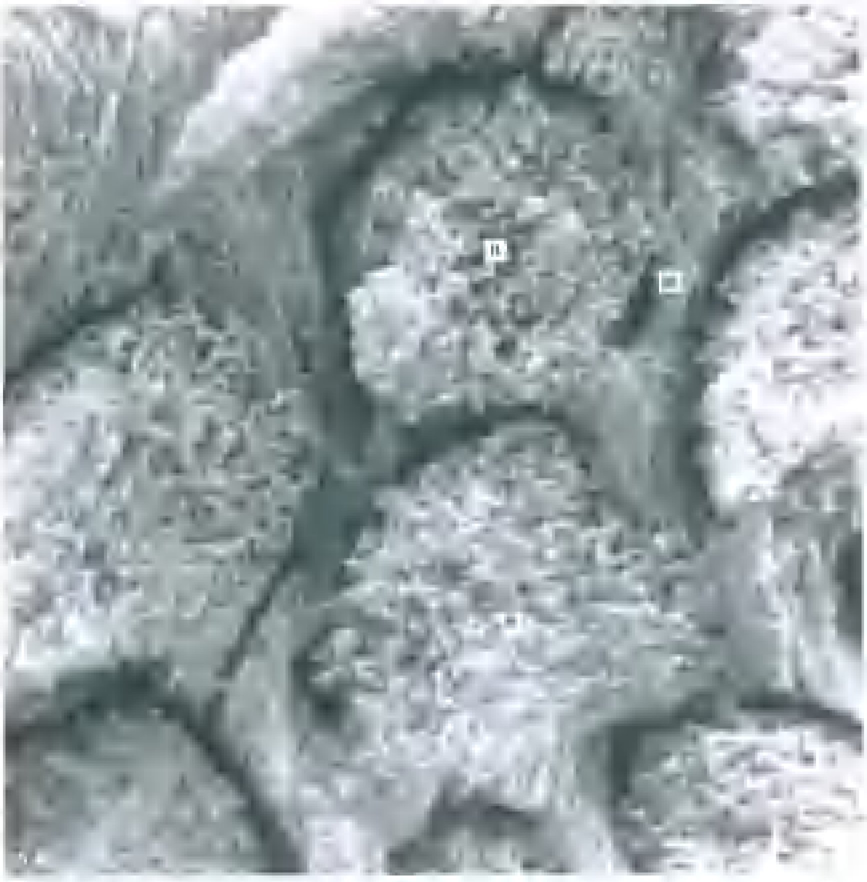
The classical description of the enamel lesion histology has been based on the white spot lesion positioned at the cervical margin of the interdental facet on the proximal surfaces. Typically, as described in the previous section, the lesion appears triangular in sections cut through the central lesion part. Carious dissolution follows the direction of the rods. Systematic measurements of enamel porosity along traverses following the rod direction make it possible to understand the morphogenesis of the conically shaped approximal lesion [6]. Figure 5.42 shows the principal morphological characteristics of a typical lesion. A line is drawn that has been designated the central traverse (CT), in the rod direction from the deepest point of lesion penetration to the surface. The highest degree of tissue porosity is always observed along this line irrespective of lesion depth.

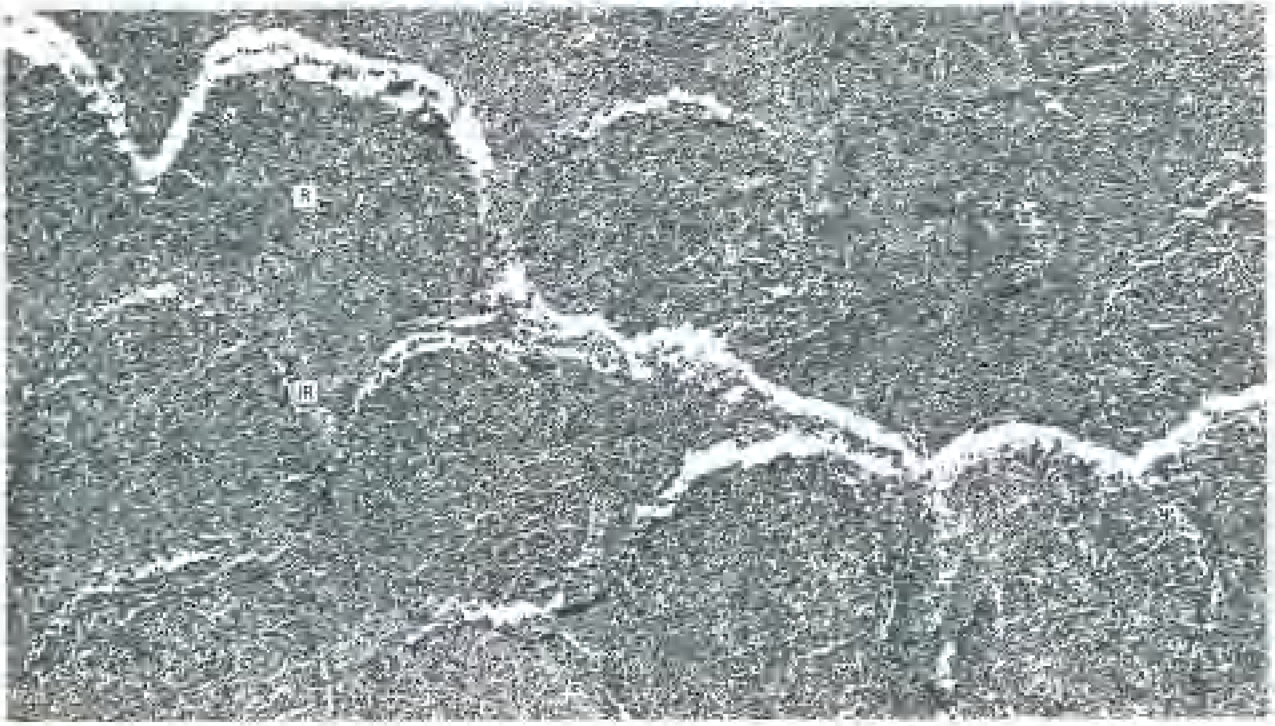
Initiation, spread, and progress of the approximal lesion is a simple reflection of the specific environment created by the microbial communities (the biofilm) on the enamel surface in the approximal space. Conversely, if bacteria are offered similar growth conditions anywhere in the dentition by allowing biofilms to become established then the metabolism in this biofilm produces similar types of lesions.

Arrest of the caries lesion

For several years it has been common to use the word 'remineralization' synonymously with arrest of caries lesion progression. This is misleading for several reasons, however. Most important, of course, is the fact that the first step in arrest of further lesion progress is removal of the acid-producing origin of the disease, the cariogenic plaque. Second, clinical changes associated with lesion arrest are partly explainable in terms of wear and polishing of the partly dissolved external microsurface of the active lesion. Thus, there is no sign of salivary surface repair of

5.39





Figures 5.39 Microradiograph of ground section from enamel lesion demonstrating preferential subsurface loss of mineral. Note the variation in mineral loss, but the structure of prism pattern remains.

Figures 5.40 and 5.41 Scanning and transmission electronmicrographs from body of the lesion showing partly dissolved enamel with enlarged gaps between rod (R) and interrod (IR) enamel. Note in Fig. 5.41 that the wide empty spaces represent artifacts caused by tissue preparation (sectioning). Figure 5.41 courtesy of *Arch Oral Biol.*

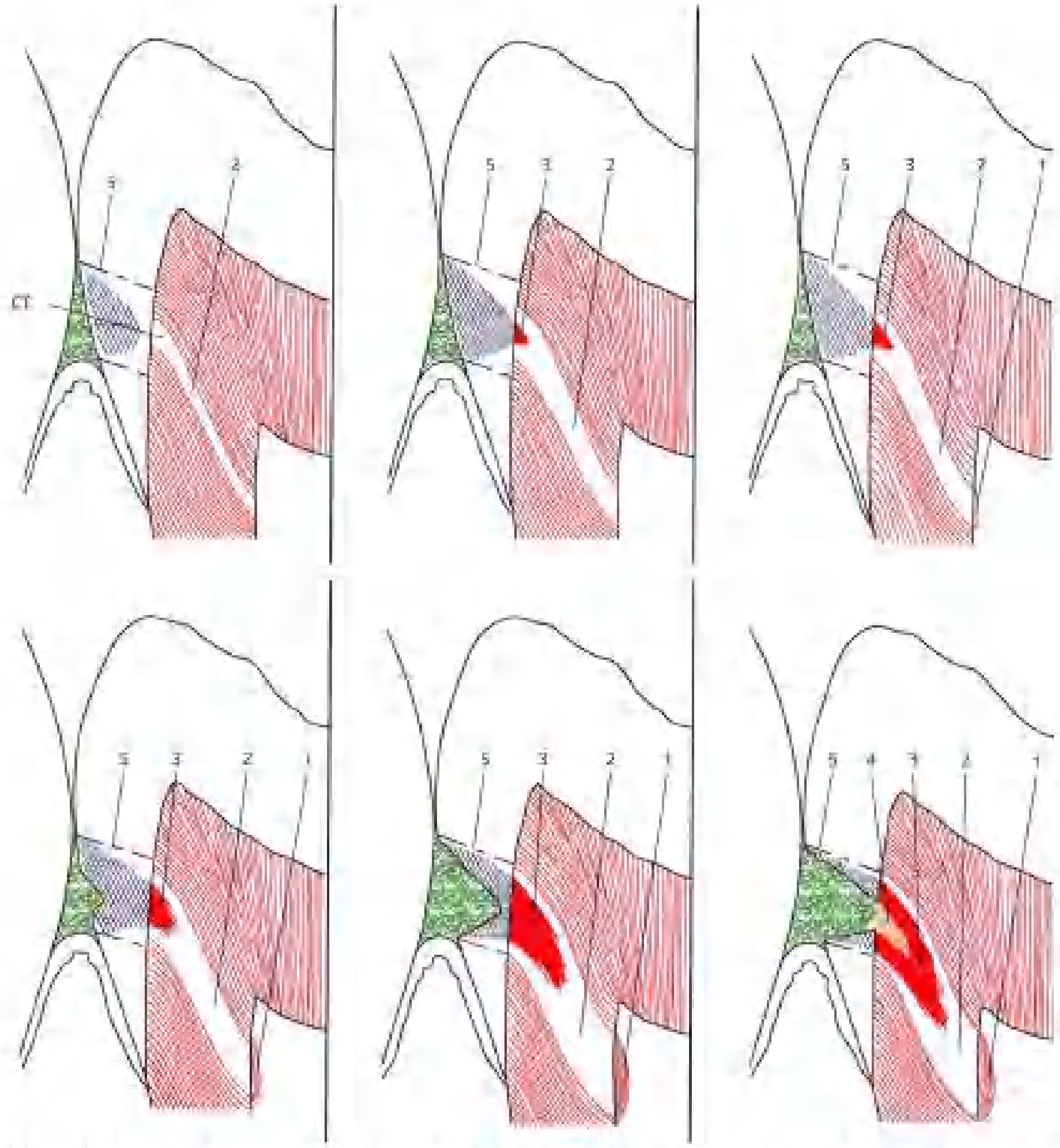


Figure 5.42 Schematic illustration of progressive stages of lesion formation: (1) reactive dentin; (2) sclerotic reaction or translucent (transparent) zone; (3) zone of demineralization; (4) zone of bacterial invasion and destruction; and (5) peripheral rod direction. CT, central traverse line. Modified from [6].

the arrested surface lesion in accordance with surface alterations *in vivo* after artificial etching with acid (Chapter 9). Collectively, these studies demonstrate that the clinical impression of repair after acid etching of the surface is not due to mineral deposition but instead is the result of salivary deposits (the pellicle) masking the characteristic etch pattern. In 1960, Mannerberg [31] demonstrated in a series of studies that changes in surface enamel micromorphology after etching were a result of abrasion, and not precipitation of salivary minerals. *In vivo*, the enamel surfaces are not restored by salivary repair mechanisms after direct loss of surface minerals. This is likely to be a result of the aforementioned salivary inhibitors, which prevent spontaneous and selective precipitation of calcium phosphate or crystal growth of these salts onto the enamel surface.

Concerning redeposition of mineral through the surface layer into the internal (subsurface) lesion *in vivo*, available data suggest that the surface layer in itself forms a diffusion barrier against subsurface uptake of mineral [29]. For this reason, it is a well-known clinical phenomenon that arrested lesions with an intact surface layer remain as scars in the tissue (Figs 3.13 and 9.17). This does not preclude that there are subtle alterations at the crystal level between oral fluids supersaturated with respect to dental apatites (see Chapter 9) and enamel crystals. However, it is worthwhile briefly considering the clinical elements of the most oft-cited study on lesion arrest, because this study conventionally has been taken as proof of the so-called 'remineralization phenomenon.'

Backer Dirks [3] studied 184 buccal surfaces of maxillary first molars in the same children at 8 years of age and again at 15 years. Table 5.1 indicates the clinical diagnoses. The last column shows the diagnoses at age 15, and the arrows point to the changes that have taken place with the individual lesion during the study period. Of the 72 surfaces with white spot lesion at 8 years of age, 37 (51%) were sound at age 15, while 26 (36%) remained unchanged and 9 progressed to cavitation stage. To understand these results it is important to remember that the gingival level at the buccal surface of the maxillary first molars undergoes a marked change between the ages of 8 and 15 years. During this period there is a gradual recession of the gingival margin along the surface of the tooth and a continuing exposure of the clinical crown. Also during this period the second maxillary molar erupts, leading to a further repositioning of the gingival attachment on the distal part of the first molar. Thus, the physiologic passive exposure of the tooth leads to a change in local conditions for plaque accumulation. For this reason, in his original report Backer Dirks considered the lesion arrest and lesion regression to be mainly a result of the altered environmental conditions due to better use of the fully erupted teeth, which promoted natural removal of bacterial accumulations, and hence lesion arrest. Prolonged wear of particularly superficial enamel lesions eventually leads to a complete wearing away of opaque enamel, giving the impression of a repaired lesion (as seen corresponding to the wear facet approximally).

In short, this means that lesion arrest *in vivo* is always the result of mechanical removal of cariogenic plaque. Toothbrushing and professional plaque removal not only result in arrest of further progression, but also in enamel lesions often regressing to an extent where they are not readily recognized in the clinic.

The use of the word *remineralization* as being synonymous with lesion arrest is particularly unfortunate because it is often stated that remineralization only occurs in cases with an intact surface layer. However, as will be seen later in this chapter, cavitated lesions can still arrest when plaque accumulation is sufficiently controlled [30]. Because the surface layer acts as a diffusion barrier against subsurface uptake of mineral, its removal may promote mineral deposition in the exposed porous enamel.

Careful clinical examination, particularly of adults, often reveals several arrested lesions at various stages. Most often the arrested approximal lesion is seen on teeth where the adjacent tooth has been extracted, whereby the local environmental conditions have been changed completely. Often, opaque bands can be discerned on the labial surface of incisor teeth indicating arrested lesions that developed during eruption of the teeth. Inactive lesions with a long history are often discolored due to the uptake of dyes (Chapter 5). Classically, such lesions are designated chronic lesions, arrested lesions, or brown spot lesions. Typically, gentle probing will reveal that they have the same hardness as normal enamel, in contrast to the more soft and rough surface of the active lesion. Therefore, they are often described as remineralized lesions as well. However, as previously mentioned, remineralization is not the cause of the arrest of further progress of the lesion, although reprecipitation of mineral from oral fluids may be a consequence of lesion arrest.

The chemical and structural aspects of these particular de- and remineralization phenomena are addressed in detail in Chapter 9.

Table 5.1 Distribution of buccal surfaces of maxillary first permanent molars in three categories of diagnosis at age 8 and age 15 of the same surfaces. From [3]. Reproduced with permission of Sage Publications.

Diagnosis	Age (years)		Total
	8	15	
Sound	93	76 37	113
White-spot lesion	72	15 26	41
Caries with cavitation	19	4 9 19	32
			184

Occlusal caries

Numerous epidemiological data and common clinical experience have repeatedly taught us that occlusal surfaces of posterior teeth are the most vulnerable sites for dental caries. Conventionally, the high incidence of caries on these surfaces has been directly related to the narrow and inaccessible pits and fissures on occlusal surfaces (see Chapter 3), and for that reason it has been natural in the past simply to refer to occlusal caries as 'fissure caries.' Recent clinical and structural studies combined with accepted knowledge, however, have made it possible to dismiss the narrow fissures as being per se the focus for caries initiation on posterior surfaces, and for that reason we prefer the term occlusal caries in this chapter [9–11, 14].

It is a common clinical experience that caries on occlusal surfaces does not involve the entire fissure system with the same intensity but merely occurs as a localized phenomenon. This can be understood when looking at a permanent molar occlusal surface in a stereomicroscope, where it presents itself as an elaborate landscape, with high mountains separated by a variety of valleys, some of which are deep rifts and others appear like open river valleys. Each tooth type in the dentition has its own specific occlusal surface anatomy, and caries is usually detected in relation to the same specific anatomical configuration in identical tooth types. In the maxillary molar, for example, the central and the distal fossae are sites that typically accumulate plaque, and hence are also sites where caries most often occurs. In general terms, occlusal caries initiation takes place in locations where bacterial accumulations are best protected against functional wear [9]. Thus, two factors have been considered of importance for plaque accumulation and caries initiation on occlusal surfaces: (1) stage of eruption or functional usage of teeth and (2) tooth-specific anatomy [9–11].

Figures 5.43, 5.44, 5.45, 5.46, 5.47, and 5.48 show six different stages of occlusal caries. Progressive destruction of the occlusal surface is initiated by a local process either in the deepest part of the open groove–fossa system (see Fig. 5.56) due to accumulation of bacterial deposits and/or *along* the entrance to deep, narrow fissures (Fig. 5.49). In such areas, which already offer protection against physical


5.43


5.44


5.46

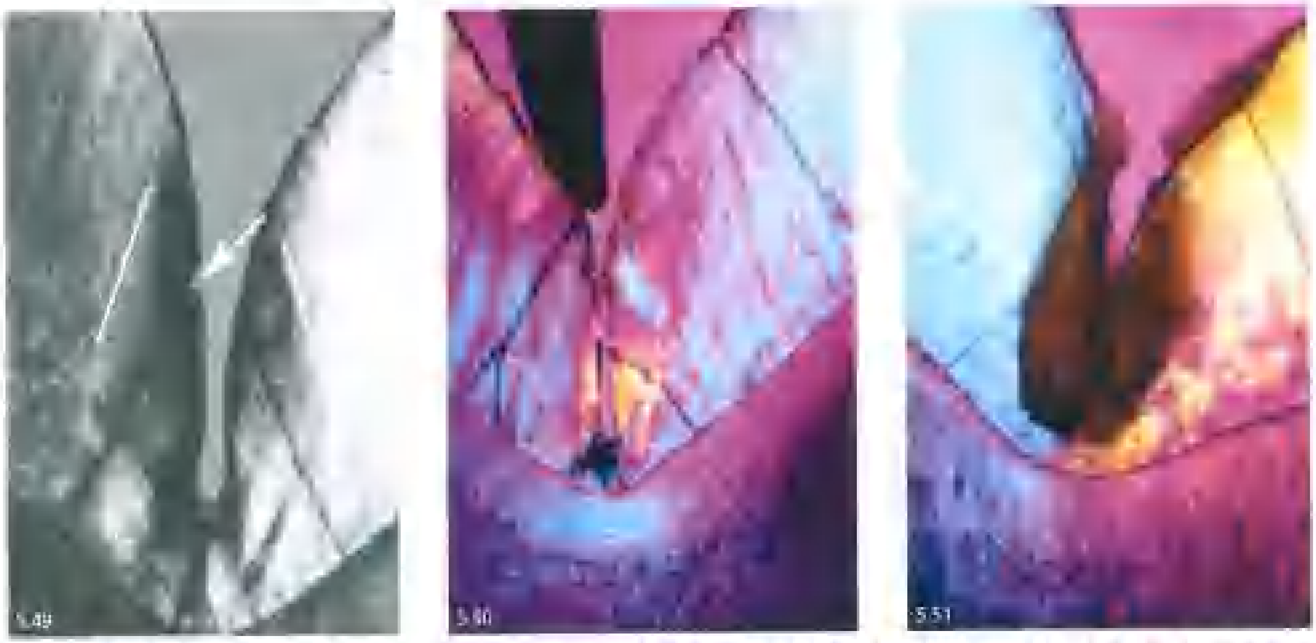

5.47

Figures 5.43–5.48 Histological sections through teeth exhibiting different stages of progression of occlusal caries lesions. By comparing these natural lesions with the diagram in Fig. 5.56 it will be appreciated why occlusal caries presents itself as undermining the enamel. If left 'untreated' a caries lesion stimulates the pulpo-dentinal organ to carry out reparative processes in the form of sclerotic (hypermineralized) dentin and at the pulpal interface reactive (tertiary) dentin. If the microbial mass is not removed then the final outcome will be necrosis of the pulp and periapical inflammatory reactions (Fig. 5.48). Courtesy of Professor T. Yanagisawa from the Hanagawa collection

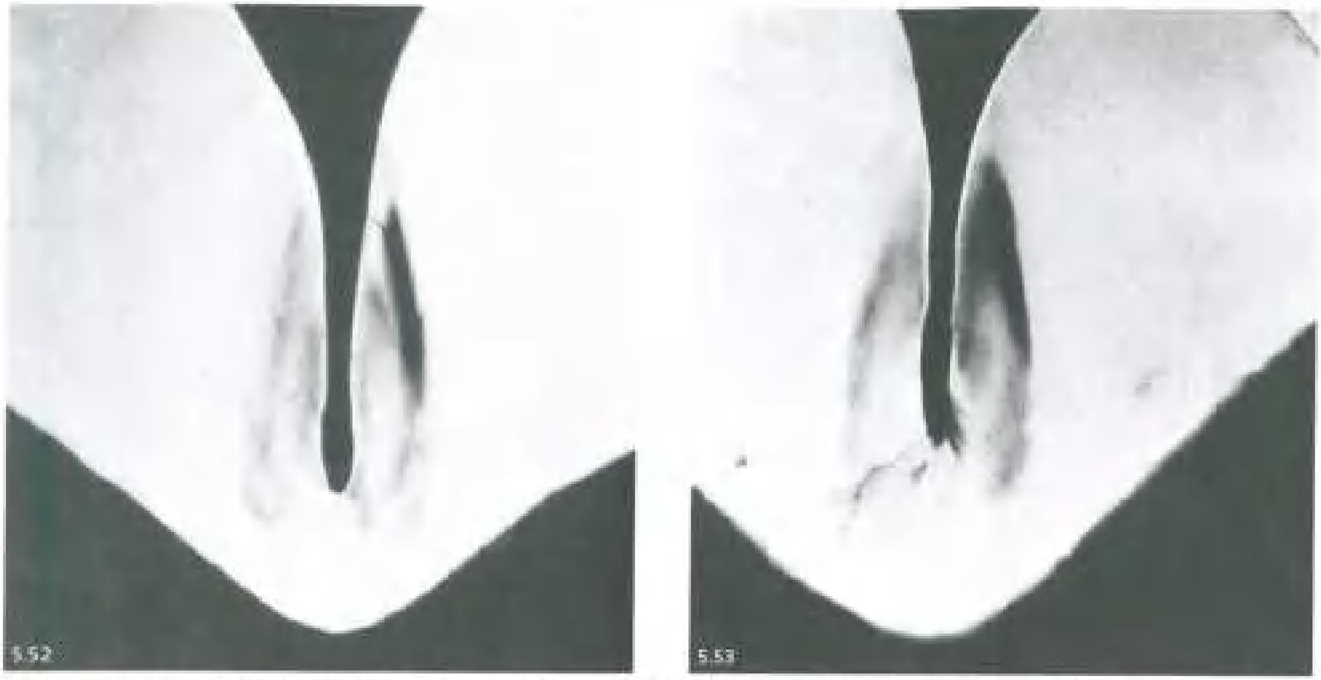
wear (Figs 5.44) the formation of microcavities (e.g., resulting from vigorous probing!) further improves local conditions for lodgment and growth of oral bacteria. Compare in this context Figs 5.50 and 5.51 with Fig. 5.49. When a standard probe is forced into a fissure entrance that is partly demineralized this easily results in minor surface disruptions. This accelerates demineralization and destruction, which again improves local conditions for bacterial growth (Fig. 3.45).

Caries lesions at the entrance to occlusal fissures may not develop with the same intensity on both sides of the fissure wall (Figs 5.52 and 5.55). They develop as subsurface lesions and spread in the directions of the rods (Fig. 5.49), and at a certain stage the lesions on either side join along the bottom of the fissure (Fig. 5.51) or they may first merge when the dentin is involved (Figs 5.54 and 5.55). Thereafter, the spread is similar to lesions that develop in the fossa–groove system. The lesions appear as truncated cones, and the dentin demineralization along the enamel–dentin junction spreads along the mantle dentin once the cavities are filled with microorganisms. This enhances the clinical impression of 'undermining' of the enamel margins (Figs 5.49 and 5.50). Thus, opening up of an occlusal caries lesion often gives the less experienced dentist the impression of 'much larger demineralization' than they anticipate from the immediate clinical inspection (compare clinical features in figures of occlusal caries in Chapter 3 with these histological pictures).

To understand the (rarely rapid) progression of occlusal caries under natural conditions (i.e., in people living in communities without provision of dental health care) it is necessary to appreciate the particular anatomical configuration of the occlusal surface where caries is initiated. It is crucial to understand the process in three dimensions as caries on occlusal surfaces most often is initiated in fossae, which are the depressions where two or more interlobal grooves meet. For this reason, several surfaces are involved in the initial dissolution. Because enamel demineralization always follows the rods, it is natural that the enamel lesion initiated in a fossa gradually assumes the shape of a cone with its base towards the enamel–dentinal junction (see the schematic drawings in Fig. 5.56). The dentin reaction reflects basically the rod direction in the enamel involved. Sections cut through such a lesion thus give the two-dimensional impression of two separated and independent lesions. In a fossa, however, where several surfaces are involved, the lesion entity is, in reality, shaped as a cone in three dimensions. It is no wonder, then, that textbooks over the years have paid special attention to the 'undermining' character of occlusal caries. However, in the light of the structural arrangement of the rods in the various parts of an occlusal surface in molars in particular, the mode of lesion growth in these surfaces is not particularly surprising. With progressing enamel destruction a proper cavity is formed, and again the outlines of the cavity reflect the arrangement of rods in the area. The cavity is thus shaped as a truncated



Figures 5.49–5.51 Sections through occlusal fissures examined in polarized light. When examined dry in air an early subsurface caries lesion and surface porosities are seen in Fig. 5.49. The arrow shows a surface defect probably caused by vigorous probing. The dotted lines indicate prism direction. The bottoms of such fissures are having a structural complexity often with increased amount of developmental proteins which should not be considered as dental caries! In Fig. 5.50 a standard clinical probe is located at the entrance of a fissure. In Fig. 5.51 a caries lesion is confined to the enamel at both sides of the fissure. The section is examined dry in air and the lesion is thus reflecting areas where the pore volume exceeds 1%.



Figures 5.52 and 5.53 Microradiograms from two consecutive sections of the same fissure. Note the uneven distribution of demineralization.

Figures 5.54 and 5.55 Microradiogram and polarized light microscopic illustration of pattern of spread of a caries lesion. At sectioning the tissue was intact! In Fig. 5.55 a probe is located at the entrance to the fissure. Note the apparent undermining character of demineralization. See the text for explanation.

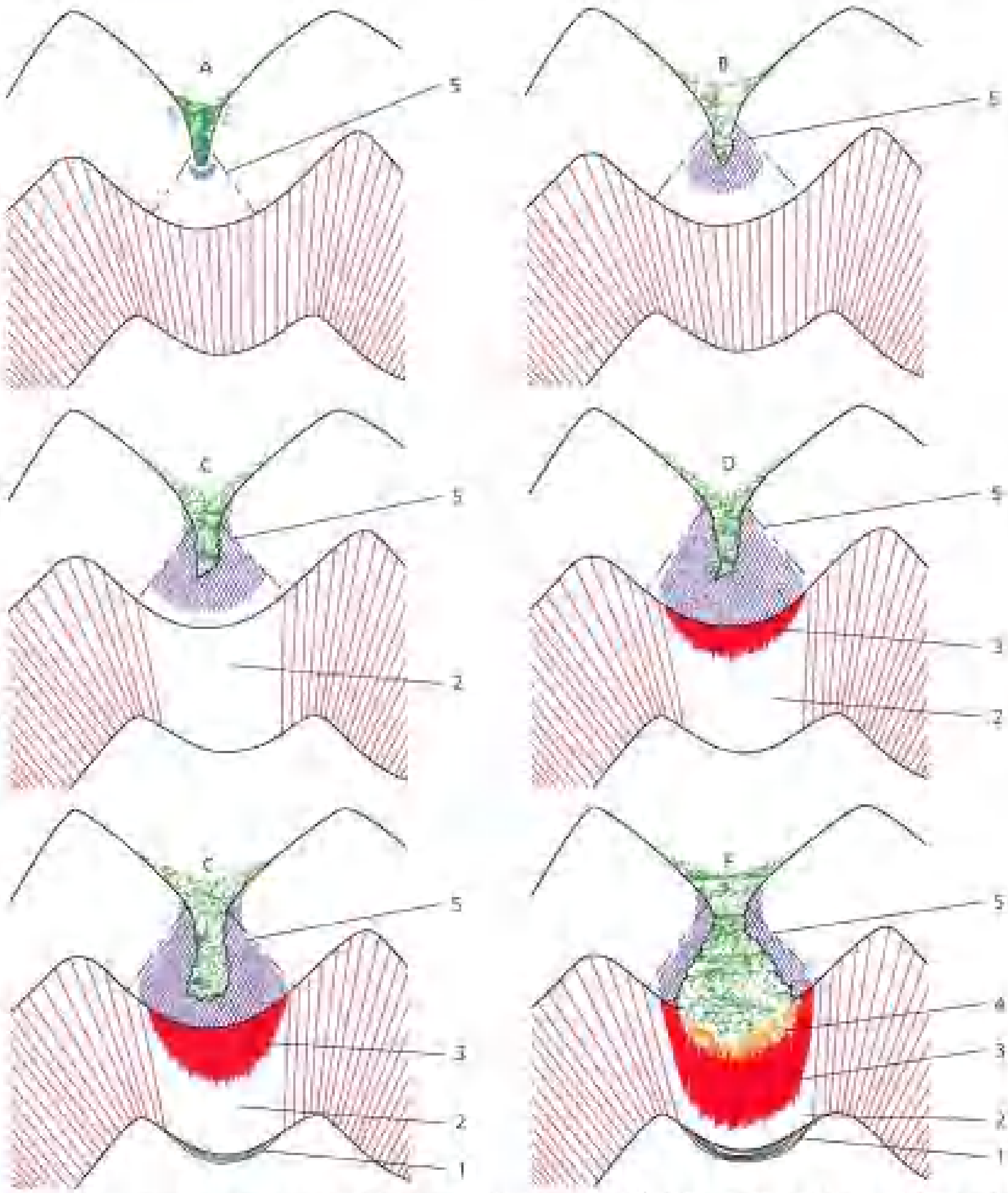


Figure 5.56 Schematic illustration of progressive stages of occlusal lesion formation in an occlusal fossa: (1) reactive dentin in the interface to the pulp; (2) sclerotic reaction or translucent (transparent) zone; (3) zone of demineralization; (4) zone of bacterial invasion and destruction; (5) dotted lines indicate the direction of the prisms. Modified from [14].

zone. The particular anatomical configuration of that part of the occlusal surface where caries begins explains why the openings of occlusal cavities are always smaller than the base. The 'closed' nature of the process obviously favors undisturbed growth of bacteria, and hence accelerated destruction of the tissue. Occlusal enamel breakdown is the result of further demineralization from one or more initially established foci rather than being a general demineralization involving the entire fissure system.

As previously mentioned, the major part of clinical and scientific concern with regard to occlusal caries has been devoted to the possible events taking place in the deep and inaccessible fissures. However, caries destruction is almost always initiated at the entrance due to metabolic activities in bacterial accumulations on the surface. It is interesting in this context that the structural organization of dental plaque in a distinct biofilm is not observed in the fissures but along the entrance of fissures. The consequences for diagnosis and prognosis of occlusal cavities will be dealt with in Chapters 10–12.

Dentin reactions to caries progression

Conventionally, enamel caries and dentin caries are described as two independent entities. This convention is to some extent understandable, because the two tissues differ markedly from each other in terms of both developmental origin and structure. The enamel is derived from the ectodermal component of the tooth germ, while the pulpo-dentinal organ is developed from the mesenchymal component. The enamel is avascular and acellular and cannot respond to injuries, whereas the dentin and the dentinal cells, the odontoblasts, are integral parts of the pulpo-dentinal organ and thus to be considered a vital tissue possessing specific defense reactions to external insults. Remember, the enamel is a microporous solid and hence it is understandable that stimuli from the oral cavity pass through the tissue into the pulpo-dentinal organ even in clinically intact enamel. With increasing porosity as a result of enamel demineralization it is to be expected that the underlying pulpo-dentinal organ reacts (Figs 5.43, 5.44, 5.45, 5.57, 5.58, and 5.59).

Therefore, changes in dentin during caries progression cannot be understood without taking the spread of the enamel lesion into account. The most common defense reaction by the pulpo-dentinal organ is tubular sclerosis, which is deposition of mineral along and within the dentinal tubules, resulting in their gradual occlusion (Figs 5.60–5.65, and 5.66) [28, 30, 32, 33, 42].

Age changes in the dentin are commonly described as a gradual mineralization of the peritubular dentin, eventually resulting in complete obturation of the tubules or tubular sclerosis. Wear of teeth accelerates tubular sclerosis. It is reasonable, therefore, to consider age-related tubular sclerosis as being the result of mild stimuli from the oral environment mediated through the enamel. Caries is another stimulus that accelerates tubular sclerosis, a process that requires the presence of a vital odontoblast (Figs 5.58, 5.59, and 5.67). The tubular sclerosis observed in conjunction with caries has been described as being either a result of initial mineralization of the peritubular space followed by calcification of the odontoblast process, or by an initial intracytoplasmic calcification followed by a secondary periodontoblastic mineralization [19]. In addition to the presence of intratubular hydroxyapatite crystals, large rhombohedral crystals have often been observed and identified as whitlockite crystals [13, 19]. At the light microscopic level it is not possible to distinguish between the different forms of sclerosis, and in sections the obturated dentinal tubules appear translucent because the mineral in the tubules makes the tissue more homogeneous, reducing the scattering of light passing through the affected tissue.

Figure 5.57 Ground section of active approximal lesion examined in transmitted light. The triangular enamel lesion reaches the enamel–dentin junction, with demineralization of the outer dentin (DZ) and sclerotic reactions (TZ) corresponding to the less advanced peripheral parts of the enamel lesion.

Sclerotic dentin is therefore often referred to as translucent (transparent) dentin or a translucent zone (Fig. 5.57).

Pulpo-dentinal reactions

Pulpo-dentinal reactions before bacterial invasion into the dentin

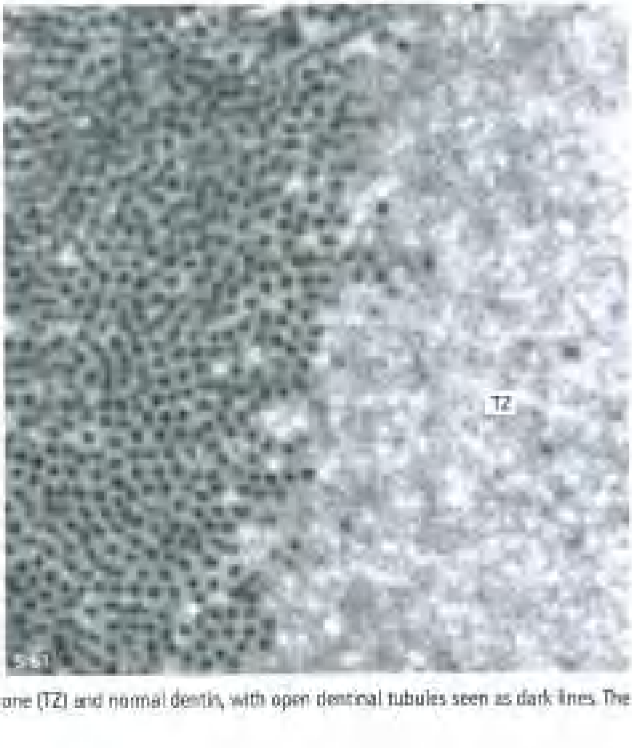
The first signs of dentin reactions beneath an enamel lesion that can be seen in the light microscope are aggregations of a few inflammatory cells and tubular sclerosis which forms corresponding to the deepest part of the progressing enamel lesion (Figs 5.58 and 5.59). Enamel demineralization increases enamel porosity, and hence also the permeability of the enamel, and it is therefore no wonder that the first mild stimuli initiating the defense reaction reach the dentin corresponding to the most porous part of the enamel lesion. Because the light microscope is a relatively coarse level of examination, it is obvious that much earlier dentin reactions have been noted at the biochemical and histochemical level. Initial tubular sclerosis is seen before the advancing front of

5.58

5.59

Figures 5.58 and 5.59 Histological ground sections in the mesiodistal direction through human mandibular premolars and molars. In the approximal surfaces caries lesions extend at a varying depth towards the dentin. Note how sclerotic reactions in dentin (the translucent zone) and pulp may appear even at these stages of lesion development. Figure 5.59 is a higher magnification of the approximal space between the premolars. Note how the lesions penetrate in depth below the contact area. The approximal space appears partly empty because substantial shrinkage occurs during tissue preparation (the gingiva has been edematous and swollen) and some of the microbial deposits are lost. Courtesy of Professor T. Yanagizawa from the Hanagawa collection.

5.60



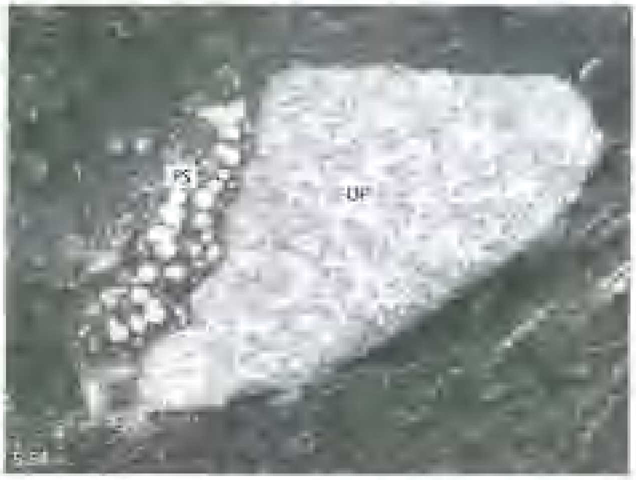
5.61

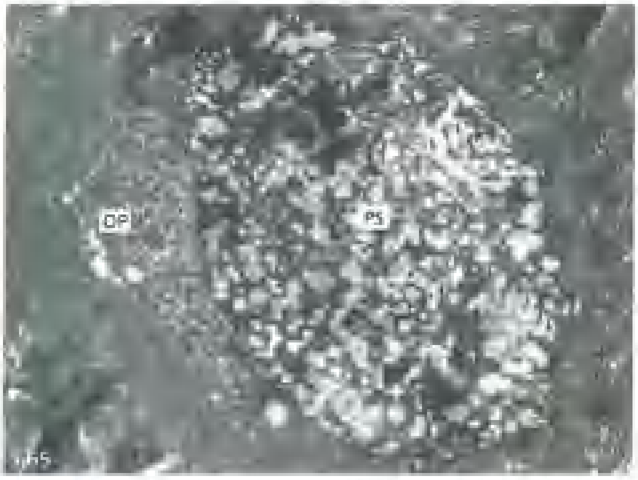
Figures 5.60 and 5.61 Microradiographs of the border between the translucent zone (TZ) and normal dentin, with open dentinal tubules seen as dark lines. The dotted line in Fig. 5.60 indicates plane of view in Fig. 5.61.

Figure 5.62 Transmission electron micrograph from translucent zone showing two completely occluded dentinal tubules (ODT). Reproduced with permission of Karger Publishers.

the enamel lesion reaches the enamel–dentinal junction. When contact between the enamel lesion and the enamel-dentin junction is established, the first sign of dentin demineralization can be seen along the junction in terms of brownish discoloration (see the front cover). For many years it has been common in textbooks to read that the dentin demineralization is spreading in a lateral direction along the enamel–dentin junction because it has been implicitly assumed that the anatomical discontinuity between the two tissues favors penetration of destructive agents.

However, systematic studies on this issue – in smooth surface caries – concluded that brownish dentin demineralizations never extend beyond the limits of the enamel lesion contact area with the enamel–dentin junction [6] before a caries cavity extending into dentin is developed. The tubular





Figures 5.63 Figure 5.63: Transverse section of a dentin tubule showing advanced mineralization of the periodontoblastic space (PS). OP: Odontoblast process; ID: intertubular dentin. Reproduced with permission of Karger Publishers.

Figure 5.64 Transverse section of odontoblast process (OP) and partly mineralized peri-odontoblastic space (PS). Reproduced with permission of Karger Publishers.

Figure 5.65 Transverse section of mineralized odontoblast process (OP) and large, periodontoblastic space (PS) in which the majority of collagen fibers are mineralized. Reproduced with permission of Karger Publishers.

Figure 5.66 Completely mineralized dentinal tubule (DT). Reproduced with permission of Karger Publishers.

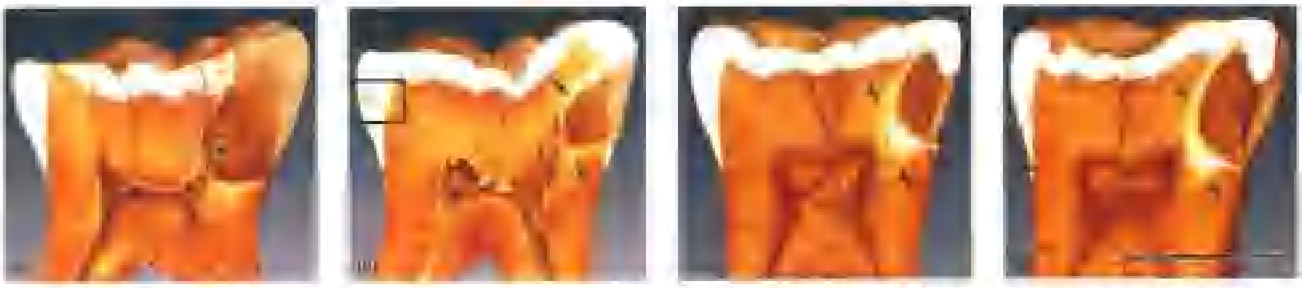


Figure 5.67 Four consecutive micro-computed tomography scans through deep caries lesion in a 2000-year-old tooth from Imperial Rome. The lesion had penetrated into the pulp where reactive dentin is indicated with an asterisk (a). Note the very pronounced sclerotic dentin reactions (hypermineralization) that delineate the base of the dentin caries cavity – indicated by arrows on (b), (c), and (d). The framed area in (b) shows an early caries lesion through enamel with a dentin demineralization at the enamel–dentin border.

sclerosis observed early on corresponding to the central demineralization in the enamel part of the lesion may be an attempt to 'wall off' the lesion. It seems logical to interpret the dentinal sclerosis lateral to the central demineralization as a reaction to stimuli processed along the direction of the rods from the less advanced parts of the enamel lesion approaching the enamel–dentin junction. The dentinal changes represent a continuum of pulpo-dentinal reactions to variations in acid challenge at the enamel surface with transmission of the stimulus through the enamel in the directions of the rods [6]. The implication of this understanding, of course, is that when acid production ends at the surface, due to regular disturbance or removal of the cariogenic microbial biomass, then further demineralization is stopped, resulting in arrest of further lesion progression. As previously mentioned, the mineral uptake in the enamel and in the dentin from the saliva is very limited after arrest of the disease, and for that reason demineralized enamel as well as demineralized dentin remain as scars in the tissue (Fig. 5.68).

Conventionally, dentin involvement has been assumed to be a stage in caries progression that required operative treatment in order to arrest further destruction, and many studies have therefore focused on possibilities to detect this stage on radiographs. The common use of 'dentin involvement', however, is too vaguely defined to cover the continuum of changes occurring in the pulpo-dentinal organ during caries progression and, therefore, is useless as an indicator for operative treatment.

In the next section we will look at the gradual destruction of the enamel and the eventual exposure of the pulpo-dentinal organ to the oral environment.

Enamel destruction and bacterial invasion

In order to understand the gradual exposure of the pulpo-dentinal organ during progressive lesion formation it is important to appreciate that even though substantial amounts of minerals have been removed from the enamel, and the lesion thus characterized as porous, the remaining mineral still preserves the overall structural composition of the enamel (Figs 5.57 and 5.59). We are not dealing with an 'empty' space beneath the surface zone but with a certain degree of mineral loss in a still highly mineralized tissue. The first signs of surface breakdown are therefore limited to the outermost enamel and presumably created by mechanical injuries during mastication, microtraumas during interdental wear, or by careless probing. If such areas are not kept relatively free of dental plaque, the process will

Figure 5.68 Microradiograph of ground section through inactive approximal lesion that has been arrested for several years. The small cavity in the surface of the enamel may have facilitated some redeposition of mineral, but otherwise this degree of demineralization can remain unchanged lifelong.

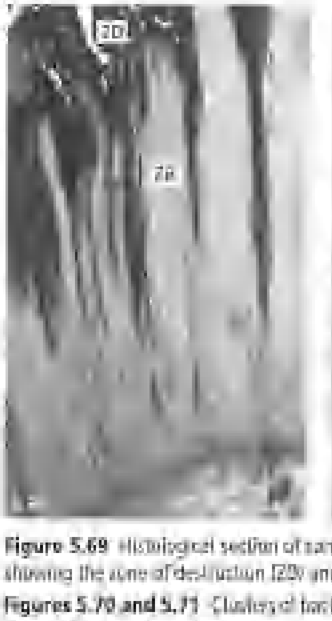
continue because the bacteria harbored in the microcavity, all other matters being equal, will receive more protection than those on the surface, which again will favor the ecological shift toward anaerobic and acid producing bacteria, as described in Chapter 7. The progressive destruction of the enamel or the gradual enlargement of the cavity is therefore the combined result of continued acid production in the protected microbial biomass and mechanical microtraumas.

Considering the role that bacteria and their metabolic products play in inflammatory reactions it is no wonder that questions about the time for 'bacterial invasion' have been the focus of attention for many clinicians in order to define more precisely the time for operative intervention. Because major interest has been devoted to initial caries or to advanced stages with dentin destruction, little is known about the events taking place during the progressive destruction of the enamel before exposure of the dentin. It is therefore relevant to distinguish between the limited (if any) destructive capacity of isolated groups of bacteria in the tissue and that of the protected microbial biomass in the enamel cavity growing with direct access to the nutrient-rich oral environment [47]. Occasionally, bacteria may be found within the porous enamel and some may penetrate along the organic meshwork in the enamel (e.g. the lamellae). Proper superficial tubular invasion of bacteria in coronal dentin has not been documented before direct exposure of the dentin to the bacterial biomass in the cavity.

In principle, this stage in dentin exposure can be compared with conditions occurring when bacteria accumulate directly on exposed root surfaces and lead to active root-surface caries. The outermost dentin – mantle dentin – in both coronal and root dentin does not immediately allow microorganisms to invade dentin tubules. Since initial root-surface lesions can be arrested by proper nonoperative treatment [34], it is possible to conclude that superficial bacterial invasion into the dentinal tubules cannot per se be used as an indication for operative treatment. It is relevant, therefore, to raise the question: What is the possible harmful effect of these invaders into an environment showing little evidence of hospitality compared to the masses of acid-producing surface bacteria? There is no doubt that the microbiota in the dentinal tubules are able to excrete metabolic end-products that may be associated with destruction (see Chapter 7). However, their relative contribution to the destruction compared with bacteria in the necrotic dentin and bacteria harbored in the cavity may be extremely limited. It is reasonable, therefore, to assume that bacterial invasion also into the dentinal tubules is merely a sign of lesion progress rather than being an integrated and significant part of the destruction [47].

Following exposure of the dentin to the masses of bacteria in the cavity, the most superficial part of the dentin will soon be decomposed due to the action of acids and proteolytic enzymes. This zone is referred to as the zone of destruction (Fig. 5.42). Beneath this zone tubular invasion of bacteria may be seen in rapidly progressing lesions (Figs 5.69 and 5.70). In such lesions, which in contemporary populations may be rather rare, it is not uncommon to see so-called dead tracts in the dentin, which means that the odontoblast processes are destroyed without having produced tubular sclerosis. Such empty tubules are particularly invaded by bacteria, and occasionally groups of tubules coalesce to form so-called liquefaction foci (Fig. 5.71). Between the zone of bacterial penetration and the sclerotic dentin, the translucent zone, there is a zone of demineralization resulting from acids produced in the biomass of anaerobic and aciduric bacteria in the cavity.

The first reaction in the pulpo-dentinal organ was tubular sclerosis. When the apex of an enamel lesion reaches the enamel–dentinal junction, the superficial part of the dentin undergoes demineralization, which clinically can be seen as a yellow-brownish discoloration of the soft tissue. The discoloration may be a result of the biochemical changes of the collagenous dentin due to the demineralization. As the process continues, the defense mechanism in terms of tubular sclerosis will proceed both along the advancing front and along the borders of the cavity (Figs 5.67 and 5.72). This assumes that the rate of lesion progress is such that the predominant number of odontoblasts remains viable in order to be able to mount the hypermineralization defense and seal off the process. This is evident in the example shown in Figs 5.67 and 5.72, which originates from individuals who lived 2000 years ago in Imperial Rome – and in areas of Tanzania a few decades ago where there is a natural fluoride content in the water of 2–2.5 ppm. In both cases oral hygiene has been limited, but the Roman teeth have most



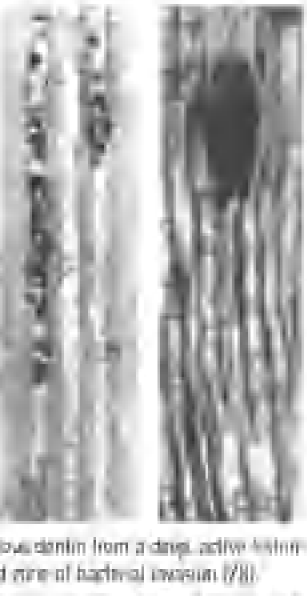


Figure 5.69 Histological section of carious dentin from a deep, active lesion showing the zone of destruction (ZD) and zone of bacterial invasion (ZB).

Figures 5.70 and 5.71 Clusters of bacteria penetrating dentinal tubules and forming liquefaction foci.

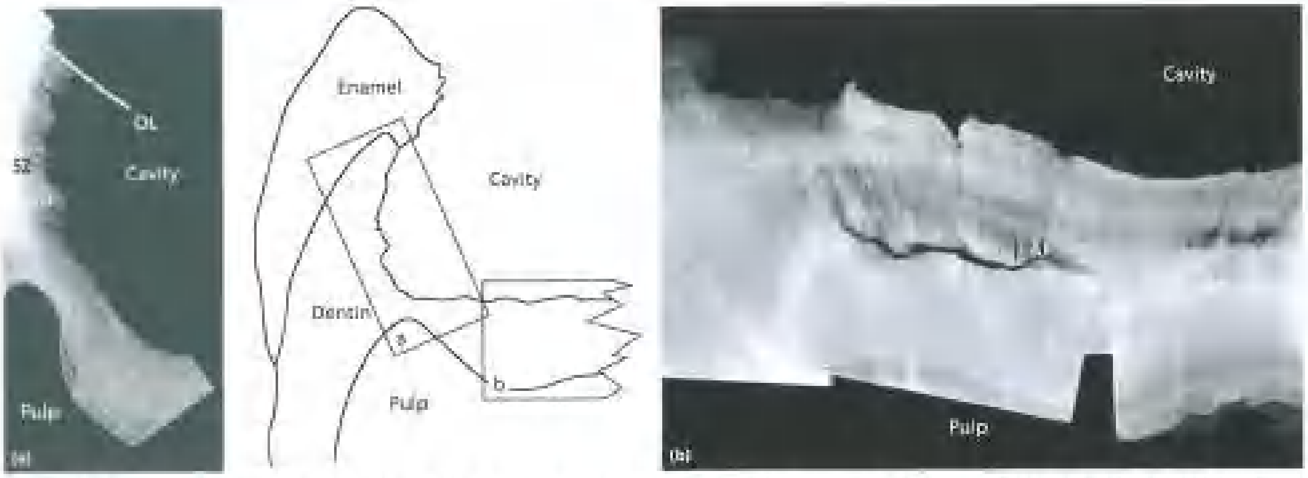


Figure 5.72 Drawing showing the location of where two microradiograms are made along the walls of two different deep caries lesions that had never been interfered with. The teeth, originating from Tanzanians, exhibited dental fluorosis, which explains the hypermineralized Owens contour line (OL) in (a). It is striking that the zone of demineralization (ZD) is not very thick and delineated by the sclerotic zone (SZ) – compare with Fig. 5.67. RD: reactive dentin. In (b) the base of a very deep occlusal cavity is shown again with a relatively narrow zone of demineralization (ZD). It should be noted how the dentin towards the pulp shows 'clouds' of hypermineralization in the sclerotic zone (SZ).

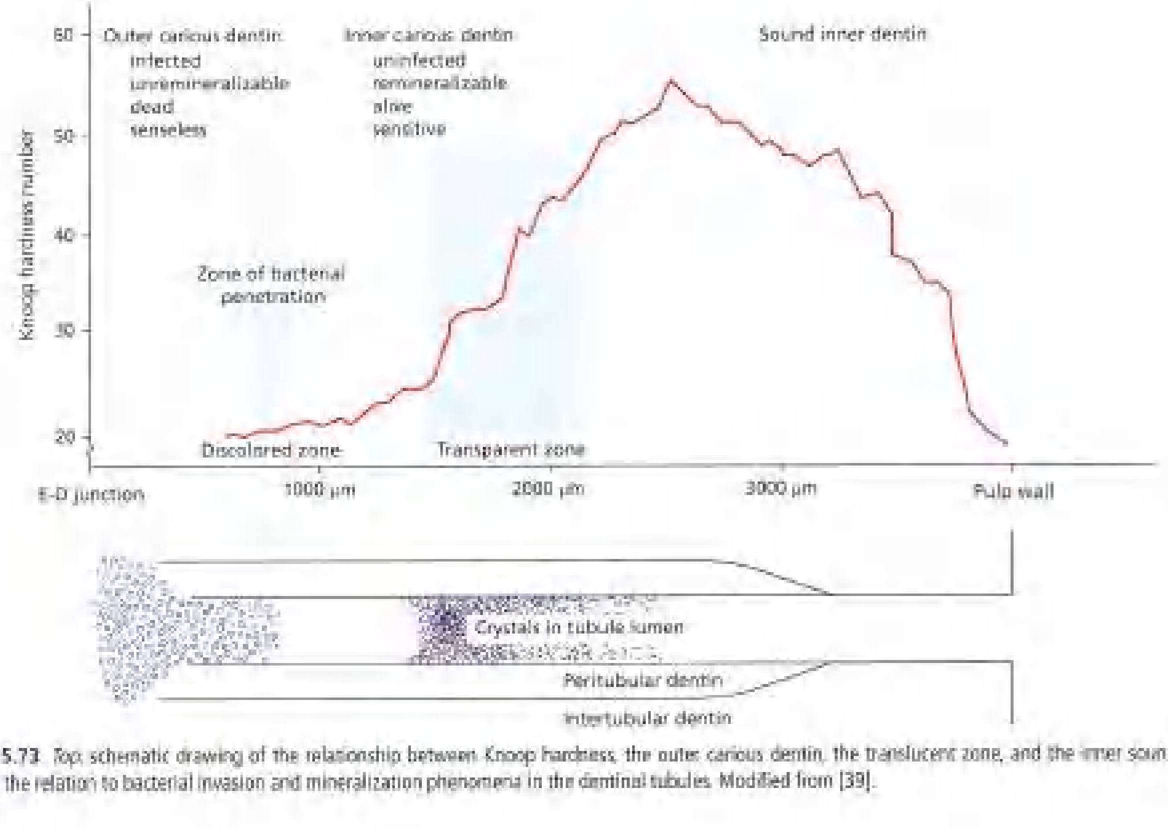


Figure 5.73 *Top*: schematic drawing of the relationship between Knoop hardness, the outer carious dentin, the translucent zone, and the inner sound dentin. *Bottom*: the relation to bacterial invasion and mineralization phenomena in the dentinal tubules. Modified from [39].

likely been treated with various pain relief interventions [17]. The message to be drawn from these examples is that even in deep, slowly progressing cavities utmost care should be taken if there are vital pulps when removing soft, partly dissolved carious dentin – ***avoid*** *rotating burs unless you wish to enhance the risk for pulpal death* (see Chapter 20). It is clear then that the demineralization will take place in dentin with partly obturated tubules, explaining why the superficial part of the translucent zone is softer than the sound dentin (Fig. 5.73).

Pulp reaction

There is still some uncertainty in the literature concerning the degree of pulp reactions in relation to various stages of caries development. It is known that reactionary (reparative or tertiary) dentin may form even before bacterial invasion into the dentin [6]. And some immune cells may be found close to the dentin. The reactionary dentin is less well mineralized and contains irregular dentinal tubules. When the demineralization of the dentin approaches the pulp at a distance between 0.5 and 1 mm, varying inflammatory reactions may be seen in the subodontoblastic region. It is important to realize that there is no infection of the pulp, and the inflammatory cell reactions are therefore believed to be a result of bacterial products [32, 40, 42].

Dental caries is a slowly progressing demineralization with gradual cavity formation and a partly dissolved outer layer of dentin (Fig. 5.68) containing bacteria. Pulpal inflammation therefore, is for a long time a low-grade immunologic response characterized by a chronic inflammatory cellular response. Once the total bacterial load in a caries cavity is reduced, such a reaction may gradually regress. However, if microorganisms invade the pulpal tissue then an acute inflammatory response is created with neutrophil leukocyte accumulation and the beginning of microabscess formation. Now a point of no return has been reached. For detailed information on pulpal reactions the reader is referred to standard endodontic texts.

Root-surface caries

Clinical appearance of root caries lesions

Recession of the gingival margin is an inevitable result of poor oral hygiene and loss of periodontal attachment with age [4, 5]. Even in populations with regular oral hygiene some recession occurs, and its pattern of distribution within the elderly population is very characteristic [16]. In today's populations it is frequent that even adolescents experience some exposure of the cervical root surfaces in several teeth due to inappropriate plaque control procedures.

As the gingival margin recedes, the enamel–cementum junction becomes exposed. This region of the tooth is highly irregular and represents a particular bacterial retention site. Therefore, a majority of root caries lesions develop at this site.

It is occasionally claimed that root-surface caries may occur within a deep periodontal pocket. From a biological point of view this is not very likely as the pH of the gingival exudate flushing the pocket is above 7. It seems more likely that in such cases the carious process has originated along the gingival margin. Gingival inflammation and swelling of gingiva may subsequently lead to the impression that the lesion is 'hidden in the pocket.'

Root-surface caries comprises a continuum of clinical manifestations ranging from small, slightly softened and discolored areas to extensive, yellow-brown soft or hard areas that may eventually encircle the entire root surface (see Chapter 3). The lesions may or may not be cavitated. However, even in the case of rather extensive lesions, cavitation does not necessarily involve the pulp.

As with enamel lesions, root-surface caries lesions may be classified as 'active' or 'arrested' ('inactive') according to the following diagnostic criteria:

- *An active root-surface lesion* is a well-defined, softened area on the root surface that shows a yellowish or light-brown discoloration. The lesion is most likely covered by visible plaque. Some slowly progressing lesions may be brownish or black and reveal a leathery consistency on probing with moderate pressure.
- *An arrested (inactive) root-surface lesion* appears shiny and is relatively smooth and hard on probing with moderate pressure. The color may vary from yellowish to brownish or black. In both active and inactive lesions, cavity formation may be observed, but in the latter case the margins appear smooth. No visible microbial deposits are seen to cover such lesions.

Although characteristic in its 'classical' manifestations, there will be a range of transitory stages between active and arrested lesions. Thus, it is important to appreciate that when using the diagnosis arrested (or inactive), this is a reflection of a clinical judgment that no further progression of that lesion is expected to take place. This does not, of course, imply that there may not be minute niches within certain areas of the lesion that, if examined for example in a microscope, show bacteria and very localized demineralization. However, if at the time of examination a lesion is judged to be arrested, the lesion is considered likely to remain clinically unchanged unless the patient's oral hygiene deteriorates at that particular site [36].

If there is doubt whether to assign a lesion into the active or the inactive category, the surface texture of the lesion (soft/leathery or hard) is a more valid criterion than is the mere color of the lesion.

It is clinically important to distinguish between active and inactive lesions because root surfaces also respond to the dynamic metabolic processes in the plaque. Thus, if these processes are interfered with (e.g., by regular disturbance of the plaque), active lesions can become arrested with associated changes in surface texture and color of the lesions.

From a differential diagnostic point of view a root-surface caries lesion is easy to distinguish from other root-surface discolorations because the latter usually are widespread and ill-defined.

5.74

5.75

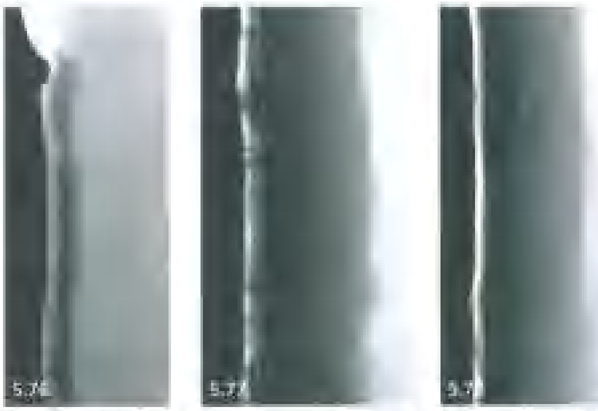
Figures 5.74 and 5.75 Microradiograms of early stages of root-surface caries. Distinct demineralization is observed throughout the cementum but also extending into the underlying dentin deep to a relatively well mineralized cementum zone. Note the laminated appearance of the cementum in Fig. 5.75, which reflects variations in the mineral content of the imbrication lines.

Histopathological features of root-caries lesions

The early root-surface caries lesion appears as a radiolucent zone in the root cementum (Figs 5.74 and 5.75). Improper toothbrushing or scaling of root surfaces often damages or removes the cementum, thus exposing the dentin. Therefore, in real life, root-surface caries often develops in the exposed dentin.

Microradiographically, mineral loss occurs deep to a relatively well-mineralized surface zone (Figs 5.76, 5.77, and 5.78) which frequently exhibits a mineral content that is higher than that of the unaffected dentin. As in enamel lesions, the surface zone varies in thickness and mineral content depending on the cariogenic challenge of the covering microbial plaque. Experimental studies have shown that, under suitable conditions, the surface zone forms within a relatively short period of time [39]. Thus, if root surfaces are covered by undisturbed plaque for 1–3 months in the oral cavity, a progressive subsurface loss of mineral occurs in the dentin concomitant with the buildup of a surface zone (Figs 5.76, 5.77, and 5.78). The high mineral content of the surface zone may reflect a selective redeposition of minerals in this region as it has been shown that the size of the apatite crystals in the surface zone is significantly larger than in normal cementum [48]; see Chapter 9.

In distinct contrast to the early enamel lesion, however, is the finding that at an early stage of root-surface caries development the surface may appear softened. This is due to microorganisms penetrating the surface zone of the lesion [37] between partly demineralized collagen fibers (Fig. 5.79). Therefore, probing of the vulnerable surface zone should be avoided as destruction of the surface may facilitate further penetration of bacteria into the dentin and impair the possibility for proper plaque control. In any case, vigorous scaling of root surfaces in caries-active patients should not be performed before it is ascertained that active carious lesions have been arrested.



Figures 5.76–5.78 Microradiograms of sections through root caries lesions that have been developed experimentally in the oral cavity during 1, 2, and 3 months. Note how the mineral content in the surface zone increases with increased duration of the cariogenic challenge while there is a progressive subsurface loss of mineral in the dentin [38].

Figure 5.79 A 1 μm thick section through the surface layer of an active root-surface caries lesion covered by microbial deposits. At this early stage, the microorganisms penetrate into the superficial layer of the cementum (arrows), which explains why the active root-surface caries lesion appears soft on probing. P: microbial plaque; C: cementum; D: dentin.

At more advanced stages of destruction the demineralization spreads into the underlying dentin, often extending several hundred micrometers below the surface (Fig. 5.80). However, even when shallow cavities are observed, the exposed dentin surface may exhibit a relatively well mineralized surface layer below which the demineralization takes place. The dentin response is similar to that described for coronal caries; that is, the pulpo-dentinal organ responds with a zone of increased mineral deep within the tissue corresponding to the width of the carious lesion at the surface. Likewise, tertiary (reactive) dentin may be formed towards the pulp, corresponding to the tubules involved.

Figure 5.80 Approximal active root-surface caries lesion covered by dental plaque (inset). A microradiogram of a section through the center of the lesions shows loss of cementum (C) corresponding to the part of the surface where extensive loss of mineral has occurred. The body of the lesion is located deep to a surface zone which varies in mineral content. The dentinal tubules affected by the caries attack show the zone of sclerosis (SZ), and towards the pulp tertiary dentin (reactive dentin) has formed (TD) [36]. E: enamel.

Arrested lesions (Fig. 5.81) demonstrate that a pronounced surface abrasion has taken place. Furthermore, redeposition of mineral may have occurred deep within the dentin. In such lesions it may be possible to identify localized radiolucencies which apparently, at the time of examination, have been 'active sites.' In view of the knowledge presented above it is clear that regular plaque removal from the surface of active root surface caries lesions is not likely to eliminate the microorganisms that have penetrated deep into the dentin. However, based on the clinical experience that root caries lesions can be converted from active into

Figure 5.81 (a) Section through an inactive root-surface caries lesion. When examined in transmitted light (b) and by microradiography (c), it is apparent that a considerable surface abrasion has occurred. Part of the lesion has been abraded away, but a localized radiolucent area remains, possibly reflecting a caries-active site [36].

Figure 5.82 Section through an arrested root-surface lesion where the microradiographic picture demonstrates extensive calculus formation extending into microcavities. Note the subsurface lesion cervical to the rim of calculus. E: enamel; CA: calculus.

inactive stages by nonoperative treatment [34] (see Chapter 3), it may be appreciated that *neither antimicrobial nor operative treatment are required to control the microorganisms within the root dentin*. In fact, a change in the environmental conditions prevailing in the dental plaque covering a root caries lesion may result in mineral deposition within the microbial mass (calculus formation). Thus, calculus may be found partially occluding root-surface defects corresponding to the arrested caries lesions (Fig. 5.82).

Background literature

Black GV. *Konservierende Zahnheilkunde*. Berlin: Verlag von Hermann Meusser, 1914.

Fejerskov O, Nyvad B. Dental caries in the aging individual. In: Holm-Pedersen P, Löe H, eds. *Textbook of geriatric dentistry*, 2nd ed. Copenhagen: Munksgaard, 1996: 338–72.

Fejerskov O, Thylstrup A. Dental enamel. In: Mjör I, Fejerskov O, eds. *Human oral embryology and histology*. Copenhagen: Munksgaard, 1986: 50–89.

Frank RM. Structural events in the caries process in enamel, cementum and dentin. *J Dent Res* 1990; **69** (special issue): 559–66.

Holmen L, Thylstrup A. Natural caries development and its arrestment. In: Leach SA, ed. *Factors relating to demineralization and remineralization of the teeth*. London: IRL Press, 1986: 139–52.

Reeves R, Stanley HR. The relationship of bacterial penetration and pulpal pathosis in carious teeth. *Oral Surg* 1966; **22**: 59–65.

Schmidt WJ, Keil A. *Polarizing microscopy of dental tissues*. Oxford: Pergamon Press, 1971.

Silverstone LM. Structure of carious enamel including the early lesion. *Oral Sci Rev* 1973; **3**: 100–60.

Warshawsky H, Josephsen K, Thylstrup A, Fejerskov O. The development of enamel structure in rat incisors as compared to the teeth of monkey and man. *Anat Rec* 1981; **200**: 371–99.

References

1. Årtun J, Thylstrup A. Clinical and scanning electron microscopic study of surface changes of incipient enamel caries lesions after debonding. *Scand J Dent Res* 1986; **94**: 193–210.
2. Årtun J, Thylstrup A. A three-year clinical and SEM study of surface changes of carious enamel lesions after inactivation. *Am J Dentofac Orthop* 1989; **95**: 327–33.
3. Becker Dirks O. Posteruptive changes in dental enamel. *J Dent Res* 1966; **45**: 503–11.
4. Baelum V. The epidemiology of destructive periodontal disease. Thesis. Aarhus: Aarhus University, Royal Dental College, 1998.
5. Baelum V, Manji F, Fejerskov O. The distribution of periodontal destruction in populations in non-industrialized countries: evidence for the existence of high risk groups and individuals. In: Johnson NW, ed. *Risk markers for oral diseases. Vol. 3. Periodontal diseases. Markers of disease susceptibility and activity*. Cambridge: Cambridge University Press, 1991: 27–74.
6. Bjørndal L. Carieslæsionens tidlige udvikling i emalje og pulpa-dentin organet. Dissertation. Copenhagen: University of Copenhagen, 1991.
7. Black GV. *Konservierende Zahnheilkunde*. Berlin: Verlag von Hermann Meusser, 1914.
8. Boyde A. Amelogenesis and the structure of enamel. In: Cohen B, Kramer IRH, eds. *Scientific foundations of dentistry*. London: Heinemann Medical Books, 1976: 335–52.
9. Carvalho JC, Ekstrand KR, Thylstrup A. Dental plaque and caries on occlusal surfaces of first permanent molars in relation to stage of eruption. *J Dent Res* 1989; **68**: 773–9.
10. Carvalho JC, Ekstrand KR, Thylstrup A. Results of 1 year of non-operative occlusal caries treatment of erupting permanent first molars. *Community Dent Oral Epidemiol* 1991; **19**: 23–8.
11. Carvalho JC, Ekstrand KR, Thylstrup A. Results of 3 years of non-operative occlusal caries treatment of erupting permanent first molars. *Community Dent Oral Epidemiol* 1992; **20**: 187–92.
12. Daculsi G, Menanteau J, Kerebel LM, Mitre D. Length and shape of enamel crystals. *Calcif Tiss Int* 1984; **36**: 550–5.
13. Daculsi G, LeGeros RZ, Jean A, Kerebel B. Possible physico-chemical processes in human dentin caries. *J Dent Res* 1987; **66**: 1356–9.
14. Ekstrand K, Carlsen O, Thylstrup A. Morphometric analysis of occlusal groove-fossa-system in mandibular third molar. *Scand J Dent Res* 1991; **99**: 196–204.
15. Fejerskov O, Josephsen K, Nyvad B. Surface ultrastructure of unerupted mature human enamel. *Caries Res* 1984; **18**: 302–14.
16. Fejerskov O, Baelum V, Østergaard ES. Root caries in Scandinavia in the 1980s – and future trends to be expected in dental caries experience in adults. *Adv Dent Res* 1993; **7**: 4–14.
17. Fejerskov O, Bilde PG, Bizarro M, Connelly JN, Thomsen JS, Nyvad B. Dental caries in Rome, 50–100 AD. *Caries Res* 2012; **46**: 467–73.
18. Fejerskov O, Larsen MJ, Richards A, Baelum V. Dental tissue effects of fluoride. *Adv Dent Res* 1994; **8**: 15–31.
19. Frank RM, Voegel JC. Ultrastructure of the human odontoblast process and its mineralization during dental caries. *Caries Res* 1980; **14**: 367–80.
20. Haikel Y, Frank RM, Voegel JC. Scanning electron microscopy of the human enamel surface layer of incipient carious lesions. *Caries Res* 1983; **17**: 1–13.
21. Hay DI. Specific functional salivary proteins. In: Guggenheim B, ed. *Cariology today*. Basel: Karger, 1984: 98–108.
22. Holmen L, Thylstrup A. Variations in 'normal' enamel surface as visualized in the SEM. In: Ruch JV, Belcourt A, eds. *Tooth morphogenesis and differentiation II*. Paris: INSERM, 1984: 283–94.

23. Holmen L, Thylstrup A, Øgaard B, Kragh F. A polarized light microscopic study of progressive stages of enamel caries *in vivo*. *Caries Res* 1985; **19**: 348–54.
24. Holmen L, Thylstrup A, Øgaard B, Kragh F. A scanning electron microscopic study of progressive stages of enamel caries in vivo. *Caries Res* 1985; **19**: 355–67.
25. Holmen L, Thylstrup A, Årtun J. Clinical and histological features observed during arrestment of active enamel carious lesions in vivo. *Caries Res* 1987; **21**: 546–54.
26. Holmen L, Thylstrup A, Årtun J. Surface changes during the arrest of active enamel carious lesions in vivo. A scanning electron microscope study. *Acta Odontol Scand* 1987; **45**: 383–90.
27. Johnson NW. Some aspects of the ultrastructure of early human enamel caries seen with the electron microscope. *Arch Oral Biol* 1967; **12**: 1505–21.
28. Johnson NW, Taylor BR, Berman DS. The response of deciduous dentine to caries studied by correlated light and electron microscopy. *Caries Res* 1969; **3**: 348–68.
29. Larsen MJ, Fejerskov O. Chemical and structural challenges in remineralization of dental enamel lesions. *Scand J Dent Res* 1989; **97**: 285–96.
30. Levine RS. The microradiographic features of dentine caries. *Br Dent J* 1974; **137**: 301–6.
31. Mannerberg F. Appearance of tooth surface as observed in shadowed replicas in various age groups, in long-term studies, after tooth-brushing, in cases of erosion and after exposure to citrus fruit juice. *Odontol Rev* 1960; **11** (Suppl 6).
32. Massler M. Pulpal reactions to dental caries. *Int Dent J* 1967; **17**: 441–60.
33. Mjör IA. Dentine and the pulp. In: Mjör IA, ed. *Reaction patterns in human teeth*. Boca Raton, FL: CRC Press, 1983: 63–156.
34. Nyvad B, Fejerskov O. Active root surface caries converted into inactive caries as a response to oral hygiene. *Scand J Dent Res* 1986; **94**: 281–4.
35. Nyvad B, Fejerskov O. Transmission electron microscopy of early microbial colonization of human enamel and root surface in vivo. *Scand J Dent Res* 1987; **95**: 297–307.
36. Nyvad B, Fejerskov O. Active and inactive root surface caries – structural entities? In: Thylstrup A, Leach SA, Qvist V, eds. *Dentine and dentine reactions in the oral cavity*. Oxford: IRL Press, 1987: 165–79.
37. Nyvad B, Fejerskov O. An ultrastructural study of bacterial invasion and tissue breakdown in human experimental root surface caries. *J Dent Res* 1990; **69**: 2318–25.
38. Nyvad B, ten Cate JM, Fejerskov O. Microradiography of experimental root surface caries in man. *Caries Res* 1989; **23**: 218–23.
39. Ogawa K, Yamashita Y, Ichijo T, Fusayama T. The ultrastructure and hardness of the transparent layer of human carious dentin. *J Dent Res* 1983; **62**: 7–10.
40. Shovelton DS. The maintenance of pulp vitality. *Br Dent J* 1972; **133**: 95–107.
41. Silverstone LM. Remineralization phenomena. *Caries Res* 1977; **11**: 59–84.
42. Stanley HR, Pereira JC, Spiegel E, Broom C, Schultz M. The detection and prevalence of reactive and physiologic sclerotic dentin, reparative dentin and dead tracts beneath various types of dentinal lesions according to tooth surface and age. *J Pathol* 1983; **12**: 257–89.
43. Thylstrup A, Bruun C, Holmen L. *In vivo* caries models – mechanisms for caries initiation and arrestment. *Adv Dent Res* 1994; **8**: 144–57.
44. Thylstrup A, Featherstone JDB, Fredebo L. Surface morphology and dynamics of early enamel caries development. In: Leach SA, Edgar WM, eds. *Demineralisation and remineralisation of the teeth*. London: IRL Press, 1983: 165–84.
45. Thylstrup A, Fejerskov O. Surface features of early carious enamel at various stages of activity. In: Rølla G, Sønju T, Embery G, eds. *Proceedings of a workshop on tooth surface interactions and preventive dentistry*. London: IRL Press, 1981: 193–205.
46. Thylstrup A, Fredebo L. A method for studying surface coatings and the underlying enamel features in the scanning electron microscope. In: Frank R, Leach S, eds. *Surface colloid phenomena in the oral cavity: methodological aspects*. London: IRL Press, 1982: 169–84.
47. Thylstrup A, Qvist V. Principal enamel and dentine reactions during caries progressions. In: Thylstrup A, Leach SA, Qvist V, eds. *Dentine and dentine reactions in the oral cavity*. Oxford: IRL Press, 1987: 3–16.
48. Tohda H, Fejerskov O, Yanagisawa T. Transmission electron microscopy of cementum crystals correlated with Ca and F distribution in normal and carious human root surface. *J Dent Res* 1996; **75**: 949–54.
49. Weatherell JA, Robinson C, Hallsworth AS. The concept of enamel resistance – a critical review. In: Guggenheim B, ed. *Cariology today*. Basel: Karger, 1984: 223–30.

6

Saliva and caries development

A. Bardow and A. Vissink

Introduction

In the oral cavity the enamel will be influenced by interactions between the enamel surface and the aqueous environment surrounding it (see also Chapter 9). Under physiological conditions this aqueous environment consists mostly of saliva, which makes saliva a key element in understanding the biology of dental caries. Normally, saliva can protect the enamel throughout life and, therefore, its effects are taken for granted. However, under pathological conditions, without saliva, the lack of its protective effects becomes clearly visible. Thus, most clinicians have seen patients with impaired salivary gland function who develop severe dental caries in a rapid manner and in areas of the enamel that are normally not affected by caries. Between the pathological condition of reduced or abolished saliva secretion and the normal condition of a constant flow of saliva while awake, the relationship between saliva and dental caries is, however, far from straightforward.

The role of saliva cannot be attributed to a single function of saliva, but to a complex interplay among several salivary functions. Because some of these functions are maintained by different salivary components, it becomes complex to describe the functions of saliva on dental caries. Furthermore, which functions are important vary throughout different 'stages' of biofilm formation and subsequently caries lesion development. One function may be highly important in the initial stages, but almost irrelevant in later stages. The shift in saliva protection against caries is caused mainly by changes in the biofilm structure during its formation. As an example, during biofilm formation the aqueous environment near the enamel surface becomes progressively different and isolated from saliva and, therefore, some salivary components lose their ability to protect the enamel while other components gain more effect.

This chapter describes the effects of saliva on caries lesion development within a theoretical framework where

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

the major functions are related to different 'stages or phases' of the caries process. To provide practical approaches for identification of patients in whom high caries levels may be attributed to salivary factors, this chapter also includes a description of the etiology, diagnosis, and management of salivary gland hypofunction along with brief presentations of some of the most common causes of this condition.

Saliva and salivary glands

Saliva is the fluid that constantly under awake and physiological conditions flows into the oral cavity from the many different salivary glands situated in and around the orofacial region. The majority of saliva is secreted from the major salivary glands, comprising the parotid, the submandibular, and the sublingual glands (Fig. 6.1). At the time of entry to the mouth this glandular saliva is as transparent as water, normally sterile, and contains less than 1% solids composed of electrolytes and proteins. The remaining more than 99% of saliva is just water.

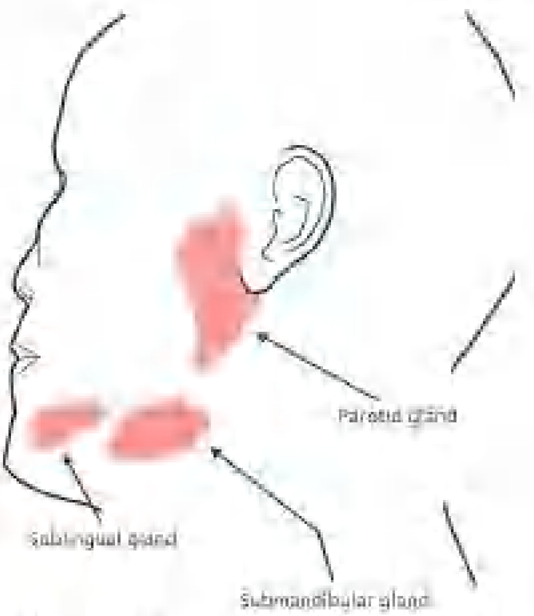


Figure 6.1 Location of the major salivary glands in humans: the parotid (strictly serous), the submandibular (seromucous), and the sublingual gland (mucoserous). The parotid gland (14–28 g), the largest salivary gland, is located bilaterally before and under the ear. The main excretory duct (parotid duct or Stensen's duct) ends in the cheek at the height of the upper molars. The submandibular gland (7–8 g) is located bilaterally under the jaw just medially of the mandibular angulus. The main excretory duct (Wharton's duct) has its entrance in the floor of the mouth, just behind the lower incisors. The sublingual gland (3 g) is located bilaterally in the floor of the mouth between the mandibular corpus and tongue. The sublingual gland secretes with numerous ducts directly to the floor of the mouth in the area where the gland is located and also via a main excretory duct (Bartholin's duct) that runs with the submandibular duct and also ends in the floor of the mouth at the level of the lower incisors. The minor salivary glands (<10 mg/gland), whose number is estimated at several hundred, are scattered among the oral mucosa of the palate (the palatinal glands that are strictly mucous), the lip (the labial glands), the cheek (the buccal glands), and tongue (the lingual glands). In the region of the papillae vallatae on the tongue are the von Ebner glands, which are strictly serous.

The viscosity is the only visible difference among secretions from different glands. Some glands produce a watery (serous) and some a more or less sticky (mucous) secretion. The difference in viscosity is caused only by the salivary proteins, which are highly specific for each gland and determine many characteristics of its secretion. Immediately after entry into the mouth the various secretions become mixed and contaminated with shed mucosal cells, food debris, vast amounts of bacteria, and gingival crevicular fluid, the amount of which is highly dependent on the degree of gingival inflammation. It is this compound and cloudy fluid that is mostly referred to as saliva, although, the term *whole saliva* more correctly distinguishes it from the gland-specific secretions. During the day between 0.5 and 1.0 L of whole saliva will have passed through the mouth, with almost no saliva during sleep.

In the unstimulated state, it is mainly the submandibular and sublingual glands that are active [51, 53] producing the majority of whole saliva (Table 6.1). Together with the numerous minor salivary glands situated in the mucosa, the submandibular and sublingual glands are the main contributors of mucous proteins (mucins) to whole saliva [41] because these glands contain mucous cell types that are able to produce mucins (Fig. 6.2). It is the mucins that are responsible for the characteristic viscous and ropy properties of whole saliva. In contrast, the parotid gland lacks the mucous cell type. Without the mucous cell type the serous cells in the parotid gland (Fig. 6.2) produce saliva with a viscosity like water, even though the protein concentration often is higher in parotid than in submandibular saliva. The importance of the parotid secretion is mainly during meals, where the parotids may produce more than half of whole saliva, compared to only one-fifth of unstimulated saliva (Table 6.1).

Table 6.1 Normal range for whole saliva flow rates and relative contribution of different gland types to whole saliva under various conditions [52]. Reproduced with permission of Thieme Publishing Group.

	Sleep	Unstimulated whole saliva	Stimulated (mechanical) whole saliva	Stimulated (sour taste) whole saliva
Flow rate (mL/min)	0	0.3–0.5	1.0–2.0	5.0–10.0*
Salivary gland contribution				
Parotid (%)	—	21	58	45
Submandibular (%)	—	70	33	45
Sublingual (%)	—	2	2	2
Minor glands (%)	—	7	7	8

*Indicates extreme flow rates obtained with strong acidic taste and mechanical stimulation combined.

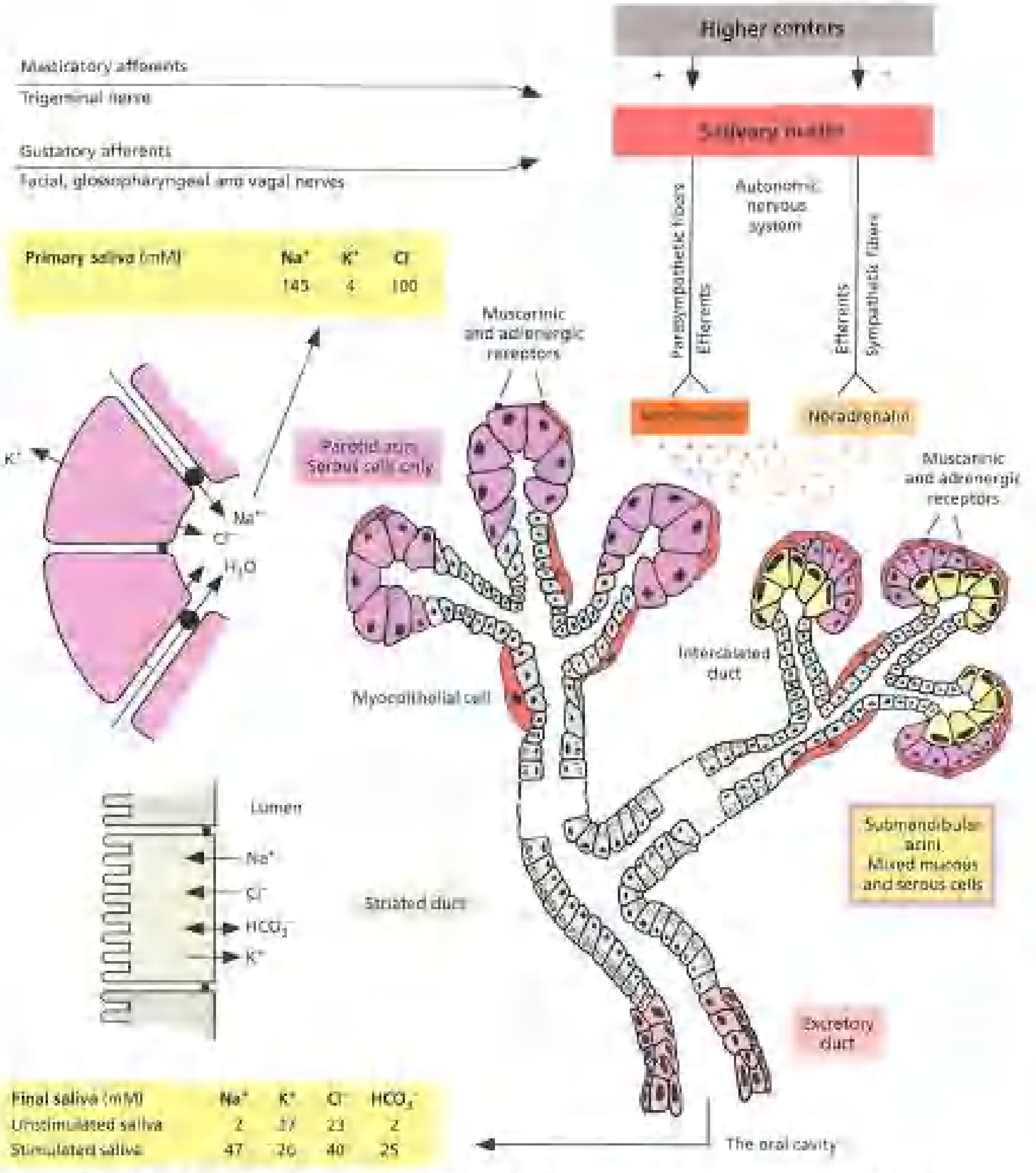


Figure 6.2 Salivary gland structure showing both serous and seromucous end-pieces, intercalated ducts, myoepithelial cells, striated ducts, and excretory ducts and their relation to the autonomic nervous system afferents and efferents. The left-side schematic drawings show the main ion channels of the acinar and ductal cells. The ductal tissue has a low water permeability, as opposed to the highly water-permeable acinar tissue. Upon stimulation, neurotransmitters bind to specific receptors that activate cell signaling pathways, which result in an increase in intracellular calcium and opening of calcium-activated ion channels in the cell membrane. Average values for the ionic composition are given for primary saliva as well as unstimulated and stimulated whole saliva.

Stimulation and control of secretion

The secretion of saliva is regulated by the autonomic nervous system [16], with both sympathetic and parasympathetic stimulation activating the salivary glands, although in a different manner (Fig. 6.2). Parasympathetic stimulation clearly provides the strongest stimulus for salivation, giving rise to high flow rates of watery saliva, whereas sympathetic stimulation leads to lower flow rates, with a more viscous and protein-rich saliva. These differences of autonomic stimulation are due to neurotransmitter-specific activation of different receptors on the glands by either sympathetic or parasympathetic stimulation.

The reflex pathways are unilateral: stimulation of one side of the mouth induces secretion from the glands on that side of the mouth. The strongest stimuli for saliva secretion are mechanical stimulation obtained by chewing and taste (chemical stimulation). Taste stimuli can be divided into sour, salt, bitter, and sweet in descending order according to how much each taste stimulates saliva secretion [47]. Sour taste induces more than twice as much saliva secretion as salty taste and many times more saliva secretion than the sweet taste of sugar. Compared with mechanical stimulation by chewing, sour taste is also a much more potent stimulant of saliva secretion. Combined mechanical stimulation by chewing and the sensation of sour and salty taste may lead to very high saliva flow rates that are sometimes thirtyfold the unstimulated level. It is relevant to know that the effect of other stimuli, like the sensation of smell and/or the sight or thought of food, is minor in humans, even though these stimuli have pronounced effects on saliva secretion in many other primates and mammals. Table 6.1 shows saliva flow rates for whole saliva under different conditions.

Chewing activates the masticatory–salivary reflex by sensory inputs mainly from mechanical receptors in the periodontal ligament, tongue, and oral mucosa via the trigeminal nerve. The sensation of taste activates the gustatory–salivary reflex by sensory signals from chemoreceptors in the taste buds within the lingual papillae, the tonsillar region, the epiglottis, the pharyngeal wall, and esophagus. These signals are conducted along the facial, glossopharyngeal, and vagal nerves to the salivatory nuclei in the medulla oblongata and the brain from where the glands are controlled by the salivatory nuclei (Fig. 6.2).

The glands

The parotid, the submandibular, and the sublingual glands are relatively large organs, but still they can be difficult to localize within the orofacial area (Fig. 6.1). The salivary glands may, however, become clearly noticeable when enlarged due to pathological conditions such as salivary gland inflammation (sialadenitis), stones (sialolithiasis), and mumps. Structurally, the glands are composed of a highly branched interior lumen, which is connected to the oral cavity via the ducts. From the glands the main excretory ducts (Stenson's, Wharton's and Bartholin's) lead saliva to the oral cavity. Within the glands the ducts become branched, so that the main excretory ducts divide into intralobular ducts. These ducts divide into smaller striated ducts that divide into even smaller intercalated ducts, which terminate at the acini, which is also named the secretory end-piece (Fig. 6.2). The luminal surfaces of the secretory end-pieces and the ducts within a salivary gland are lined with specialized epithelial cells. These can actively generate fluid, modify fluid, and secrete proteins, carbohydrates, and lipids. Owing to the high degree of branching, the secretory end-pieces are the most numerous histological structures within the gland (like leaves on a tree) and comprise about 80% of the gland mass. Each end-piece consists of polarized cells that surround a central lumen. Depending on the gland, these cells can be solely serous, solely mucous (minor palatal glands), or a mixture of both (Fig. 6.2). It is within the end-pieces that the water content of saliva is produced, and thereby the acinar cells determine the volume and flow rate of saliva. In addition, many ions and proteins are also added to the saliva from the acinar cells by autonomic nervous stimulation. Within this part of the gland, the newly secreted saliva is called primary saliva. Before this primary saliva becomes whole saliva in the mouth it is subjected to major compositional modification within the ducts.

Formation of primary saliva

Formation of primary saliva is not the result of pressure filtration of blood. On the contrary, saliva secretion is the result of energy-consuming loss of ions from the acinar cells into the lumen of the end-pieces. In the lumen, these ions will drag water with them by osmosis. Because primary saliva is generated by osmosis against plasma, this fluid will be isotonic, having concentrations of the major ions that are similar to plasma.

After stimulation by the autonomic nervous system, the actual formation of saliva requires a number of complex intracellular events. The key element in these events is an intracellular rise in the free calcium concentration within the acinar cells in the secretory end-pieces. This intracellular rise in calcium occurs as a result of binding of neurotransmitters released from both sympathetic and parasympathetic nerve endings to G-protein-coupled receptors in the salivary gland cell membranes. Acetylcholine released from parasympathetic nerve endings will bind to the muscarinic cholinergic receptors, and noradrenaline released from sympathetic nerves binds to the α_1-adrenergic receptors. Binding of neurotransmitters to both these receptors gives rise to a cascade of intracellular events that lead to rapid oscillatory increases in intracellular free calcium. Each calcium increase opens calcium-activated potassium channels located away from the lumen into the bloodstream, as well as calcium-activated chloride channels leading into the lumen (Fig. 6.2). The accumulation of chloride ions in the acinar lumen creates a negative intraluminal potential that drives interstitial sodium into the lumen from between the acinar cells. Owing to increased osmotic pressure within the lumen, this movement of salt drives water, also from between the cells as well as from the cells via aquaporins (AQP5), the latter making the acinar cells shrink during the process of secretion [38]. To maintain continuous secretion, the chloride loss from the acinar cells needs to be compensated by an uptake of chloride, an uptake that is dependent on the sodium gradient generated by the sodium–potassium pump. This dependency on the sodium gradient makes saliva formation a highly energy-consuming process for the acinar cells.

Together with the primary saliva water content, many proteins are also secreted. Stimulation of the muscarinic cholinergic and the α_1-adrenergic receptors will cause some protein secretion from the acinar cells into the primary saliva. In addition, protein secretion is also highly activated by binding of noradrenalin to β-adrenergic G-protein-coupled receptors in the acinar cells. Especially in the salivary glands, the β-adrenergic pathway seems to be the principal signal for exocytosis of protein-containing granules, and is thus important for establishing the physiological saliva protein concentration. In a simplified perspective, binding of acetylcholine (parasympathetic) to its cognate receptor on the acinar cells stimulates the secretion of large volumes of watery saliva, whereas the combined activation of β-adrenergic and α_1-adrenergic receptors by binding of noradrenaline (sympathetic) stimulates a smaller volume of saliva, but with a high concentration of salivary proteins.

Modification of primary saliva

The movement of saliva from the secretory end-piece to the duct is caused by the continuous formation of new primary saliva and contracting forces from myoepithelial cells surrounding the end-pieces (Fig. 6.2). Within the striated ducts a drastic compositional modification takes place without changes to the saliva water content. This can occur because the membranes of the duct cells have low permeability to water, and the tight junctions connecting the duct cells have a very low permeability to both ions and water. The modification comprises both reabsorption of some ions from primary saliva and excretion of other ions into the ductal saliva as well as the secretion of important proteins into saliva. The main event is reabsorption of sodium and chloride as the isotonic primary saliva passes through the striated ducts. In the resting state with low flow rates, the sodium concentration may be reduced a hundredfold after passage through the striated ducts compared with primary saliva. Chloride also decreases manyfold at low flow rates due to reabsorption, although not as much as sodium. As a result, low flow rates with a long passage time in the ducts allow for a nearly complete reabsorption of the ions that were the driving force for the formation of primary saliva in the secretory end-pieces. In contrast, high flow rates result in increased sodium and chloride concentrations (Fig. 6.3), not because of compositional changes in primary saliva, but because short passage times reduce the time available for reabsorption [49]. Thus, high concentrations at high flow rates are related to the structure of the glands, where a high number of end-pieces secrete primary saliva into a lower number of striated ducts, which at some point reach their maximal capacity for reabsorption.

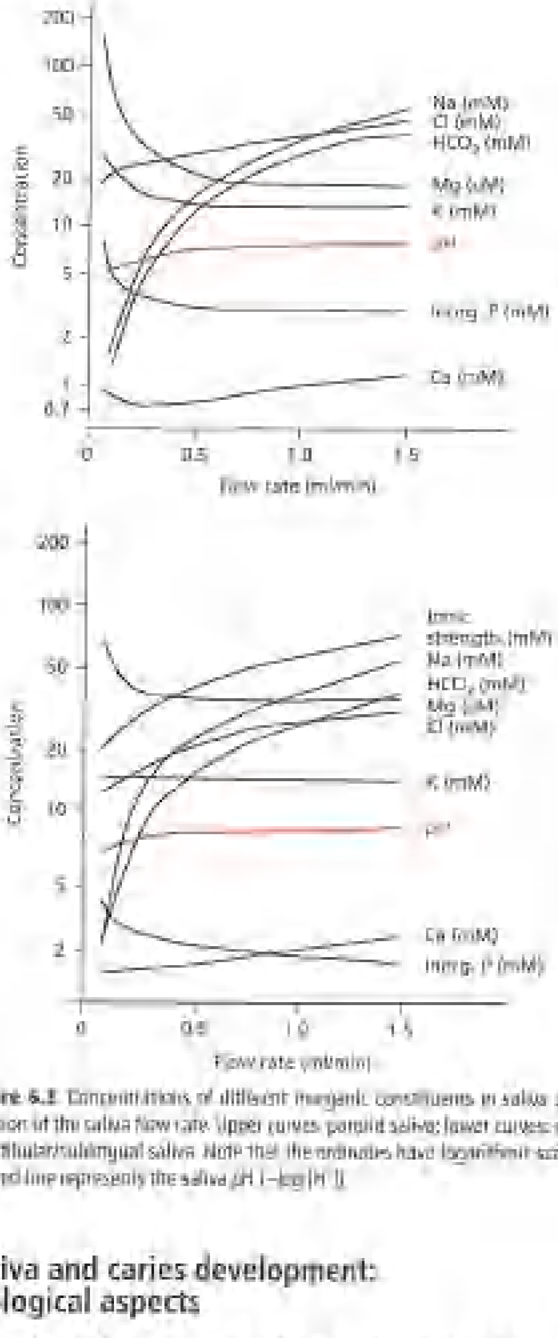
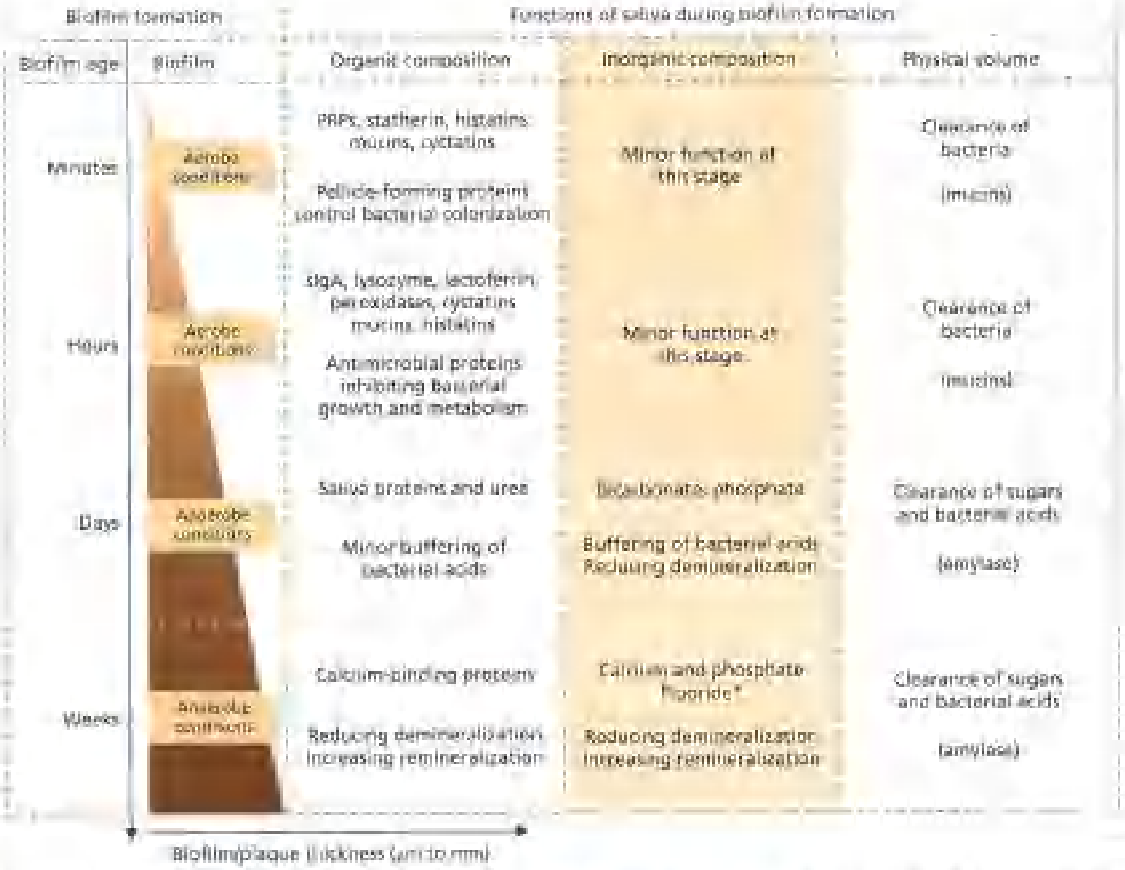


Figure 6.3 Concentrations of different inorganic constituents in saliva as a function of the saliva flow rate. Upper curves: parotid saliva; lower curves: submandibular/sublingual saliva. Note that the ordinates have logarithmic scales. The red line represents the saliva pH (−log[H$^+$]).

Saliva and caries development: biological aspects

Naturally, saliva interacts with normal and healthy tooth surfaces and influences all metabolic processes in the biofilm as well as the physicochemical processes following the caries lesion formation. However, it is not the same salivary functions and components that are important at different 'stages' of caries lesion development. Indeed, the salivary functions and components that are relevant against caries are determined by the thickness, permeability, and acid-producing capacity of the biofilm (Fig. 6.4). Thus, distinguishing between different 'stages' of biofilm formation and caries development, each function and its benefit against dental caries can be placed at a specific time within



Biofilm formation		Functions of saliva during biofilm formation		
Biofilm age	Biofilm	Organic composition	Inorganic composition	Physical volume
Minutes	Aerobe conditions	PRPs, statherin, histatins mucins, cystatins Pellicle-forming proteins control bacterial colonization	Minor function at this stage	Clearance of bacteria (mucins)
Hours	Aerobe conditions	sIgA, lysozyme, lactoferrin, peroxidases, cystatins mucins, histatins Antimicrobial proteins inhibiting bacterial growth and metabolism	Minor function at this stage	Clearance of bacteria (mucins)
Days	Anaerobe conditions	Saliva proteins and urea Minor buffering of bacterial acids	Bicarbonate, phosphate Buffering of bacterial acids Reducing demineralization	Clearance of sugars and bacterial acids (amylase)
Weeks	Anaerobic conditions	Calcium-binding proteins Reducing demineralization Increasing remineralization	Calcium and phosphate Fluoride* Reducing demineralization Increasing remineralization	Clearance of sugars and bacterial acids (amylase)

Figure 6.4 Functions of saliva and its components in relation to the age, thickness, and acid-producing capacity of the biofilm. The components shown in parentheses (mucins and amylase) increase the effect of the physical volume at various 'stages' of the caries process. All 'stages' may be present within the same dentition at the same time.

this process. It is relevant, therefore, to describe what happens in the first minutes and hours of biofilm formation on clinically sound tooth surfaces separately from what happens during the caries lesion process (Fig. 6.4).

Formation of the pellicle

When enamel is exposed to saliva a proteinaceous film called the *acquired pellicle* will form on its surface; *acquired* relates to fact that this film is formed after tooth eruption. Because the hydroxyapatite crystals in the enamel are negatively charged with a positively charged ionic outer layer, primarily of calcium, electrostatic interactions will attract negatively charged macromolecules from saliva to its surface (Fig. 6.5). It has been shown that the first negatively charged molecules from saliva are nearly instantaneously adsorbed onto the enamel [18]. Negative charges can be found in acidic side-chains of many salivary proteins, such as the sialic acid residues in MUC5B, the larger mucin from the submandibular and sublingual glands. This protein and the proline-rich proteins (PRPs), histatin and statherin are some of the first adsorbed onto enamel. Hereafter, further pellicle formation takes place by complex protein–protein interactions between already adsorbed proteins (immobilized on the enamel surface due to electrostatic interactions) and proteins as well as protein aggregates from saliva. Normally, the pellicle becomes around 1 μm in thickness and will not continue to grow unlimited, but enters a balance between adsorption and desorption of saliva proteins. At this point most salivary proteins can be identified in the pellicle, although regional variations in the salivary film composition and velocity will make the composition of the pellicle site-specific [19]. The pellicle is important because it will be the base for subsequent adhesion or repulsion of microorganisms. Experimentally, this generally results in the adherence of fewer bacteria onto enamel. This process, however, is highly complex because some proteins within the pellicle also facilitate specific binding of some microorganisms by acting as receptors. Thereby, the pellicle layer, even if thin, plays a critical role by controlling bacterial colonization. Selective colonization by nonpathogenic bacteria may perhaps impact the progression of caries already from this early stage of the process.

Within the pellicle matrix, molecule movements are much slower than in whole saliva. In this way the pellicle

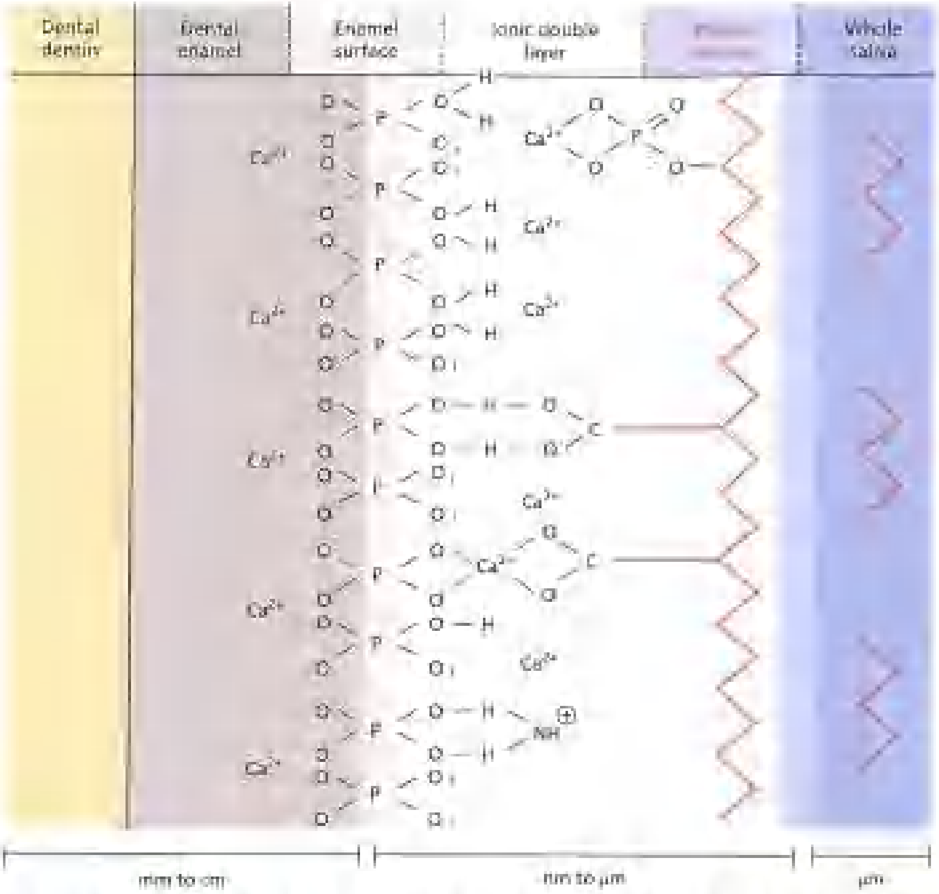


Figure 6.5 Development of the pellicle on a clean enamel surface showing the dentin, the enamel, the enamel surface with its negatively charged hydroxyapatite crystals having the phosphate groups nearest to the surface, the positively charged ionic double layer with much more calcium than phosphate, the first negatively charged proteins attached to this double layer, and whole saliva as the source of the pellicle proteins. The first proteins to form a pellicle are mainly the PRPs and statherin. Adapted from [18] Hannig and Joiner 2006.

also serves as a diffusion barrier to dietary acids and thereby protects against dental erosion, the other major disease of the enamel and dentin. The pellicle probably also facilitates remineralization as it maintains calcium and phosphate close to the tooth surface during exposure to acids. Screening of pellicles from healthy individuals has shown considerable variations in protection of enamel surfaces against acids [10]. However, little is known about what type of pellicle (or pellicle proteins) is protective against dietary acids, but a thick pellicle will most likely be more protective than a thin one.

Important pellicle proteins

Almost all salivary proteins are glycoproteins; that is, they contain variable amounts of carbohydrates linked to the protein core. Glycoproteins are often classified according to their cell origin and are further subclassified based on their biological properties. A characteristic feature is that one glycoprotein may occur in multiple forms (polymorphism) having several functions and functional differences. Mucous glycoproteins (mucins) are produced by mucous salivary gland cells and have high molecular weight and contain more than 60% carbohydrates [48]. Often, mucins are considered synonymous with salivary glycoproteins. However, the term glycoprotein covers all carbohydrate-linked proteins, and so this group also includes the serous saliva proteins. Serous glycoproteins contain less carbohydrate than mucins do and are produced by the serous acinar cells (Fig. 6.2).

PRPs secreted from human parotid and submandibular glands are very abundant proteins in saliva and the pellicle, and may constitute as much as 25–30% of all proteins in saliva. This salivary protein fraction can be further subdivided because PRPs form a complex group with a large number of genetic variants. PRPs can promote selective attachment of bacteria to apatitic surfaces. Studies have shown that racial genetic differences in PRPs between Caucasians and African-Americans may be related to differences in colonization by *Streptococcus mutans* and caries incidence [56], so that genetic differences in pellicle proteins could be related to caries incidence [32]. Another important pellicle precursor protein is statherin. This protein has many properties similar to PRPs and is present in both parotid and submandibular saliva. In the pellicle, statherin is known to promote the adhesion of *Actinomyces viscosus* to tooth surfaces. Although bacterial proteases degrade many pellicle proteins, PRPs and statherin concentrations are so high that these proteins have time enough to exert their function before being degraded by enzymes.

In spite of the pellicle being nearly always present on the enamel, professional polishing with rubber cups and powders, as well as acid etching and bleaching, will remove the pellicle proteins from its surface. In contrast, the pellicle is generally not removed by the everyday mechanical action of toothbrushing. The fate of the pellicle during toothbrushing, however, may depend on the type of toothpaste used. Thus, anionic detergents like sodium lauryl sulfate (SLS) often used in toothpaste may delay adsorption of new pellicle proteins to the enamel surfaces after cleaning [43]. Here, negatively charged molecules like SLS can interact with the electrostatic mechanisms of the molecules involved in pellicle formation (Fig. 6.5). Removal and/or delayed pellicle formation, resulting in a thinner pellicle, may leave the tooth surface more vulnerable than normal to chemical impact from dietary acids [10].

Functions of saliva on newly formed biofilms

Bacterial strategies for attachment and colonization have developed through millions of years, and bacterial biofilms are abundant within the oral cavity and shared by many mammals. Many bacterial species have become highly adapted for attachment and subsequently colonization of the oral surfaces in their aqueous and moist environment. Such bacteria will be able to override the protection offered by the pellicle and thereby also manage to colonize the enamel surfaces. In spite of these highly adapted bacterial strategies for colonization, the biofilm that is formed directly on the pellicle is permeable to most molecules. So, at this early stage, the biofilm allows for passage of most molecules and proteins from saliva. Many salivary proteins have antimicrobial properties and reduce the number of pathogens on enamel surfaces. Equally important is the flow of saliva passing through the oral cavity. This constant flow restricts the total number of bacteria and nutrients available for colonization.

Antimicrobial proteins and peptides

The major antimicrobial proteins of saliva are listed in Table 6.2. Most of these proteins can inhibit the adherence, metabolism, or even the viability of cariogenic microorganisms. A very characteristic feature for salivary proteins is a high degree of functional redundancy, meaning that different proteins have similar functions [31]. Thus, many antimicrobial functions of saliva are supported by a concerted action of several proteins. For this reason, an increase in the concentration of a single antimicrobial protein in saliva does not seem to reduce dental caries. Thus, antimicrobial salivary proteins seem mainly to be important for the control of microbial overgrowth in the mouth. Many antimicrobial proteins probably exert their main biological activities on surfaces, like the pellicle, rather than in liquid phase.

Table 6.2 Major antimicrobial proteins of human whole saliva.

Protein	Major target/function
Non-immunoglobulin (innate) proteins	
Lysozyme	Gram-positive bacteria, *Candida*
Lactoferrin	Bacteria, yeasts, viruses
Salivary peroxidase and myeloperoxidase	Antimicrobial, decomposition of H_2O_2
Cystatins	Antiviral, protease inhibitors
Histatins	Antifungal, antibacterial
Agglutinins	
Parotid saliva glycoprotein, including gp340	Agglutination/aggregation of a number of microorganisms
Mucins	Same
Immunoglobulins	
Secretory IgA	Inhibition of adhesion
IgG (very low concentrations in saliva)	Enhancement of phagocytosis
IgM (very low concentration in saliva)	Enhancement of phagocytosis

Lysozyme in whole saliva comes from major and minor salivary glands, gingival crevicular fluid, and salivary leukocytes. The classical concept of the antimicrobial action of lysozyme is based on its muramidase activity; that is, the ability to hydrolyze the β(1→4) bond between *N*-acetylmuramic acid and *N*-acetyl-glucosamine in the peptidoglycan layer of the bacterial cell wall, especially in Gram-positive bacteria. In addition to its muramidase activity, lysozyme as a strongly cationic protein can activate bacterial autolysins, which can also destroy the cell walls. Another antimicrobial protein is lactoferrin, which is an iron-binding glycoprotein secreted by the serous cells of major and minor salivary glands. Lactoferrin has bacteriostatic, bactericidal, fungicidal, antiviral, and anti-inflammatory activity [2]. The biological function of lactoferrin is attributed to its expropriation of iron from microorganisms.

Peroxidase systems in human saliva comprise two enzymes, salivary gland-derived peroxidase (SP) and leukocyte-derived myeloperoxidase (MP), together with thiocyanate (SCN^-) ions and hydrogen peroxide (H_2O_2). Thiocyanate is a filtrate from serum, and most H_2O_2 originates from aerobic oral bacteria. Peroxidases catalyze the oxidation of SCN^- by H_2O_2 to the antimicrobial component, hypothiocyanite ($OSCN^-$):

$$H_2O_2 + SCN^- \text{ (SP and/or MP)} \rightarrow OSCN^- + H_2O$$

Salivary peroxidase systems have two major biological functions: antimicrobial activity and protection of host

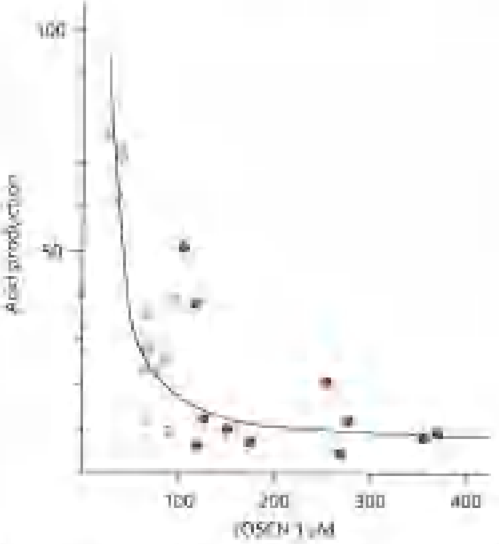


Figure 6.6 Glucose-stimulated acid production in dental biofilm of subjects with different concentrations of hypothiocyanite [OSCN⁻] in whole saliva. Gray circles show physiological levels of [OSCN⁻] in whole saliva and red circles show artificially increased [OSCN⁻] values obtained with oral hygiene products, in this case by enzyme-containing toothpaste.

proteins and cells from the toxicity of H_2O_2. Peroxidase systems are effective against a variety of oral microorganisms, many anaerobes (periodontal pathogens), and also some viruses. In more developed biofilms, the antimetabolic activity may be of importance, since the more hypothiocyanite there is in saliva the less acid is produced by the biofilm after stimulation with glucose (Fig. 6.6). If the salivary levels of $OSCN^-$ are increased artificially by peroxidase systems from oral hygiene products like toothpaste, plaque acidogenicity becomes further decreased after application of the product (red circles in Fig. 6.6). Thus, the decrease in plaque acidogenicity and level of $OSCN^-$ obtained by oral hygiene products are both greater than normal salivary values. However, owing to the clearing effect of saliva, the effect of the toothpaste systems is probably mostly temporary.

Cystatins (cystein-containing phosphoproteins) are considered to be protective by inhibiting unwanted proteolysis of salivary proteins. Cystatins in saliva and acquired pellicle inhibit selected bacterial proteases and proteases originating from lysed leukocytes. Cystatins also affect calcium phosphate precipitation and may have some antiviral activity, suggesting multifunctionality of these molecules. Other antimicrobial peptides in parotid and submandibular saliva are the histatins (Table 6.2), which have a broad antimicrobial spectrum against bacteria as well as antimicrobial properties against oral yeasts [20].

Clearance and aggregation of oral bacteria

Apart from the nonspecific antimicrobial effects (i.e., not a result of immunization) offered by many salivary proteins, the sheer flow of saliva also has a major influence on the oral ecosystem. Thus, an important function of saliva is to dilute and eliminate pathogenic microorganisms and their substrates. This is a physiological process usually referred to as salivary clearance or, more commonly, oral clearance. Because the flow of saliva is combined with the swallowing reflex, the clearing effect is highly increased due to actual elimination of substances away from the oral cavity into the esophagus. At subnormal unstimulated saliva flow rates (i.e., ≤0.2 mL/min) the clearing effect is highly prolonged, leading to an accumulation of substances as well as bacteria in the oral cavity. At subnormal saliva flow rates the ecology of the mouth shifts towards a more acidic environment where the growth of acid-tolerating and -producing bacteria is favored (Chapter 10). Bacterial clearance, however, is not only related to the flow of saliva, but also to its composition.

Agglutinins are glycoproteins that have the capacity to interact with unattached bacteria, resulting in clumping of bacteria into large aggregates (see also Table 6.2). These aggregates are more easily flushed away by saliva and swallowed than single bacteria are, which increases the overall oral clearance of bacteria. The most potent one is the high molecular weight glycoprotein gp340, which has been found in human parotid saliva. The concentration of this agglutinin is much lower than other antimicrobial proteins, but just 0.1 µg (less than 1% of the total saliva protein concentration) can agglutinate up to 10^8 bacteria.

The mucins in saliva, which are of acinar cell origin, constitute a family with two members: MUC5B and MUC7 [2]. These are often also designated as high and low molecular weight mucins, respectively. These molecules are asymmetrical molecules with an open, randomly organized structure in which the carbohydrate side-chains often end in negatively charged groups, such as sialic acid. Mucins also aggregate oral bacteria, thereby accelerating the clearance of bacteria from the mouth. Several studies have reported an inverse relationship between the agglutinating activity of saliva and colonization by *S. mutans*. The mechanism of aggregation seems to be oligosaccharides in mucins that mimic those in the mucosal cell surface and thus competitively inhibit the adhesion of bacterial cells to soft tissues by blocking reactive groups, adhesins, on bacterial cell surfaces. By related mechanisms, mucins also mediate specific bacterial adhesion to the tooth surface [46]. Apart from antimicrobial effects, an important role of mucins is also that they hold much water and, therefore, effectively lubricate and maintain the mucosal surfaces moist.

Human saliva also contains immunoglobulin in the form of secretory immunoglobulin A (sIgA). sIgA is a product of plasma cells that are passing through the gland, and sIgA is modified and secreted by both the acinar and ductal cells. sIgA is a specific defense factor (i.e., the result of immunization) that is stimulated by the presence of bacteria. sIgA aggregates bacteria so that they are easily swallowed, and sIgA also has affinity for other antimicrobial aggregating components in saliva, the mucins. Studies have shown that sIgA, unlike the unspecific antimicrobial proteins, by itself seems to offer a measureable effect against dental caries [31].

Functions of saliva on established biofilms

After the initial bacterial attachment, further biofilm formation depends on the ability of attached bacteria to produce enzyme systems called glucosyltransferases (GTFs) and fructosyltransferases (FTFs). In the presence of sucrose, GTFs and FTFs synthesize several forms of high molecular weight glucans (glucose polymers) and levans (fructose polymers) by utilizing energy from cleaving the glycosidic bond in sucrose. These sticky extracellular polysaccharide polymers become intermingled with bacteria and saliva proteins, which results in further biofilm formation and increases the ability of the oral bacteria to grow on enamel surfaces. At this 'stage' of biofilm formation the aqueous environment within the biofilm will be quite different from whole saliva, and the biofilm matrix comprises a nearly impermeable environment to the large antimicrobial proteins from saliva. This impermeable biofilm environment will induce an ecological shift that promotes growth of acid-producing and acid-tolerating anaerobic species at the expense of aerobic species (see also Chapter 10). At this point the physical flow of saliva will will be able to restrict the amount of nutrients, especially sugars, available for bacteria in the biofilm. However, the availability of sugars is also influenced by the amylase enzyme.

Amylase activity

The most abundant enzyme in human saliva is α-amylase, which accounts for as much as half of the gland-produced salivary protein. The majority is synthesized from the serous cells in the parotid glands and the remainder in the submandibular glands. Amylase effectively attacks random locations along chains of starch and thereby breaks down long-chain carbohydrates from ingested food into maltose, maltotriose, and dextrins. Oral bacteria can ferment maltose, and hydrolysis of maltotriose produces glucose. A diet rich in processed starch therefore provides fermentable sugars for anaerobic bacteria, and causes a pH drop in dental biofilms. From this aspect, salivary amylase activity promotes caries development.

However, amylase may also help the clearing of starch-containing food debris from teeth and mucosa after meals. This function of amylase is used commercially in washing powder and dishwasher tablets. Added industrial amylases work together with detergents at increasing the removal of food and dirt. From this theoretical aspect, salivary amylase activity could also be protective against caries, because starch-containing food debris may be removed faster from the teeth, giving the bacteria less time to utilize maltose and maltotriose.

Oral sugar clearance

When dietary sugars enter the oral cavity, saliva concentrations immediately become very high because the volume of saliva is small. Thus, between meals, the combined volume of saliva in the mouth usually amounts to only 0.8–1.2 mL [28]. This volume is spread out in a thin film that covers the surfaces of teeth and mucosa. Because many oral surfaces are in intimate contact with each other, the effective surface area is much smaller than the total area, giving rise to a saliva film that is about 70–100 μm thick (see also Fig. 6.5) and which moves towards the throat with a speed from about 1–8 mm/min [11]. Sugars normally enter the mouth as part of foodstuffs, mostly as sucrose, or become released from starch-containing food debris by salivary amylase activity, especially in the case of boiled or processed starch-containing food products. Sugars, in the form of mono- and disaccharides, have to dissolve in the small physiological volume of saliva, giving rise to very high saliva concentrations, which are not evenly distributed throughout the saliva film. Thus, a substance placed in one side of the mouth will mainly raise the salivary levels of that substance on the same side of the mouth, with very little being distributed to the other side. Also, the movement of the salivary film is much slower in the front of the upper jaw than in the lower jaw. Therefore, some regions will be exposed to ingested sugar for a relatively long time and other regions, like the incisors in the lower jaw, for a relatively short time.

Basically, oral sugar clearance is a function of dilution, caused by the flow of saliva, and elimination caused by swallowing. High saliva sugar concentrations will induce taste stimulation of the salivary glands, increasing the saliva flow rate and resulting in a swallow, which eliminates some of the sugar from the oral cavity. For each swallow the concentration of sugar will gradually decrease in a manner similar to a serial dilution in the laboratory. If the sugar concentration is plotted against time it shows a fast initial decrease after which the concentration gradually reaches zero because 'equal parts' keep being eliminated with each swallow. To compare the clearance rate among different individuals, a suitable measure of salivary clearance is needed. The time it takes to reach a certain detectable low level has been used as such a measure and called 'clearance time', but other and more complicated measures have also been used. Nonetheless, regardless of how it is measured, oral sugar clearance depends mostly on the saliva flow rate. Figure 6.7 shows the saliva sugar concentration after food intake in two individuals having different flow rates [33]. Because of differences in saliva flow rates, sugar concentrations differ about 10 times between the two subjects after 10 min, resulting in major differences in biofilm acidification exceeding one pH unit after 20 min. Figure 6.7 also shows that the clearance rate is fastest during the first minutes after sugar exposure due to the effect of stimulated salivary flow.

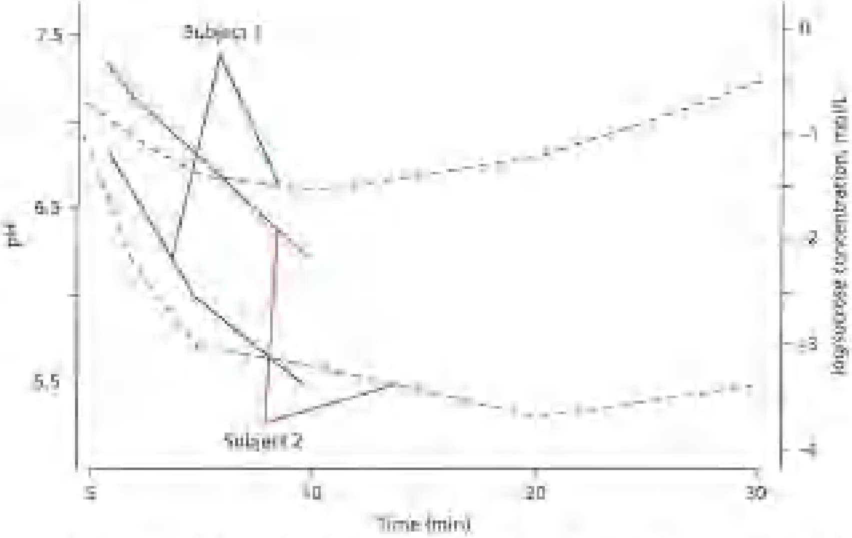


Figure 6.7 Two subjects have rinsed with a sucrose solution. Owing to differences in saliva flow rates, the two subjects differ considerably in clearance rate (solid lines), causing a large difference in the decrease in plaque pH (hatched lines) by anaerobic bacteria within the plaque. Subject 1 had a higher salivary flow rate than subject 2, who had subnormal flow rates.

Because sweet taste is a much weaker stimulant of saliva secretion than the tastes of salt and acid, the clearance rate quickly reaches the unstimulated level when sugar is ingested. Thus, unfortunately, sugar is available for bacteria in oral biofilms long after the sugar concentration in saliva has reached levels below the taste threshold for sugar.

Saliva buffer capacity and pH regulation

From the thin salivary film, small and uncharged molecules like glucose will rapidly diffuse into the biofilm that may be many times thicker than the salivary film. The amount of sugar passing the saliva–biofilm interface is dependent on the concentration gradient between saliva and biofilm–plaque fluid. Since this gradient is very steep during the first minutes, the sugar concentration in the plaque will increase rapidly. After only a few minutes it will be higher than in the saliva, where the concentration will diminish due to the clearance process. In established dental biofilms with a low permeability harboring many anaerobic species, accumulation of sugar will fuel anaerobic metabolism, cause formation of various organic acids, and lower the pH at the biofilm–enamel interface. The magnitude and duration of the pH drop is determined by the microbial composition of the biofilm (Chapter 7), the availability of sugar (Chapter 8), the oral clearance time, and by the saliva buffer capacity.

The chemical definition of buffer capacity β requires that precise titration curves are produced (Fig. 6.8). In chemistry, the buffer capacity is defined as the increase in acid concentration ΔC_A divided by the change in pH (ΔpH) that occurs as a result of acid addition (i.e., $\beta = \Delta C_A / \Delta \mathrm{pH}$). If addition of large amounts of acid results in only minor pH changes the buffer capacity is high, meaning that the fluid can resist addition of acid without major changes in pH, and vice versa. However, the chemical definition of buffer capacity β is seldom used for saliva; instead, various other and easier determinations and terms have been developed. The most popular seems to be the amount of acid that is needed to lower the pH from the original saliva pH value down to a predetermined lower value, which could be termed 'titratable base.' As shown in the upper part of Fig. 6.8, the titratable base for stimulated whole saliva down to pH 4 normally ranges between 20 and 30 mmol/L hydrogen ions, and is about twice that of unstimulated saliva. An even simpler measure for the buffer capacity of human saliva is the so-called 'buffer effect.' The buffer effect is determined by adding a fixed amount of acid to a fixed amount of saliva and then reading off a final pH value. The higher the final pH value the better the buffer effect. Test systems that use this method are available in various chair-side versions for the dental clinic. Of these different measures, only the chemical definition of buffer capacity β enables identification and quantification of individual buffer systems. By such analyses, three buffer systems have been identified in human saliva; namely, the bicarbonate, phosphate, and protein buffer systems.

The bicarbonate buffer system

In the salivary glands some bicarbonate comes from the end-pieces and some, probably most, from the ducts (Fig. 6.2). At low saliva flow rates bicarbonate from the end-pieces is reabsorbed in the striated ducts, similar to sodium and chloride, resulting in very low bicarbonate levels in unstimulated saliva. At high flow rates bicarbonate is excreted in the striated ducts, in exchange for chloride, increasing stimulated bicarbonate concentrations to venous plasma levels of

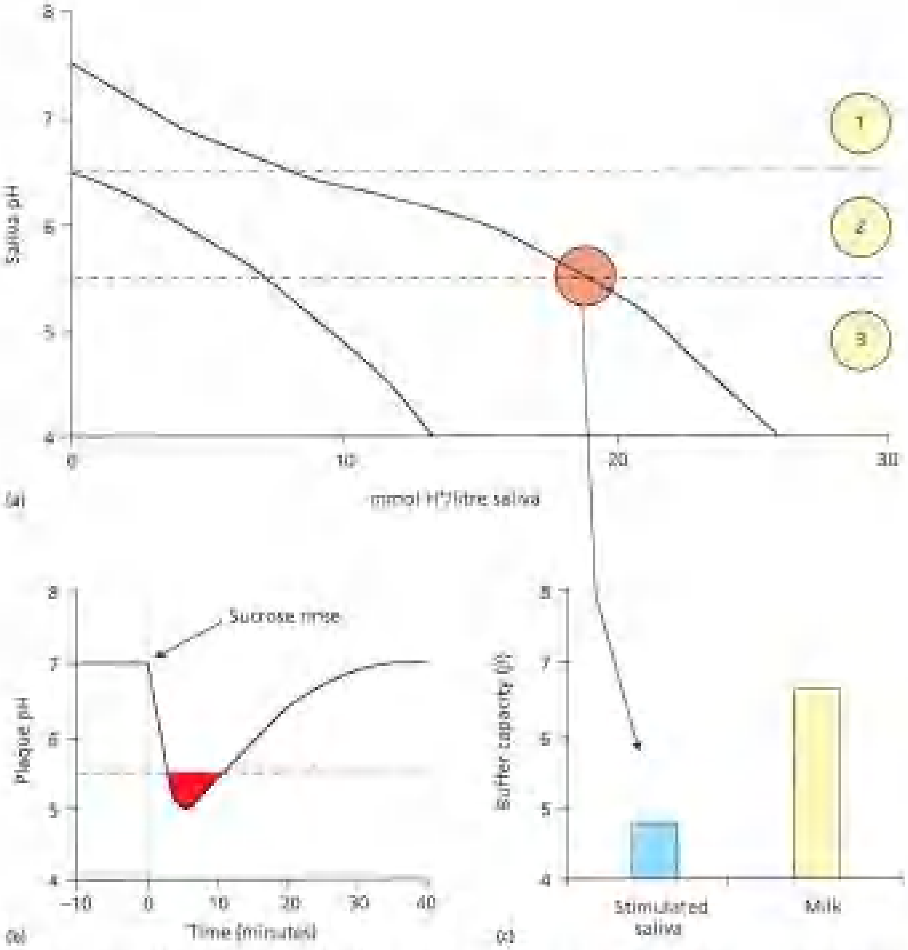


Figure 6.8 (a) Titration of whole saliva with strong acid in a closed system. The upper curve shows stimulated saliva and the lower curve shows unstimulated saliva. Above pH 5.5 the buffering capacity is high owing to the buffering ability of the phosphate (1) and bicarbonate buffer system (2). At low pH values the slope of the curve becomes steeper, indicating a lower buffer capacity mainly from salivary proteins (3). (b) A typical Stephan curve of plaque pH in response to an oral sucrose rinse. In spite of the saliva buffer capacity the plaque pH can drop rapidly after a rinse to values below the critical pH of human saliva (red area), whereafter it slowly returns to baseline. The reason for this drop is that the saliva buffer capacity is only moderate. (c) Comparison with milk in the range from pH 4 to 7 (which is indicated by the circle and the arrow from (a)) shows the buffer capacity of whole saliva is much less than that of milk.

about 25 mmol/L or even higher in highly stimulated saliva [5]. A characteristic feature of the bicarbonate buffer system is that it is composed of both dissolved ions, including bicarbonate (HCO_3^-) and carbonic acid (H_2CO_3), and also dissolved carbon dioxide gas (CO_2). Within a closed system impermeable to CO_2 the equilibrium is

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

The formation of CO_2 and water from H_2CO_3 is catalyzed by the enzyme carbonic anhydrase, which is present in the salivary glands as well as in saliva. However, the enzyme is not necessary for this reaction to occur, whereas the reverse (e.g., hydration of CO_2 to H_2CO_3) requires the enzyme. In an open system, dissolved CO_2 in saliva will also come into equilibrium with gaseous CO_2 in the surrounding air. Therefore, P_{CO_2}, the saliva partial pressure of CO_2, drops when saliva enters the mouth due to nearly instantaneous CO_2 equilibration between saliva and the airways, where P_{CO_2} is somewhat lower than in blood.

Upon buffering in a closed system the bicarbonate buffer system works in the same way as any other buffer system. The maximum buffer capacity, which equals about half the total concentration of the buffer system, is obtained at the pK_a value for H_2CO_3, which is near pH 6 in human saliva. However, because the bicarbonate buffer system is also in equilibrium with gaseous CO_2 in the surrounding air, CO_2 may be lost during buffering. This type of buffering is called phase buffering and adds an actual pH-rising capacity to the buffer system. In the mouth, therefore, which should not be considered a closed system, extensive phase buffering occurs [23], which theoretically may boost the buffer capacity of bicarbonate more than fourfold compared with its buffer capacity in a closed system [21]. More than 90% of the buffer capacity is in the range of plus/minus one pH unit around the pK value, so that bicarbonate comprises the majority of the overall saliva buffer capacity from pH 7 down to pH 5. Within this pH range, the contribution from the bicarbonate buffer system to the overall buffer capacity varies from less than half in unstimulated saliva to more than 90% in stimulated saliva. Very high bicarbonate concentrations and extensive phase buffering occur mostly with intake of acidic foodstuffs, whereas sweet foodstuffs stimulate less saliva secretion, lower bicarbonate concentrations, and lower buffer capacity. Thus, only after some sugar has been cleared may the buffer system overcome the remaining acidic challenge in the biofilm and increase the pH, as shown on the Stephan curve in Fig. 6.8.

The phosphate buffer system

Phosphates are phosphorus containing compounds. Figure 6.9 shows the so called *Bjerum diagram* where inorganic phosphate dependent on the pH consists of phosphoric acid (H_3PO_4), dihydrogen phosphate ($H_2PO_4^-$), hydrogen phosphate (HPO_4^{2-}), and phosphate (PO_4^{3-}). The sum of these four species equals the total phosphate concentration. In contrast to bicarbonate, the total phosphate concentration decreases with increasing flow. Thus, total phosphate may drop from unstimulated saliva levels as high as 10 mmol/L to stimulated saliva levels as low as 2–4 mmol/L (Fig. 6.3). Most relevant buffering will take place within the physiological pH range, where the dominant forms of phosphate are the hydrogen and $H_2PO_4^-$ forms, having a pK_a value for this equilibrium around 7. Because of higher bicarbonate concentrations, and therefore higher pH, stimulated saliva has mainly HPO_4^{2-} whereas unstimulated saliva with lower pH has mainly $H_2PO_4^-$ (Fig. 6.9). Like bicarbonate, phosphates have the highest buffer capacity in the range of plus/minus one pH unit around the pK values. Therefore, phosphate contributes to the buffer capacity from pH 8 down to pH 6, and predominantly in unstimulated saliva.

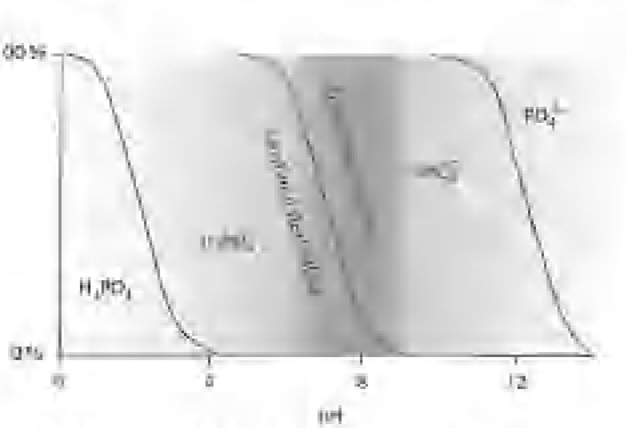


Figure 6.9 The phosphate buffer system as a function of pH (i.e., the Bjerrum diagram). Within the physiological pH range (6.0–7.5) most phosphate is on the $H_2PO_4^-$ and HPO_4^{2-} forms. The dark gray area represents the normal pH range of human saliva.

The protein buffer system

All proteins in saliva have specific functions, which are highly relevant during pellicle formation, as well as their antimicrobial effects against bacterial colonization and growth as described earlier. Apart from these specific functions, many saliva proteins are also able to act as buffers when the pH is lowered or increased below or above their isoelectric point. Below their isoelectric point proteins can accept protons and above they can release protons. Many salivary proteins have isoelectric points between pH 5 and 9; therefore, saliva proteins become relevant as buffers at acidic pH values. Thus, below pH 5, where neither phosphate nor bicarbonate contributes much to the buffer capacity, laboratory studies have shown that the saliva proteins often are the major contributors to the saliva buffer capacity. But compared with bicarbonate and phosphate, the contribution from proteins in whole saliva is low even in the acidic range. However, owing to high concentrations in the pellicle and biofilms saliva proteins most likely become important buffering substances on many oral surfaces.

Saliva and caries lesion remineralization

Repeated periods of carbohydrate metabolism by anaerobic bacteria in the biofilm produce acids as an end product of the glycolysis. At this point, the aqueous environment near the tooth surface will become increasingly different from the remainder of the oral cavity – primarily more acidic. Acidification will be further accelerated in the presence of sucrose. This fuels anaerobic metabolism and the formation of sticky polysaccharide polymers that further accelerate the development of an acidic environment. At this point in the caries process saliva has apparently failed to control biofilm formation and metabolism. However, at this late stage of the process saliva may display one of its strongest capacities against caries development. Now, the main function of saliva is to prevent further demineralization and enhance remineralization. The main salivary components responsible are the calcium and phosphate ions together with the neutral pH values provided by the buffer systems. Whole saliva also contains fluoride, and together with salivary calcium and phosphate this strongly decreases the solubility of enamel and promotes remineralization (see Chapter 9 for details).

Calcium and phosphate in saliva

Because human saliva can contain considerable amounts of calcium and phosphate, some proteins are needed to inhibit spontaneous precipitation of calcium-phosphate salts in saliva on its passage through the gland and ducts to the oral cavity. A consequence of spontaneous precipitation is the formation of salivary stones (sialolithiasis), which can occlude the ducts from the major salivary glands. Occlusion of the main ducts is painful, and without treatment the obstruction of the flow of saliva can result in salivary gland infection (sialadenitis), which left untreated can have serious health consequences. Thus, for general health it is important that calcium and phosphate can be delivered to the oral cavity without mineral precipitation in the glands and their ducts. This is achieved mainly by calcium-binding functions of the pellicle precursor proteins statherin and PRPs (Fig. 6.5). When delivered near the tooth surfaces, the resulting stable state of saliva, with high concentrations of calcium and phosphate, constitutes a protective environment that is important for the teeth.

To avoid precipitation, around 20% of saliva calcium is bound to proteins like statherin and PRPs. The remaining 80% of salivary calcium that is not firmly bound to proteins can be divided into ionized and nonionized calcium. Half the nonprotein-bound calcium is normally ionized and half is nonionized. Nonionized calcium is more or less firmly bound to phosphate and bicarbonate, as well as to some organic ions [29]. All three forms (i.e., protein bound, the ionized, and nonionized) make up the total calcium concentration in saliva. Saliva total calcium may increase slightly from unstimulated to stimulated states of secretion (Fig. 6.3) but is normally low (1–2 mmol/L). The calcium that is not bound to proteins and is ionized is identical to the saliva calcium activity, which is a key measure for ion activity products (IAPs). When saliva pH and the concentration of most ions increase at high flow rates (Fig. 6.3) less calcium will be in the ionized form and the calcium activity decreases. This is because of the increased likelihood of calcium forming pairs with other ions due to increased concentrations of all ions as well as the formation of various calcium complexes at high pH.

As for calcium, some phosphate is ionized, making up the phosphate activity, and some is nonionized. Of the four species in the buffer system, phosphate (PO_4^{3-}) takes part in the equilibrium with the hydroxyapatite crystals in the enamel. How much is in this form is determined by the saliva pH and by the dissociation constants (pK_a) for the phosphate buffer system (Fig. 6.9). Thus, pH mainly determines the concentration of phosphate (PO_4^{3-}). A change in pH of just one unit can cause a 10- to 100-fold change in the phosphate activity, which is a much greater effect than any flow-dependent variations (Fig. 6.3).

Fluoride in saliva

Physiologically, fluoride is only excreted from the salivary glands in low concentrations, which reflects the background levels of fluoride in blood and extracellular fluids [45]. When fluoride-containing products for caries control (e.g., dentifrices and rinse solutions) are accidentally swallowed, the level of fluoride in blood peaks after 30–60 min. A little is excreted back to the oral cavity via the saliva, but this contribution is small compared with the fluoride that is retained in the oral tissues after use of fluoride products. Therefore, the fluoride concentration in whole saliva is primarily dependent on equilibrium between the fluoride from food, drinks, water, and oral and hygiene products retained in the oral tissues and the fluoride in whole saliva, rather than on fluoride that is excreted with saliva to the oral cavity. Individuals with limited use of fluoride-containing products, living in areas with low concentrations of fluoride in the drinking water, often have fluoride concentrations in whole saliva more than 1000 times lower than the saliva calcium concentration. In areas with high levels of fluoride in the drinking water and/or with frequent and long-term exposure to fluoride-containing products, the whole saliva concentration of fluoride increases to a plateau of considerably higher levels [42]. As most individuals in the developed world are frequently exposed to fluoride-containing products for caries control, or high levels of fluoride in drinking water supplied by water fluoridation, persistent low levels of fluoride in whole saliva levels will require a deliberate action by the individual to avoid fluoride. Thus, although the salivary glands do not excrete the majority of the fluoride present in whole saliva during the day, fluoride should be regarded as a salivary component in modern society. However, if the exposure of fluoride is discontinued then the oral reservoirs become depleted and whole saliva fluoride levels drop to baseline within days (see Chapters 9 and 14 for details).

After exposure to fluoride products the whole saliva concentration of fluoride first increases rapidly and then decreases due to the oral clearance. The most important factor for the fluoride clearance rate is, as for sugar, the salivary flow rate. Strong-tasting toothpaste may counteract its own aim as a fluoride source, in that the stimulation of saliva flow will increase the rate of clearance of the applied fluoride. Toothbrushing before bedtime will increase the fluoride concentration during sleep when the flow rate is very low (Table 6.1), giving long periods with high fluoride concentrations in the oral fluids. With locally applied fluoride preparations, very high fluoride concentrations can be expected close to the application point and for a considerable time. Here, fluoride will diffuse from the thin saliva film into the plaque, elevating the fluoride concentration considerably. With such high concentrations in saliva and, more importantly, in plaque, mineral calcium fluoride will form. This calcium fluoride functions as a slow releaser of fluoride, which together with fluoride that is loosely bound to other tissues are released for some time after exposure.

Saliva saturation with respect to hydroxyapatite and fluorapatite

The large hydroxyapatite crystals of enamel are composed of very small unit cells. The cells are a theoretical entity, less than a cubic nanometer, containing 10 calcium, 6 phosphate, and 2 hydroxyl ions. This solid phase is in equilibrium with its corresponding ions in saliva. The IAP (i.e., the free and unbound molar concentrations raised to the power of their number in the unit cell) gives a composite measure for all the relevant ions in solution:

$$IAP_{HAp} = \left(Ca^{2+}\right)^{10}\left(PO_4^{3-}\right)^{6}\left(OH^{-}\right)^{2}$$

From this expression it can be seen that the IAP increases with increasing salivary activities of any of the three ions present in the unit cell. However, salivary pH is generally the primary factor for the IAP. Thus, a drop in pH of one unit from pH 6 to pH 5 will reduce the hydroxyl ion activity 10-fold and the phosphate ion activity many times more, which reduces the IAP significantly. The conditions are somewhat better for fluorapatite, where the pH-dependent hydroxyl ions are replaced by fluoride ions, making its ionic activity product IAP_{FAp} less sensitive to changes in pH.

Apart from the enormous effect of pH, a special condition can occur with calcium in biofilms or during intake of acidic foodstuffs. Here, calcium, which carries two positive charges, can become strongly bound to ion species with two negative charges. In the oral cavity, such compounds are mainly the conjugate bases of lactic and citric acids found in acid-producing biofilm and acidic foodstuffs. Often, the concentration of both lactate and citrate can be very high, reducing the ionized free saliva calcium concentration to very low values. Low calcium activity strongly decreases the IAPs and adds to the negative effect of low pH.

In a pure aqueous solution without saliva proteins and where complete equilibration between tooth substance and water has taken place, the IAP (IAP_{HAp} or IAP_{FAp}) will be equal to the solubility product. At mouth temperature the solubility product for hydroxyapatite is small (10^{-117} mol^{18}/L^{18}) [35], but is even smaller for fluorapatite, making this salt less soluble. If the IAP in saliva is larger than the solubility product then saliva is supersaturated and remineralization may occur, and if it is smaller then saliva is undersaturated and demineralization may occur. However, because of the pellicle, supersaturation or undersaturation does not imply that something will happen, only that it can happen. Thus, when an undersaturated fluid comes in contact with enamel, the pellicle often delays the harmful effects. Sometimes this delay is long enough for the harmful effects to be removed by clearance or buffering, so that demineralization may not occur in spite of undersaturation.

Critical pH values and remineralization

When the IAP is equal to the solubility product for hydroxyapatite the solution is saturated and no demineralization or remineralization will occur. In dental literature, the pH value corresponding to saturation is often denoted as the critical pH value. The main determinants of the critical pH are the total calcium and phosphate concentrations in saliva. In healthy human saliva with normal concentrations of calcium and phosphate, the average critical pH is 5.5 [46]; below this pH the enamel can dissolve. Unstimulated saliva generally has a lower critical pH than stimulated saliva due to higher total phosphate concentrations [12]. The critical pH, however, may be much different from 5.5 in other fluids, like soft drinks and drinking water, as well as within the pellicle and dental biofilm. Thus, the critical pH is not constant, but more a dynamic variable that can vary by several pH units depending on the fluid in question. Adding further to the complexity, individual variations in saliva total calcium and phosphate concentrations make the critical pH a person-specific parameter. Low calcium and phosphate concentrations result in a high critical pH that allows enamel to dissolve at nearby neutral pH values and greatly decrease the capacity of saliva to remineralize enamel. This may be relevant in children, who generally have lower saliva calcium concentrations than adults do and, therefore, a higher critical pH [3], which in part may explain the increased susceptibility to caries during childhood. A critical pH can also be calculated for fluorapatite. Based on average concentrations for fluoride, calcium, and phosphate and a different solubility product for fluorapatite, the critical pH for fluorapatite in saliva is about one unit lower than for hydroxyapatite and close to pH 4.5, but also with individual variations.

Other caries-related components in saliva

Whole saliva may contain numerous 'nonsalivary' substances other than fluoride which also have an effect on dental caries. Most of these substances enter saliva as a reflection of altered levels in the bloodstream, and become relevant only in patients suffering from special medical conditions. One example is the saliva level of urea, which can become very high in patients with chronic renal failure (CRF) and leads to increased saliva pH and buffer capacity. Urea will also diffuse into biofilms, where bacterial enzymatic and metabolic activity will lead to reactions that bind hydrogen ions and further increase pH. Therefore, baseline plaque pH values are often high in patients with CRF. Owing to elevated pH levels in the biofilm, it is not unusual that these patients have little caries in spite of having high plaque scores [1]. Another example of a caries-related substance in saliva is glucose from the bloodstream. Salivary glucose may be pathologically and persistently high in patients with untreated or poorly controlled diabetes. Especially in untreated cases of diabetes, glucose levels in saliva can be very high, resulting in increased caries. But also among treated patients, poorly controlled patients may develop more caries than patients with good metabolic control [50]. In this special case, oral sugar clearance is of little help, because saliva is the primary supplier of glucose to the dental biofilm; thus, in this special case, the elevated glucose cannot be cleared by saliva.

Saliva and caries development: clinical aspects

Identification of patients with subnormal saliva flow rates (i.e., below the normal range) at or around the time of onset of the reduction in flow is mandatory for avoidance of accelerated caries lesion progression, especially in the case of subnormal unstimulated saliva flow rates. Normal flow rates for unstimulated whole saliva are between 0.2 and 0.5 mL/min, or even higher in some individuals. For paraffin chewing, stimulated whole saliva normal flow rates are between 1.0 and 2.0 mL/min. Whole saliva flow rates, however, may be much higher when chewing and strong acidic taste are combined. Thus, physiological whole saliva flow rates from 5 mL/min up to extremes of 10 mL/min may occur with this type of stimulation (Table 6.1).

The principal causative factor for nearly all problems with dry mouth (xerostomia), and the clinical findings associated with it, is subnormal saliva flow rates and/or the condition of hyposalivation. Hyposalivation refers to the state of pathologically low saliva flow rates and is an accepted diagnosis (code K11.7 in the International Classification of Diseases) as well as xerostomia (R68.2). The criteria for hyposalivation is an unstimulated whole saliva flow rate of ≤0.1 mL/min and/or a chewing stimulated whole saliva flow rate of ≤0.5 mL/min. It should be stressed that the severity of hyposalivation cannot be predicted with certainty from xerostomia, but needs a clinical examination with determination of saliva flow rates. One of the most profound reductions in saliva flow rates is seen in cancer patients after curative radiotherapy, where a severe and often pathological reduction of salivary flow rates persists throughout life. The consequences in irradiated patients are: being awakened at night because of intense oral dryness; oral functions like speech, chewing, and swallowing are thwarted because of insufficient wetting and lubrication of the mucosal surfaces; and swallowing and chewing are impeded because of difficulties forming a bolus. The oral mucosa may appear dry, atrophic, pale or hyperemic. The lips may be chapped or fissured and there may be scaling and fissuring at the corners of the mouth (angular cheilosis). The dorsum of the tongue may be dry and furrowed or, alternatively, may appear red and hyperemic as a result of the presence of a fungal infection (Fig. 6.10). These conditions are, in general, typical for hyposalivation of any origin that has persisted for some time, and understandably these conditions decrease the quality of life considerably in patients with hyposalivation.

Dental findings in patients with low saliva flow rates

Xerostomia is a very uncomfortable condition, and patients often shift their diet to soft, sticky, carbohydrate-rich food. This shift in diet will further accelerate caries (see also Chapter 8), and an otherwise healthy dentition may be severely affected by carious and/or erosive demineralization and in a rapid manner unlike anything seen in individuals with normal saliva flow rates [17]. Early hyposalivation-related dental carious lesions are similar to normal white spot lesions. However, already at this point, something remarkable about the lesions in these patients is that they occur in areas of the dentition that are normally relatively immune to dental caries, like the incisors in the lower jaw (Fig. 6.10). In more advanced stages of hyposalivation-related dental caries various types of lesions can be observed [15, 26]. Lesions often begin on the labial surface at the cervical area of the incisors and canines (Fig. 6.11). Such lesions may extend superficially around the entire cervical area of the tooth, and then progress inwardly, resulting in complete amputation of the crown. Advanced stages of hyposalivation-related dental caries may also result in a more generalized superficial defect that first affects the buccal and later the lingual or palatal surfaces of the tooth crowns (Fig. 6.11). When present, this lesion often begins as a diffuse, punctuate defect and then progresses to a generalized, irregular erosion of the affected tooth surfaces. Especially in radiotherapy patients, teeth and such erosion-like defects may become heavily brown–black discolored due to long-term use of chlorhexidine.

Figure 6.10 Clinical manifestations of dry mouth in a woman with Sjögren's syndrome: (a) multiple caries lesions; (b) dry mucosal surfaces and tongue in the same patient.

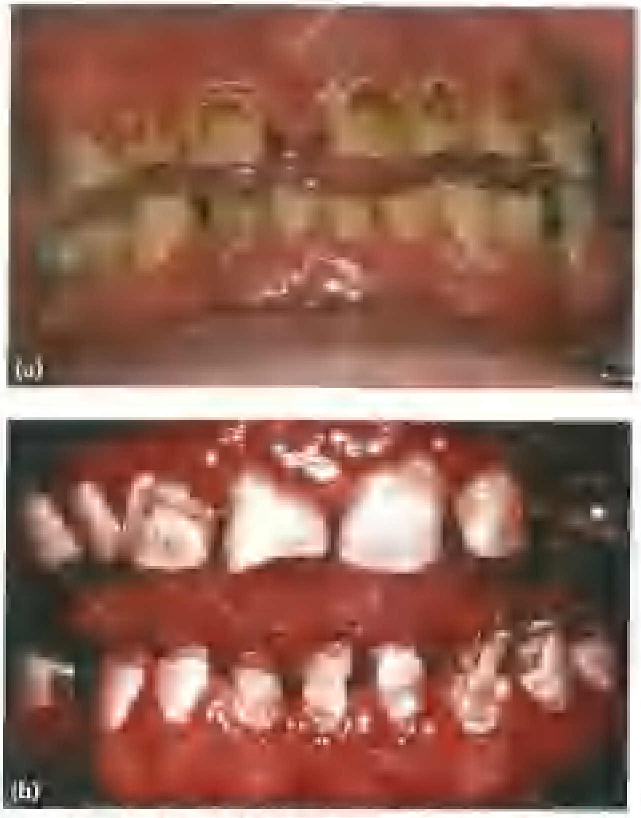


Figure 6.11 Dental caries related to subnormal flow rates and hyposalivation: (a) cervical lesions, (b) more generalized superficial erosion-like defects of the crown.

Causes of subnormal saliva flow rates and hyposalivation

A large number of diseases and conditions (Table 6.3) chronically affect salivary gland function [24] and mostly result in subnormal saliva flow rates, hyposalivation, altered salivary composition, and/or xerostomia. Some of these are related to gland pathology (e.g., autoimmune and endocrine disorders) or to the pathophysiological conditions of the host (e.g., metabolic disturbances), whereas others affect the gland innervation (e.g., neurological disorders) or are a result of treatment of a disease (e.g., head and neck radiotherapy). The most common cause, however, is by far the use of routinely prescribed types of medications.

Medication

Drugs are the most common cause of chronic xerostomia and the most common cause of salivary gland hypofunction. Many commonly prescribed drugs cause reduction in saliva flow rates to subnormal levels or even hyposalivation. As described, saliva secretion is under autonomous control and activated by sympathetic as well as parasympathetic stimulation by neurotransmitters. These neurotransmitters bind to specific receptors on the acinar cells within the gland, adrenergic and cholinergic, and activate secretion of ions, water, and proteins. Any drug that has the ability to bind and block these receptors, and thus decrease the activity in any of the two branches of the autonomic nervous system, will also have an effect on saliva secretion. Inhibition of cholinergic receptors by anticholinergic medication (e.g., many antidepressants, antihistamines, and some drugs against hypertension) will have a profound effect on secretion of saliva and, therefore, often lead to xerostomia. Drugs that selectively block the adrenergic receptors, such as the beta-blocker propranolol, will reduce the total protein concentrations in the salivary secretions. Drug-related oral dryness is therefore usually due to adverse side effects of anticholinergic medication, but may also be the result of interactions with drugs that selectively block the beta-adrenergic receptors due to reduced protein secretion. A comprehensive list of medications having xerogenic side effects can be found on the Internet (www.drymouth.info). Equally important is that the risk of subnormal flow rates increases with the number of drugs taken by the patient, regardless of which drugs, so that subnormal flow becomes very common with more than three drugs per day.

Sjögren's syndrome

Sjögren's syndrome (SS) is an autoimmune inflammatory disorder of exocrine glands (i.e., glands secreting via a duct to an external environment), particularly the lacrimal and salivary glands. The syndrome can occur at all ages, but the median age of presentation is around 50 years. Within the age group of 50–70 years, the prevalence of SS is around 3000 patients in 100 000 citizens, for the overall population it ranges from 500 to 1000 diagnosed patients in 100 000 citizens [25]. SS affects more females than males with a ratio of 9:1. Xerostomia and dry eyes are frequently proffered as presenting symptoms, sometimes together with extraglandular manifestations [26]. Primary SS is in many cases a primary, idiopathic condition of unknown etiology. The syndrome, however, may also be secondary to other connective tissue diseases, such as rheumatoid arthritis, systemic lupus erythematosus, scleroderma, and mixed connective tissue disease. In these cases the condition is designated as secondary SS (sSS). In rheumatoid arthritis, the prevalence of sSS is around 30%, and in the case of systemic lupus erythematosus 20% of patients fulfill the criteria for sSS. Furthermore, SS is associated with autoimmune thyroid disease, primary biliary cirrhosis, and autoimmune gastritis. This underscores the autoimmune nature of the disease.

Radiotherapy

Head and neck cancers (HNCs) are malignant tumors of the upper aerodigestive tract, and 90% are squamous cell carcinomas arising from the epithelia lining of the oral

Table 6.3 Influence of different conditions on salivary gland function. The three most important causes of a reduced salivary gland function are drugs, Sjögren's syndrome, and head and neck radiotherapy.

	Flow rate	Changed Composition	Xerostomia	Caries
Drugs				
Secretragogues	↑	+/–	–	↓
Xerogenic drugs	↓	+	+	↑
Sjögren's syndrome	↓	+	+	↑
Head and neck radiotherapy	↓	+	+	↑
Chronic inflammatory connective tissue diseases				
Scleroderma	↓	?	+	↑
Mixed connective tissue disease	↓	?	+	↑
Chronic inflammatory bowel diseases				
Crohn's disease	→	+	+	?
Ulcerative colitis	→	+	–	?
Coeliac disease	→	+	–	?
Autoimmune liver diseases	↓	?	+	?
Musculoskeletal disorders				
Fibromyalgia	↓	?	+	?
Chronic fatigue syndrome	↓	?	+	?
Amyloidosis	↓	?	+	?
Endocrine disorders				
Diabetes mellitus	↓	+/-	+	?
Hyperthyroidism	↑	+	–	?
Hypothyroidism	↓	?	+	?
Cushing's syndrome	→	+	–	?
Addison's disease	→	+	–	?
Neurological disorders				
CNS trauma	↓	?	?	?
Cerebral palsy	↓	+	?	?
Bell's palsy	↓	?	?	?
Parkinson's disease	↓	+	+	?
Alzheimer's disease	↓	+	+	?
Holmes–Adie syndrome	↓	?	+	?
Burning mouth syndrome	→	+	+	?
Infectious diseases				
Epidemic parotitis	?	?	?	?
HIV/AIDS	↓	+/–	+	?
Hepatitis C virus	↓	?	+	?
Epstein–Barr virus	?	?	?	?
Tuberculosis	?	?	?	?
Local bacterial salivary gland infections	↓	+	?	?
Genetic disorders				
Salivary gland aplasia	↓	?	?	↑
Cystic fibrosis	↓	+	?	?
Ectodermal dysplasia	↓	+	–	↑
Prader–Willi syndrome	↓	+	?	?
Metabolic disturbances				
Water and salt balance	↓	+	+	?
Sodium retention syndrome	↓	+	+	?
Malnutrition	↓	+	+	?
Eating disorders				
Bulimia nervosa	↓	+/-	+	↑
Anorexia nervosa	↓	+	+	↑
Cancer-associated disturbances				
Chemotherapy	↓	+/–	+	?
Graft-versus-host disease	↓	+	+	?
Advanced cancer/terminally ill patients	↓	?	+	?

↓ decreased flow rate or caries risk; ↑ increased flow rate or caries risk (in case of bulimia and anorexia also increased risk on erosion); → unchanged flow rate or caries risk; + yes; – no; +/– differing results; ? possibly affected and/or awaiting clinical studies. Table is modified from [24].

cavity, nasopharynx, oropharynx, and hypopharynx. The incidence of HNCs is about 4.4 new cases per year in 100 000 citizens in North and South America, but nearly twice as high in Europe, and almost three times higher in South East Asia [36]. However, incidence numbers may vary depending on whether or not cancers of the larynx are included. Variations among World Health Organization regions are due to differences in exposure to carcinogens like tobacco, alcohol, and betel leaves, and HNCs affect more males than females, with a ratio of 2:1. Advanced cases are treated with surgery followed by radiotherapy [13]. Conventional radiotherapy for advanced HNCs typically involves administering high doses of radiation through neighboring structures, including the major salivary glands, an approach that increases the chance of survival. However, a high dose of radiation to these structures is nearly synonymous with a profound and permanent reduction in saliva secretion, resulting in irreversible xerostomia and hyposalivation. The decreased or abolished flow of saliva causes a marked increase in the risk of dental caries, dental erosion, and oral infections. The introduction of intensity-modulated radiation therapy (IMRT), by which the cumulative radiation dose to the salivary glands can be reduced, has resulted in sparing of salivary gland function and is accompanied by considerably higher post-treatment saliva flow rates and less xerostomia than with conventional radiotherapy (Fig. 6.12). Today, however, IMRT treatment is only possible for a selected group of patients.

Evaluation of salivary gland function

The high natural and condition-related variation in saliva secretion over the day makes it very important to use standardized conditions when determining flow rates. Factors that influence the secretion of saliva are, among others, the time of the day and the duration of the collection time. Short collection periods tend to yield unreliable values and should be avoided. For reliable monitoring, it is recommended that unstimulated saliva is collected over 10–15 min. For further standardization, the patients must refrain from eating and drinking at least 90 min prior to the test, and avoid swallowing and oral movements during collection. It is advised to perform all determinations at the same, fixed time of the day (e.g., between 9.00 and 12.00 a.m.) [9, 34, 39, 40]. Regardless of the method, subjects should void their mouth of saliva prior to collection, by rinsing the mouth thoroughly with tap water. Subjects should be seated comfortably with their eyes open and head tilted slightly forward (Fig. 6.13). Common methods for collecting whole saliva include the draining method and the spitting methods; less common methods include the suction method and the swab (absorbent) method. Common stimuli are chewing on tasteless paraffin wax or, much less preferably, chewing gum, because of major variations in taste and thus gustatory stimulation.

Draining and spitting methods

For the draining method, unstimulated whole saliva is allowed to drip passively off the lower lip into a preweighed or graduated test tube or sampling container (Fig. 6.13).

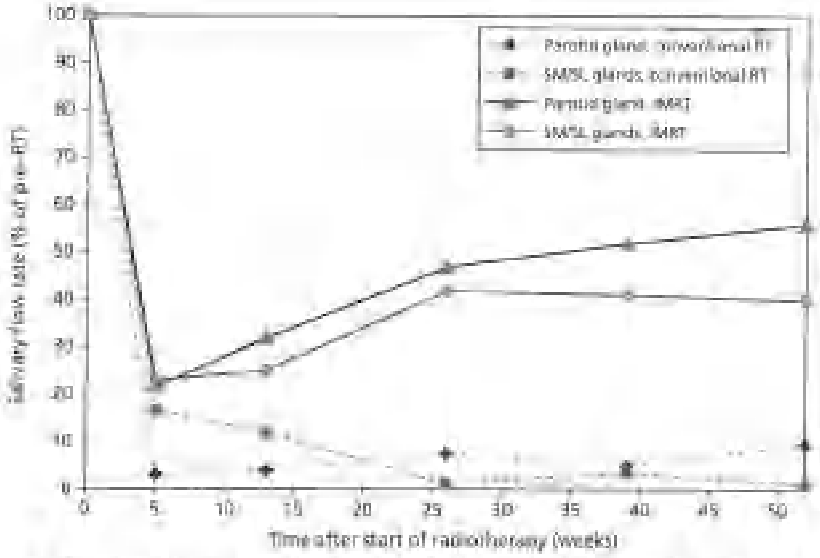


Figure 6.12 Percentage reduction in flow rate of stimulated parotid and submandibular–sublingual (SMSL) saliva as a function of time after start of radiotherapy (RT). Upper lines show parotid-sparing three-dimensional/intensity-modulated RT (IMRT) and lower lines conventional RT including the parotid, submandibular and sublingual glands in the treatment area [58]. Reproduced with permission of Elsevier.

Figure 6.13 Measurement of the whole saliva flow rate by the draining method. Materials required are a plastic cup for collection and weight with two digits (a) and a stopwatch (b). During saliva collection the patient is placed in a relaxed hunched-over position with the face tilted slightly downwards (c). For stimulation, chewing on paraffin wax is a standard, which enables comparison of the results with normal values, and here the spitting method is used.

The subject is instructed to expectorate all remaining saliva into the test tube at the end of the collection period, which normally is set to last 10 or 15 min. The amount of saliva is determined by weighing (assuming a specific gravity of 1 g/cm^3) or read from the scale on the graduated test tube in which the saliva is collected [53]. This method is only used for unstimulated whole saliva, and shows a very high reproducibility with proper clinical settings. Chewing-stimulated whole saliva flow rates are ideally determined by the spitting method and by chewing a standard-size tasteless gum base of paraffin wax (1.5 g, melting point 42 °C). In this method, saliva is allowed to accumulate in the floor of the mouth, from where the subject is instructed to spit it out into the preweighed or graduated test tube or a sampling container every 60 s or more. The method can also be used for unstimulated whole saliva, although the spitting action, if not performed as passively as possible, might have some stimulating effect. Standard values for normal physiological flow rates are as described earlier, an unstimulated flow rate of 0.2–0.5 mL/min and paraffin-chewing-stimulated flow rate of 1.0–2.0 mL/min, and always determined by either the draining or the spitting method.

Suction and absorbent methods

In the suction method, saliva is continuously sucked or aspirated from the floor of the mouth into a graduated test tube. However, compared with the draining and spitting methods, the suction process poses a risk of unintentional stimulation. In the absorbent method, saliva is collected (absorbed) by preweighed swabs, cotton rolls, or gauze sponges placed in the mouth at the orifices of the major salivary glands. This method is often the only choice for patients with neurodegenerative diseases [37]. A commercial version is the Salivette method (Sarstedt AG, Germany). Using this method, saliva collection is carried out by chewing a synthetic swab, which can be treated with citric acid for further saliva stimulation. After saliva collection, centrifuging the swab recovers the saliva sample as a clear fluid that can be used for analyses of constituents like drugs (illegal and legal), hormones, or steroids monitoring.

Saliva flow rates and caries risk assessment

There is abundant evidence that subnormal saliva flow rates and hyposalivation generally cause a marked increase in the prevalence and incidence of dental caries, and if not recognized in time, and treated correctly, the increase will become severe and can lead to rampant caries. The cause of the changes is not only attributed to the effects of saliva on the tooth surfaces, but also to an ecological shift within the oral cavity. Thus, as described in Chapter 7, subnormal saliva flow rates change the oral ecology towards increased numbers of acid-producing and acid-tolerating bacteria. Also, changes in the output of antimicrobial proteins and agglutinating proteins as well as a decreased saliva pH, will further accelerate these ecological changes towards a more acidic oral environment in the dry-mouth patient. The ecological changes often result in an overgrowth of bacteria, making caries progress extremely rapidly. Thus, the most strongly related salivary parameter to dental caries is the saliva flow rate [31], and, as mentioned earlier, especially the unstimulated flow rate [6, 7]. When used in the dental clinic for caries risk assessment, the draining or the spitting method are the gold standards and should always be 'first choice' for salivary diagnostics.

Correctly performed determination of the saliva flow rate is a valuable clinical measure and considerably more related to dental caries than the concentrations of various components within the saliva [31]. The main effect of a subnormal unstimulated saliva flow rate on dental caries is an acceleration of the rate of demineralization within the caries lesion. This acceleration is caused by an alteration of all the functions of saliva against caries development, especially a low oral sugar clearance, reduced remineralization potential of saliva, reduced buffer capacity and reduced output of antimicrobial proteins. Figure 6.14 shows the relation between the unstimulated whole saliva flow rate and experimental root caries lesions in a group of subjects covering a broad range of unstimulated saliva flow rates (0.0 to very high levels near 1.0 mL/min). As shown in this experimental study, the lesion depth increases with decreasing unstimulated saliva flow rates, and especially with subnormal flow rates the lesion depth becomes greatly increased. Thus, subnormal unstimulated whole saliva flow rates (i.e., below 0.2 mL/min) always increase the risk for rapid caries lesion progression. The effect of the flow rate on the degree of mineralization in the surface layer of the caries lesion is also shown in Fig. 6.14 (see also Chapter 5). With subnormal unstimulated flow rates the level of mineralization becomes very low, amounting to only some 20–30% of the mineralization level in healthy root surfaces and half the mineralization in subjects with normal unstimulated saliva flow rates. In the normal range for the unstimulated saliva flow rates, however, the relation between saliva flow rates and caries is vague, if it even exists (Fig. 6.14). In these experimental studies [6, 7], root caries lesions were developed under undisturbed biofilm, without toothbrushing, and without the use of fluoride toothpastes. The relations therefore, may primarily reflect 'later stages' of the caries process.

With subnormal flow rates, the normal process of tooth remineralization is interrupted. This favors demineralization at the expense of remineralization. Various other experimental caries studies have shown that enamel placed in the mouth of a severe dry-mouth patient whose oral hygiene is poor can be completely demineralized within just a few months [22, 27]. On the other hand, enamel placed in the mouth of a healthy patient with good oral hygiene hardly shows any signs of demineralization in the same period.

Compositional analyses of saliva

In patients with subnormal saliva flow rates or hyposalivation, compositional analyses seem unnecessary because most saliva components will be affected by the low flow

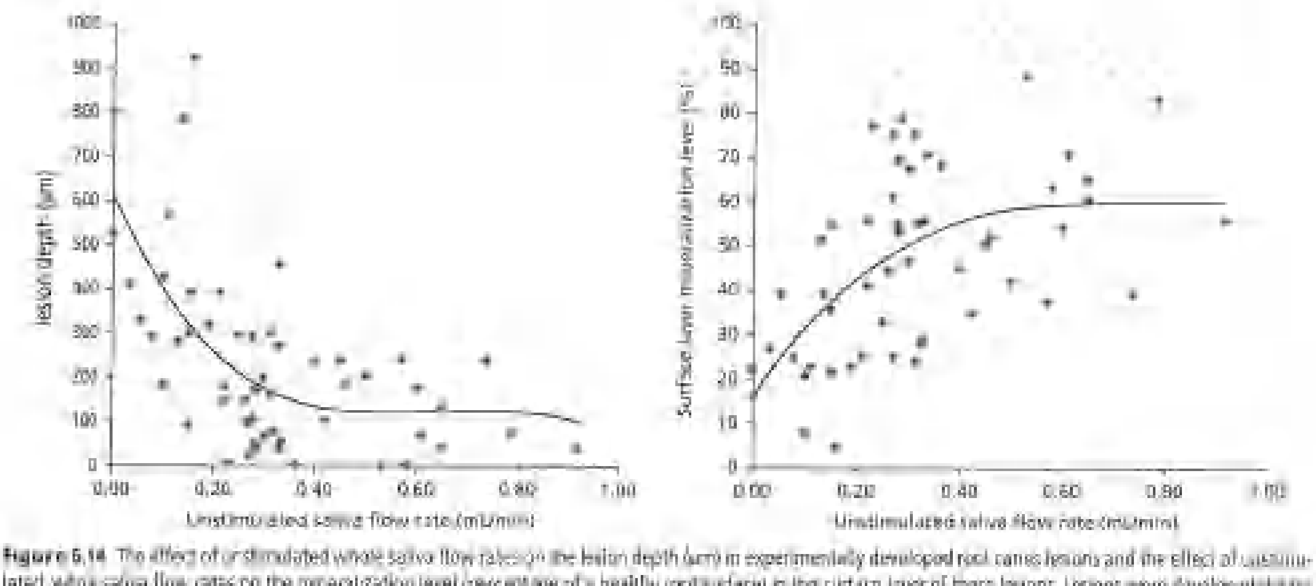


Figure 6.14 The effect of unstimulated whole saliva flow rates on the lesion depth (µm) in experimentally developed root caries lesions and the effect of unstimulated whole saliva flow rates on the mineralization level (percentage of a healthy root surface) in the surface layer of these lesions. Lesions were developed during a period of 2 months with undisturbed biofilm formation and without exposure to fluoride-containing oral hygiene products [6, 7].

rate. However, in individuals with normal saliva flow rates and an unexplainable rapid caries lesion progression, compositional analyses may seem tempting. Nevertheless, no study has clearly pinpointed robust compositional salivary variables that can be predictive of caries lesion progression among healthy individuals with normal saliva flow rates, even among individuals with major differences in caries [8]. This is because of an extensive functional redundancy among various salivary constituents [31]. Thus, most functions of saliva are due to a combined effect of many components (Fig. 6.4). Determining only single components in the saliva will not help the clinician in gaining solid results about the individual's capacity to avoid caries. Among the most predictive salivary components for caries are the saliva buffer capacity, the saliva calcium and phosphate concentrations, and levels of the immunoglobulin sIgA [31]. However, probably the majority of the salivary components discussed in this chapter need to be determined to give a meaningful and composite measure of a specific individual's capacity against dental caries. From this perspective, most likely some individuals have a saliva composition that is more protective against caries than other individuals, and vice versa. But owing to the complexity of these relations, compositional saliva analyses are not currently a scientifically established measure for caries diagnostics. Thus, compared with the flow rate, which may also be determined by the dental hygienist, such analyses are expensive and time consuming while offering very little diagnostic value at this point in time.

Management of salivary gland hypofunction

The treatment of xerostomia, subnormal saliva flow rates, and hyposalivation should be based on the following considerations:

1. If stimulation of the flow of saliva is feasible to relieve oral dryness, this approach may readily diminish the oral problems including caries.
2. If the saliva cannot be adequately stimulated, it has to be determined whether 'coating' the surfaces of the oral mucosa can diminish the feeling of dry mouth.
3. If not, then assess what else can be done to preserve and protect the teeth and the oral soft tissues and provide relief to the patient.

These assessments should be carefully evaluated: some patients will respond to a single treatment, while others will require a combination of treatments. Unfortunately, some patients may not respond to the management of oral dryness, although much can be done to calm the patient and guard the oral cavity against injury and disease [34]. Management of the patient with xerostomia and salivary gland hypofunction starts with the dentist and dental hygienist (Table 6.4). Patients with hyposalivation require frequent dental visits (usually every 3–4 months) and must work closely with their dentist and dental hygienist to maintain optimal dental health. Patients with salivary gland disorders must maintain meticulous oral hygiene (see also Chapter 16). Interdental brushes and mechanical toothbrushes are helpful for those with gingival recession and oral-motor or behavioral complications. Regular cleaning of the tongue with a tongue scraper is also highly recommended for an overall reduction of bacteria in the oral cavity. The team of oral health professionals must play an important role in providing guidance (clinical instructions and written instructions) to the dry-mouth patient.

Table 6.4 *Management strategies for xerostomia and salivary hypofunction*

Management strategy	Examples
Preventive therapies	Optimal oral hygiene, supplemental fluoride, remineralizing solutions, noncariogenic diet without sucrose
Symptomatic (palliative) treatments	Water, oral rinses, gels, mouthwashes, saliva substitutes, increased humidification, minimize caffeine and alcohol
Local or topical salivary stimulation	Sugar-free gums, mints, and lozenges
Drug-induced stimulation	Parasympathomimetic secretogogues: cevimeline and pilocarpine

In addition to optimal oral hygiene and mouth care, the use of topical fluorides in these patients is absolutely critical for the control of dental caries. There are many different fluoride therapies available (see also Chapter 13). The dosage chosen and the frequency of application should be based on the severity of the salivary hypofunction and the rate of caries development [4, 22, 27]. In dry-mouth patients, acidic gels should be replaced by neutral sodium fluoride gels to avoid mucosal reactions. A 5000 ppm fluoridated toothpaste, used twice daily, is more effective in controlling caries lesion progression than regular toothpaste is [14] and can be recommended for patients with subnormal flow rates or hyposalivation. Remineralizing solutions, containing combinations of calcium, phosphate, and proteins, may also be used to reduce caries in patients with hyposalivation [57]. Various acidic, but still nonerosive, saliva stimulants seem to be suited to dry mouth relief, given that the products are thoroughly tested in dry-mouth patients [30]. The taste-induced increased saliva flow and retention of fluoride in the oral tissues provide relief of symptoms and an additional caries protection. Finally, patients should be counseled to follow a diet that avoids cariogenic saliva stimulants, food, and beverages (see Chapter 8). Nonfermentable dietary sweeteners, such as sorbitol and aspartame or saccharine, are recommended [55]. So too is sucralose, a chlorinated, noncariogenic sweetener, and polyols such as xylitol. Thus, any substitute for sucrose is highly recommendable, especially for this patient group.

Concluding remarks

The dentist and dental hygienist should go to great lengths at being diligent to preserve the dentition in any patient with subnormal saliva flow rates. Hence, rampant dental caries and severe dental erosion may develop very rapidly if serious measures are not taken to ensure that these diseases are under control. Thus, saliva secretion normally inhibits bacterial colonization and growth and reduces the deleterious effects of anaerobic metabolism in dental biofilms by its remineralization and buffering capacity, as well as providing the dental enamel with a protective pellicle against dietary acids. When this protection from saliva is absent, frequent visits to the dentist and dental hygienist, including painstaking measures to ensure meticulous oral hygiene, appropriate dietary advice, and optimal fluoride treatment, are crucial to help preserve the dentition against rampant dental caries and severe erosion.

Background literature

Bardow A, Pedersen AML, Nauntofte B. Saliva. In: Miles TS, Nauntofte B, Svensson P, eds. *Clinical oral physiology*. Copenhagen: Quintessence, 2004: 17–51.

Bradley PJ, Guntinas-Lichius O. *Salivary gland disorders and diseases: diagnosis and management*. Stuttgart: Georg Thieme, 2011.

Edgar WM, Dawes C, O'Mullane DM. *Saliva and oral health*, 3rd ed. London: British Dental Association, 2004.

Ferguson DB. The salivary glands and their secretions. In: Ferguson DB, ed. *Oral bioscience*. Edinburgh: Churchill Livingstone, 1999: 117–50.

Garrett JR, Ekström J, Anderson LC. *Neural mechanisms of salivary gland secretion*. Basel: Karger, 1999.

Sreebny LM, Vissink A, eds. *Dry mouth. The malevolent symptom: a clinical guide*. Ames, IA: Wiley–Blackwell, 2010.

Tucker AS, Miletich I, eds. *Salivary glands. Development, adaptations and disease*. Basel: Karger, 2010.

Wong DT. *Salivary diagnostics*. Ames, IA: Wiley–Blackwell, 2008.

References

1. Al-Nowaiser A, Roberts GJ, Trompeter RS, Wilson M, Lucas VS. Oral health in children with chronic renal failure. *Pediatr Nephrol* 2003; 18: 39–45.
2. Amerongen AV, Veerman EC. Saliva – the defender of the oral cavity. *Oral Dis* 2002; 8: 12–22.
3. Anderson P, Hector MP, Rampersad MA. Critical pH in resting and stimulated whole saliva in groups of children and adults. *Int J Paediatr Dent* 2001; 11: 266–73.
4. Anusavice KJ. Dental caries: risk assessment and treatment solutions for an elderly population. *Compend Contin Educ Dent* 2002; 23 (Suppl 10): 12–20.
5. Bardow A, Madsen J, Nauntofte B. The bicarbonate concentration in human saliva does not exceed the plasma level under normal physiological conditions. *Clin Oral Investig* 2000; 4: 245–53.
6. Bardow A, Nyvad B, Nauntofte B. Relationships between medication intake, complaints of dry mouth, salivary flow rate and composition, and the rate of tooth demineralization in situ. *Arch Oral Biol* 2001; 46: 413–23.
7. Bardow A, ten Cate JM, Nauntofte B, Nyvad B. Effect of unstimulated saliva flow rate on experimental root caries. *Caries Res* 2003; 37: 232–6.
8. Bardow A, Lykkeaa J, Qvist V, Ekstrand K, Twetman S, Fiehn NE. Saliva composition in three selected groups with normal stimulated salivary flow rates but yet major differences in caries experience and dental erosion. *Acta Odontol Scand* 2013; 71: 466–73.
9. Burlage FR, Pijpe J, Coppes RP, Hemels ME, Meertens H, Canrinus A, Vissink A. Variability of flow rate when collecting stimulated human parotid saliva. *Eur J Oral Sci* 2005; 113: 386–90.
10. Bruvo M, Moe D, Kirkeby S, Vorum H, Bardow A. Individual variations in protective effects of experimentally formed salivary pellicles. *Caries Res* 2009; 43: 163–70.
11. Dawes C. An analysis of factors influencing diffusion from dental plaque into a moving film of saliva and the implications for caries. *J Dent Res* 1989; 68: 1483–8.
12. Dawes C. What is the critical pH and why does a tooth dissolve in acid? *J Can Dent Assoc* 2003; 69: 722–4.
13. Eisbruch A. The causes of dry mouth: a broad panoply. Head and neck radiotherapy: an iatrogenic factor. In: Sreebny LM, Vissink A, eds. *Dry mouth, the malevolent symptom*. Ames, IA: Wiley–Blackwell, 2010: 139–51.
14. Ekstrand KR, Poulsen JE, Hede B, Twetman S, Qvist V, Ellwood RP. A randomized clinical trial of the anti-caries efficacy of 5,000 compared to 1,450ppm fluoridated toothpaste on root caries lesions in elderly disabled nursing home residents. *Caries Res* 2013; 47: 391–8.
15. Frank RM, Herdly J, Philippe E. Acquired dental defects and salivary gland lesions after irradiation for carcinoma. *J Am Dent Assoc* 1965; 70: 868–83.
16. Garrett JR, Proctor GB. Control of salivation. In: Linden RWA, ed. *The scientific basis of eating. Taste and smell, salivation, mastication and swallowing and their dysfunctions*. Frontiers of Oral Biology. Vol. 9. Basel: Karger, 1998: 135–55.
17. Hamlet S, Faull J, Klein B, Aref A, Fontanesi J, Stachler R, Shamsa F, Jones L, Simpson M. Mastication and swallowing in patients with postirradiation xerostomia. *Int J Radiat Oncol Biol Phys* 1997; 37: 789–96.
18. Hannig M, Joiner A. The structure, function and properties of the acquired pellicle. In: Duckworth RM, ed. *The teeth and their environment. Physical, chemical and biochemical influences*. Monographs in Oral Science. Vol. 19. Basel: Karger, 2006: 29–64.
19. Hannig C, Hannig M, Attin T. Enzymes in the acquired enamel pellicle. *Eur J Oral Sci* 2005; 113: 2–13.
20. Helmerhorst EJ, Hodgson R, van't Hof W, Veerman EC, Allison C, Nieuw Amerongen AV. The effects of histatin-derived basic antimicrobial peptides on oral biofilms. *J Dent Res* 1999; 78: 1245–50.
21. Izutsu KT. Theory and measurement of the buffer value of bicarbonate in saliva. *J Theor Biol* 1981; 90: 397–403.
22. Jansma J, Vissink A, Jongebloed WL. Natural and induced radiation caries: a SEM study. *Am J Dent* 1993; 6: 130–6.
23. Jensdottir T, Nauntofte B, Buchwald C, Bardow A. Effects of sucking acidic candy on whole-mouth saliva composition. *Caries Res* 2005; 39: 468–74.
24. Jensen SB, Lynge Pedersen AM, Nauntofte B. The causes of dry mouth: a broad panoply. Other causes of dry mouth: the list is endless. In: Sreebny LM, Vissink A, eds. *Dry mouth: the malevolent symptom*. Ames, IA: Wiley–Blackwell, 2010: 158–82.
25. Kallenberg CGM. The causes of dry mouth: a broad panoply. The autoimmune connection. In: Sreebny LM, Vissink A, eds. *Dry mouth: the malevolent symptom*. Ames, IA: Wiley–Blackwell, 2010: 128–38.
26. Karmiol M, Walsh RF. Dental caries after radiotherapy of the oral regions. *J Am Dent Assoc* 1975; 91: 838–45.
27. Kielbassa AM, Hinkelbein W, Hellwig E, Meyer-Lückel H. Radiation-related damage to dentition. *Lancet Oncol* 2006; 7: 326–35.
28. Lagerlöf F, Dawes C. The volume of saliva in the mouth before and after swallowing. *J Dent Res* 1984; 63: 618–21.
29. Lagerlöf F, Lindqvist L. A method for determining concentrations of calcium complexes in human parotid saliva by gel filtration. *Arch Oral Biol* 1982; 27: 735–8.
30. Lajer C, Buchwald C, Nauntofte B, Specht L, Bardow A, Jensdottir T. Erosive potential of saliva stimulating tablets with and without fluoride in irradiated head and neck cancer patients. *Radiother Oncol* 2009; 93: 534–8.
31. Leone CW, Oppenheim FG. Physical and chemical aspects of saliva as indicators of risk for dental caries in humans. *J Dent Educ* 2001; 65: 1054–62.
32. Levine M. Susceptibility to dental caries and the salivary proline-rich proteins. *Int J Dent* 2011; 2011: 953412.

33. Lindfors B, Lagerlöf F. Effect of sucrose concentration in saliva after a sucrose rinse on the hydronium ion concentration in dental plaque. *Caries Res* 1988; **22**: 7–10.
34. Márton K, Boros I, Fejérdy P, Madléna M. Evaluation of unstimulated flow rates of whole and palatal saliva in healthy patients wearing complete dentures and in patients with Sjogren's syndrome. *J Prosthet Dent* 2004; **91**: 577–81.
35. McDowell H, Gregory TM, Brown WE. Solubility of $Ca_5(PO_4)_3OH$ in the system $Ca(OH)_2$–H_3PO_4–H_2O at 5, 15, 25, and 37 °C. *J Res Natl Bur Stand* 1977; **81A**: 273–81.
36. Mehanna H, Paleri V, West CM, Nutting C. Head and neck cancer – part 1: epidemiology, presentation, and prevention. *BMJ* 2010; **341**: C4684.
37. Møller E, Karlsborg M, Bardow A, Lykkeaa J, Nissen FH, Bakke M. Treatment of severe drooling with botulinum toxin in amyotrophic lateral sclerosis and Parkinson's disease: efficacy and possible mechanisms. *Acta Odontol Scand* 2011; **69**: 151–7.
38. Nauntofte B. Regulation of electrolyte and fluid secretion in salivary acinar cells. *Am J Physiol* 1992; **263**: G823–37.
39. Navazesh M. Methods for collecting saliva. *Ann N Y Acad Sci* 1993; **694**: 72–7.
40. Navazesh M, Christensen CM. A comparison of whole mouth resting and stimulated salivary measurement procedures. *J Dent Res* 1982; **61**: 1158–62.
41. Nieuw Amerongen AVN, Bolscher JGM, Veerman ECI. Salivary mucins: protective functions in relation to their diversity. *Glycobiology* 1995; **5**: 733–40.
42. Richards A, Machiulskiene V, Nyvad B, Baelum V. Saliva fluoride before and during 3 years of supervised use of fluoride toothpaste. *Clin Oral Investig* 2013; **17**: 2057–63.
43. Rykke M, Rölla G, Sønju T. Effect of sodium lauryl sulfate on protein adsorption to hydroxyapatite *in vitro* and on pellicle formation *in vivo*. *Scand J Dent Res* 1990; **98**: 135–43.
44. Schmidt-Nielsen B. The solubility of tooth substance in relation to the composition of saliva. *Acta Odontol Scand* 1946; **7** (Suppl 2): 1–88.
45. Shannon IL, Feller RP, Chauncey HH. Fluoride in human parotid saliva. *J Dent Res* 1976; **55**: 506–9.
46. Slomiany BL, Murty VLN, Piotrowski J, Slomiany A. Salivary mucins in oral mucosal defense. *Gen Pharmacol* 1996; **27**: 761–71.
47. Speirs RL. The effects of interactions between gustatory stimuli on the reflex flow-rate of human parotid saliva. *Arch Oral Biol* 1971; **16**: 351–65.
48. Tabak LA. In defense of the oral cavity – structure, biosynthesis and function of salivary mucins. *Annu Rev Physiol* 1995; **57**: 547–64.
49. Thaysen JH, Thorn NA, Schwartz IL. Excretion of sodium, potassium, chloride and carbon dioxide in human parotid saliva. *Am J Physiol* 1954; **178**: 155–9.
50. Twetman S, Johansson I, Birkhed D, Nederfors T. Caries incidence in young type 1 diabetes mellitus patients in relation to metabolic control and caries-associated risk factors. *Caries Res* 2002; **36**: 31–5.
51. Veerman ECI, van den Keijbus PAM, Vissink A, Nieuw Amerongen AV. Human glandular salivas: their separate collection and analysis. *Eur J Oral Sci* 1996; **104**: 346–52.
52. Veerman ECI, van Nieuw Amerongen A, Vissink A. Evaluation of saliva – normal and in disease. In: Bradley PJ, Guntinas-Lichius O, eds. *Salivary gland disorders and diseases: diagnosis and management*. Stuttgart: Thieme, 2011: 19–26.
53. Vissink A, Wolff A, Veerman ECI. Saliva collectors. In: Wong DT, ed. *Salivary diagnostics*. Ames, IA: Wiley-Blackwell, 2008: 69–76.
54. Vissink A, Mitchell JB, Baum BJ, Limesand KH, Jensen SB, Fox PC, Elting LS, Langendijk JA, Coppes RP, Reyland ME. Clinical management of salivary gland hypofunction and xerostomia in head and neck cancer patients: successes and barriers. *Int J Radiat Oncol Biol Phys* 2010; **78**: 983–91.
55. Walsh L. Lifestyle impacts on oral health. In: Mount G, Hume W, eds. *Preservation and restoration of tooth structure*. Middlesbrough: Knowledge Books and Software Ltd, 2005: 83–110.
56. Zakhary GM, Clark RM, Bidichandani SI, Owen WL, Slayton RL, Levine M. Acidic proline-rich protein Db and caries in young children. *J Dent Res* 2007; **86**: 1176–80.
57. Zero DT. Dentifrices, mouthwashes, and remineralization/caries arrestment strategies. *BMC Oral Health* 2006; **6** (Suppl 1): S9.

7

Biofilms in caries development

P.D. Marsh, N. Takahashi, and B. Nyvad

Introduction

Dental caries is the result of the metabolic activities of bacteria growing in microbial communities on teeth as biofilms (previously referred to as dental plaque) (Figs 7.1 and 7.2). Hence, the presence of microbial communities on the tooth surface is a prerequisite for caries lesions to develop. However, as discussed in Chapter 2, teeth may be covered by biofilms without always presenting with visible signs of caries. Therefore, while these biofilms are necessary, their mere presence is not sufficient for caries to occur, and other factors are involved. Indeed, the presence of these biofilms is natural and confers benefit to the host (see later). This apparent problem has challenged researchers for years, and it is only following recent developments in biofilm research that we are now beginning to get a better understanding of bacterial behavior on teeth and their role in health and disease. The aim of this chapter is to present a fresh perspective on the ecosystem in the oral cavity, particularly as it relates to the development and ecology of biofilms on teeth. Such knowledge is not only of fundamental importance for the understanding of why caries develops and progresses, but may also serve as a guide as to how caries can best be controlled in the clinic.

Dental Caries: The Disease and its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

Figures 7.1 and 7.2 Figure 7.1: Microbial biofilms on teeth become clearly visible after staining with a disclosing solution. The biofilms are typically located at retention sites along the gingival margin and extend into the interproximal space. Figure 7.2: Occlusal surface of erupting third molar. Note that heavy microbial deposits (biofilms) are related to the fissures and partly cover the cuspal slopes. This is a freshly extracted tooth where a brown dye has been used to delineate the biofilm.

The resident microflora

It has been estimated that the human body is composed of approximately 10^{14} cells, of which only 10% are mammalian. The majority are the organisms that comprise the resident microflora of the host. Acquisition of this resident microflora occurs from birth and is a natural process during which all environmentally exposed surfaces of the body become colonized. The organisms that establish and predominate on particular surfaces vary, however, depending on the biological and physical properties of each site. The mouth is no exception to this process, and distinct species of bacteria can be recovered from the mouth of infants only a few hours old. Once established, the resident microflora has a diverse composition, consisting of a wide range of Gram-positive and Gram-negative bacterial species, as well as yeasts and other types of microorganism. In addition, the composition of the oral microflora will change as the biology of the mouth alters over time.

Acquisition of the resident oral microflora

The mouth of the newborn baby is usually sterile. Acquisition depends on the successive transmission of microbes to the site of potential colonization. In the mouth, although organisms can be derived from water, food, and other nutritious fluids, the main route of transmission is via saliva. Molecular typing studies have shown that the acquisition of oral streptococci and Gram-negative species in children is predominantly from their mother (vertical transmission). Indeed, it has been proposed that reducing the carriage of mutans streptococci in mothers could prevent transmission of these bacteria to their offspring, and thereby potentially delay the onset of caries [41].

The diversity of the oral microflora increases during the first months of life. The earliest colonizers of a site are termed pioneer species, and these are streptococci, particularly *Streptococcus salivarius*, *Streptococcus mitis*, and *Streptococcus oralis*. With time, Gram-negative anaerobes appear, including *Prevotella melaninogenica*, *Fusobacterium nucleatum*, and *Veillonella* spp. The eruption of the dentition creates novel habitats for microbial colonization because teeth provide the only nonshedding surfaces within the body to which the resident microflora can normally attach and so substantial biofilms can develop [57, 58]. Desquamation ensures that the microbial load on mucosal surfaces is relatively low, although substantial accumulations of bacteria can develop on the tongue. Mutans streptococci and *Streptococcus sanguinis* (previously named *Streptococcus sanguis*) generally only appear in the normal mouth following tooth eruption, and the development and maturation of dental biofilms creates conditions suitable for a greater range of more fastidious bacteria. In addition, the flow of gingival crevicular fluid (GCF) not only introduces components of the host defenses (neutrophils, complement, antibodies) but also provides host molecules (e.g., hemoglobin, hemopexin, transferrin) that act as a source of essential nutrients for the many fastidious obligate anaerobes found at this site.

The oral microflora continues to increase in diversity over time until, eventually, a stable situation is reached, termed the climax community. The microbial populations that comprise such a climax community remain stable with time, despite regular minor perturbations to the local environment due to changes in diet, hormonal levels, oral hygiene, and so on. The stability is termed 'microbial homeostasis'; this is not a passive response by the organisms but reflects a highly dynamic equilibrium between the resident microflora and the local environmental conditions at that site in the host [54, 55]. A major change in the habitat, such as the frequent consumption of dietary sugars, can disrupt microbial homeostasis and drive imbalances among the species comprising the resident microflora, a consequence of which can be an increased predisposition to disease. A recognition and acceptance of this ecological relationship can lead to the identification of more appropriate approaches to caries control (see later this chapter) [56].

Changes in the microflora occur during the life of an individual as a direct or an indirect effect of ageing [78]. Direct effects such as the waning of cell-mediated immunity, can lead to increases in the carriage of nonoral bacteria (e.g., staphylococci and enterobacteria). Indirect effects include the increased wearing of dentures among the elderly, which promotes colonization by yeasts. Older people are also more likely to be on long-term medication, a common side effect of which is a reduced salivary flow rate promoting colonization by lactobacilli and yeasts.

Benefits of the resident oral microflora

The resident microflora plays an important role in the normal development of the host, and functions as part of the innate host defenses. Recent research has demonstrated that the resident oral microflora has critical functions for the host. Patients on long-term, broad-spectrum antibiotic therapy can have their normal oral bacterial community suppressed, leading to overgrowth by yeasts or nonoral bacterial species. Thus, the normal oral microflora acts as a barrier to permanent colonization by transient organisms, some of which are potentially pathogenic [54]. Mechanisms involved in colonization resistance by resident oral organisms include:

- saturation of microbial attachment sites,
- more effective competition for essential nutrients,
- creation of conditions unfavorable to the growth of invading microbes, and
- the production of inhibitory factors (e.g., bacteriocins, hydrogen peroxide).

Evidence is emerging that there is active communication ("cross-talk") between the host and its resident microflora in order to effectively maintain a beneficial and symbiotic relationship. Some oral streptococci are able to signal to the host and downregulate potential pro-inflammatory responses whilst also stimulating important host response pathways, such as interferon responses, and promoting beneficial effects on the cytoskeleton [17]. Thus, the host has evolved to tolerate resident microorganisms without initiating a damaging inflammatory response, while also being able to mount an efficient defense against pathogens. Pathogenic and resident bacteria may initiate different intracellular signaling pathways and innate immune responses in epithelial cells.

Resident oral bacteria also play an important role in maintaining many important gastrointestinal and cardiovascular systems, via the metabolism of dietary nitrate. Approximately 25% of ingested nitrate is secreted in saliva where facultatively anaerobic oral resident bacteria reduce nitrate to nitrite. Nitrite affects a number of key physiological processes, including the regulation of blood flow, blood pressure, gastric integrity, and tissue protection against ischemic injury. Nitrite can be further converted to nitric oxide in the acidified stomach, and this has antimicrobial properties, and contributes to defense against enteropathogens and in the regulation of gastric mucosal blood flow and mucus formation [32, 79]. The challenge to the clinician, therefore, is to use treatment strategies that inhibit the pathogenic organism(s) and their activities whilst maintaining the beneficial properties of the resident oral microflora.

Site distribution of oral bacteria

Although the mouth is highly selective for the microorganisms that are able to colonize and become established, more than 1200 different types have now been detected in the mouth [1, 20]. The mouth is not a homogeneous environment for microbial colonization. Distinct microhabitats exist, such as mucosal surfaces (palate, cheek, tongue, etc.), the various surfaces of teeth (smooth, approximal, fissures), and the gingival crevice [60]. The biological and physical properties of each site result in only a subset of these organisms (often 20–30 distinct types) being able to predominate at an individual site [1].

Bacterial metabolism and ecological factors affecting the growth and metabolism of oral bacteria

The mouth provides both a friendly and a hostile environment for microbial growth. Resident oral microorganisms are adapted to use endogenous (host-derived) nutrients for growth (e.g., salivary proteins and glycoproteins), but superimposed on this can be sudden and irregular intakes of high concentrations of dietary carbohydrates, such as glucose, fructose, and sucrose. The mouth is overtly aerobic, and yet obligate anaerobes and facultatively anaerobic bacteria are able to persist within biofilms on oral surfaces (tongue, teeth) and comprise the most numerous group of bacteria at these sites. Organisms have to attach firmly to a surface in order to avoid being washed away by the flow of saliva and swallowed. Thus, the majority of organisms (and the most disease) are found at protected and stagnant sites around the dentition (Figs 7.1 and 7.2).

Saliva plays other roles in regulating the growth and metabolic activity of the oral microflora. Saliva helps to maintain the pH in the oral cavity at values around 6.75–7.25 and the temperature at around 35–36 °C, which is optimal for the growth of many microorganisms. Saliva contains glycoproteins and proteins that act as the primary

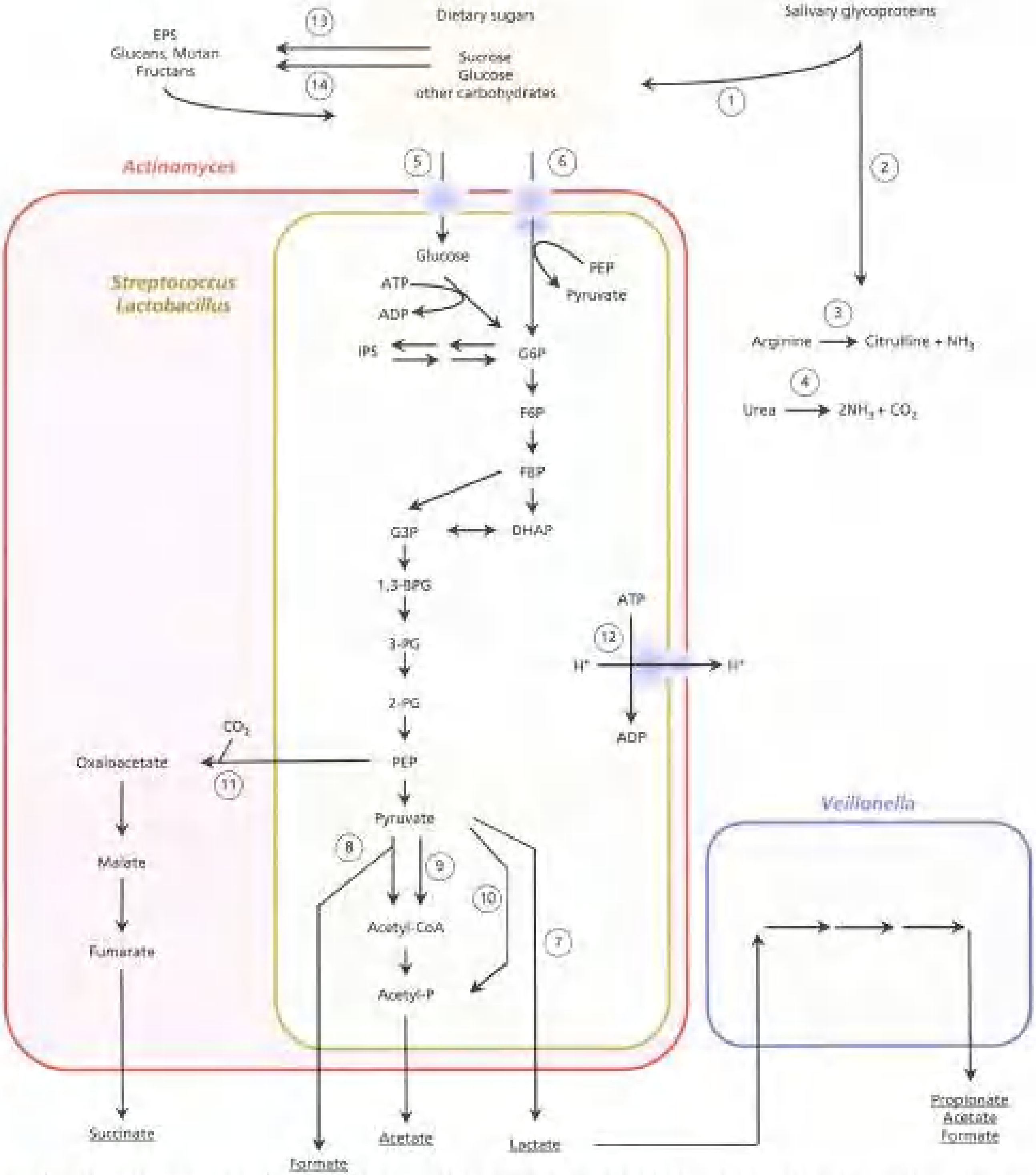


Figure 7.3 The metabolism of oral bacteria, responsible for acid production, ESP production, ISP production, and alkali production: (1) glycosidases; (2) proteases/peptidases; (3) arginine deiminase; (4) urease; (5) sugar-binding proteins; (6) PEP–PTS; (7) lactate dehydrogenase; (8) pyruvate formate-lyase; (9) pyruvate dehydrogenase; (10) pyruvate oxidase; (11) PEP carboxylase/PEP carboxykinase; (12) proton-translocating ATPase; (13) glucosyltransferases; (14) fructosyltransferases.

source of carbohydrates, peptides, and amino acids for microbial growth. Bacteria have to function cooperatively in order to degrade the oligosaccharide side chains and peptide core chains of glycoproteins such as mucins (Fig. 7.3, reactions 1 and 2). Acid is produced relatively slowly from the metabolism of these compounds, and ammonia and bicarbonate are produced from amino acids as a counterpart for acid. Arginine deiminase (Fig. 7.3, reaction 3) and the subsequent degradation of citrulline produce ammonia and carbon dioxide. Urea contained in saliva can also contribute to the production of ammonia and carbon dioxide (Fig. 7.3, reaction 4), and so there is only a low risk of enamel demineralization. Importantly, saliva is a sufficient source of nutrients to sustain the growth of a natural and diverse oral microflora in the absence of other nutrients. Lastly, saliva delivers a spectrum of innate and specific immune host defense factors that are essential for the maintenance of a healthy mouth [60] (see Chapter 6).

A carbohydrate-rich diet increases the acid production and growth rate of many oral bacteria. Thus, it has been shown that the accumulation of dental plaque after 4 days, as regards extension, weight, and actual numbers of bacteria, is higher when individuals consume a diet supplemented with sucrose candies compared with a control diet without added sucrose [80]. What may be clinically more important, however, is that a sucrose-rich diet could change the composition of the microflora by generating a low pH capable of inhibiting the growth of many of the beneficial bacteria found naturally in dental plaque, thereby selecting for the more acid-tolerant species (see later for details).

Dental biofilm bacteria such as streptococci and *Actinomyces* can utilize most dietary sugars [76, 90, 91]. These bacteria incorporate mono-, di-, and oligosaccharides through cell-membrane-associated sugar-binding proteins and/or the phosphoenolpyruvate:sugar phosphotransferase system (PEP–PTS; Fig. 7.3, reactions 5 and 6). The former system permeates sugars into cells and subsequently phosphorylates them using ATP. The PEP–PTS is a 'group translocation' system, which transports sugars into cells along with phosphorylation of sugars by a high-energy phosphoryl bond of PEP. The PEP-PTS consists of two components: sugar-specific proteins for sugar translocation (cell membrane bound) and nonspecific proteins for transport of a high-energy phosphoryl bond of PEP to translocated sugars (intracellularly located). Polysaccharides such as starch can also be utilized in dental plaque as fermentable substrates, in combination with salivary alpha-amylase, which degrades starch into oligosaccharides, maltose, and glucose efficiently [3]. Incorporated sugars are metabolized through classic glycolysis (Embden–Meyerhof–Parnas pathway), in which one molecule of glucose is degraded into two molecules of pyruvate. Under anaerobic conditions, pyruvate can be further degraded into lactate by lactate dehydrogenase, and to formate and acetate by pyruvate formate-lyase (Fig. 7.3, reactions 7 and 8). In the presence of oxygen, pyruvate can be converted to acetate by the action of pyruvate dehydrogenase or pyruvate oxidase (Fig. 7.3, reactions 9 and 10). Moreover, in the presence of bicarbonate, a natural salivary component, PEP can be converted to succinate with bicarbonate assimilation by phosphoenolpyruvate carboxylase and/or phosphoenolpyruvate carboxykinase (Fig. 7.3, reaction 11). When sugars are supplied in abundance, glycogen-like intracellular polysaccharides (IPSs) can be formed from glucose 6-phosphate and stored as endogenous energy reserves. These polysaccharides can be utilized when supplies of exogenous sugars are limiting, such as overnight, resulting in further acid production. *Streptococcus* and *Actinomyces* strains with a high activity of IPS formation therefore possess several acidogenic pathways.

The acidic end-products formed by bacterial sugar metabolism can be further degraded by some members of dental biofilm bacteria. For example, *Veillonella* species utilize lactate as an energy and carbon source under anaerobic conditions and produce propionate, acetate, and formate, together with hydrogen gas and carbon dioxide. Lactate can also be utilized by *Actinomyces* and lactobacilli under aerobic conditions and converted to acetate and carbon dioxide. Formate and hydrogen gas can be used as energy sources and electron donors in metabolic reactions by other biofilm bacteria such as *Campylobacter rectus*.

Sucrose can also be converted by the bacterial enzymes glucosyltransferases and fructosyltransferases into glucans and fructans. Water-insoluble glucans produced by mutans streptococci are called mutan. Both glucans and fructans can consolidate bacterial attachment and contribute to the biofilm matrix but these latter polysaccharides can also be metabolized and used as extracellular nutrient storage compounds (Fig. 7.3, reactions 13 and 14).

Dental biofilms: development, structure, composition, and properties

In order to persist, oral microorganisms have to attach to a surface and grow to form a biofilm, otherwise they will be lost from the habitat. The properties of bacteria growing as a biofilm are distinct from those expressed when the same organisms are growing in liquid culture (planktonic cells) [18, 57, 58]. In the dental literature, the terms dental plaque and dental biofilm are often used interchangeably, but throughout this chapter we have purposely used the term *biofilm* to signify the common features among biofilms forming on teeth and biofilms forming in other natural environments.

Development and structure of young dental biofilms

The development of dental biofilms can be divided into several arbitrary stages, as revealed by experimental studies in situ [68]:

- pellicle formation;
- attachment of early bacterial colonizers (0–24 h);
- co-adhesion and growth of attached bacteria leading to the formation of microcolonies (4–24 h);
- microbial succession leading to increased species diversity concomitant with continued co-adhesion and growth of microcolonies (1–7 days);
- climax community/mature biofilm (1 week or older).

Figures 7.4 and 7.5 Scanning electron micrographs demonstrating microbial colonization of human enamel 4 h after cleaning [70]. Figure 7.4: After 4 h exposure the enamel is covered by pellicle, which is a granular deposit, primarily located in Tomes' processes pits (TP) and in perikymatal grooves (P). Figure 7.5: The first bacteria to colonize the tooth surface are of the coccobacillary type (B). Note that the granular deposit does not cover the tooth surface in a uniform layer (PE). Reproduced with permission of John Wiley & Sons.

It should be appreciated that biofilm formation is a highly dynamic process, and that attachment, growth, removal, and reattachment of bacteria may occur at the same time.

Pellicle formation

Microorganisms do not directly colonize the mineralized tooth surface. The teeth are always covered by an acellular proteinaceous film; this is the pellicle that starts to form on a cleaned tooth surface within minutes (Figs 7.4 and 7.5). In uncolonized areas the pellicle reaches a thickness of 0.01–1 μm within 24 h. The major constituents of the pellicle are salivary glycoproteins, phosphoproteins, lipids, and, to a lesser extent, components from the GCF [45] (see Chapter 6). Remnants of cell walls from dead bacteria, and other microbial products (e.g., glucosyltransferases and glucans), have also been identified in the pellicle. Some salivary molecules undergo conformational changes when they bind to the tooth surface; this can lead to exposure of new receptors for bacterial attachment (cryptitopes; see later). The pellicle is primarily located corresponding to depressions in the enamel (pits and perikymatal grooves), but it does not completely mask the anatomical characteristics of the enamel surface. Whenever bacteria are encountered at this early stage they are of the coccoid or cocco-bacillary type, mainly streptococci and *Actinomyces* [22, 23], and always reside in shallow depressions on the surface (Fig. 7.5).

The pellicle plays an important modifying role in caries and erosion because of its permeable-selective nature restricting transport of ions in and out of the dental hard tissues. The presence of a pellicle inhibits subsurface demineralization of enamel *in vitro* [100]. Frequent rinses with milk or cream increase the thickness and electron density of the pellicle [69], but it is not clear whether such modification of the pellicle provides additional protection against demineralization of the enamel.

The composition of the pellicle has received considerable interest because of its potential role in determining the composition of the initial microflora. It is most likely that, once the early colonizers have attached, the local oral environment determines which bacteria can grow and accumulate on a tooth surface [61].

Pattern of early bacterial colonization (attachment and growth)

As the microbial cell approaches the pellicle-coated surface, long-range but relatively weak physico-chemical forces between molecules on the two surfaces are generated. Initially, bacteria are held nonspecifically close to the tooth surface under the net influence of van der Waal's attractive forces as well as repulsive electrostatic forces. Within a short time, these weak physico-chemical interactions may become stronger if *adhesins* on the microbial cell surface engage in specific, short-range interactions with complementary *receptors* in the acquired pellicle. A high degree of surface hydrophobicity may facilitate attachment. Recently, it has been suggested that extracellular DNA may also be involved in the adhesion processes [37].

The selective manner by which bacteria attach to the tooth surface supports the fact that bacteria contain a recognition system on their surfaces that enables bacterial surface adhesins to bind to complementary molecules (receptors) in the pellicle [30] (Fig. 7.6). Some receptors have been identified as oligosaccharides on the protein backbone of the pellicle glycoproteins. For example, *S. sanguinis* and *S. oralis* bind specifically to terminal sialic acid residues in human salivary glycoproteins. In addition, *S. oralis* has a galactose-binding adhesin. *Actinomyces naeslundii* possesses surface appendages termed fimbriae; type 1 fimbriae mediate adherence to proteins such as proline-rich protein and statherin in the pellicle (i.e., protein–protein interactions). *Actinomyces* species can also bind to galactosyl residues in glycoproteins exposed as a result of enzymic action of bacterial neuraminidases. The modification of pellicle constituents, either enzymically (e.g., by neuraminidase) to expose new receptors or by conformation changes following adsorption to a surface to reveal previously hidden receptors (termed *cryptitopes* [31]), is an important factor in the regulation of colonization. Knowledge of the biochemical mechanisms involved in attachment could potentially be exploited to develop biofilms with reduced acidogenic properties, for example, by using molecules to saturate receptors used by aciduric bacteria, thereby blocking their adhesion.

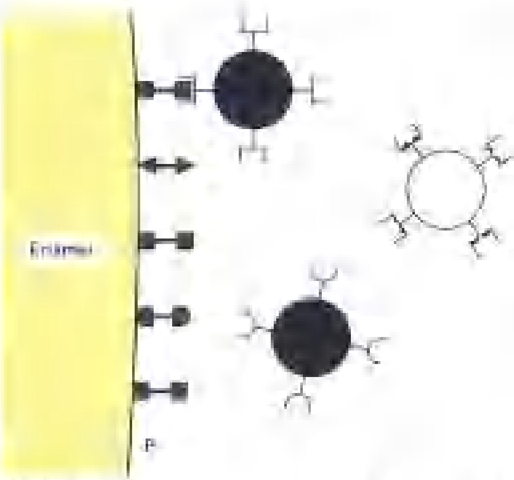
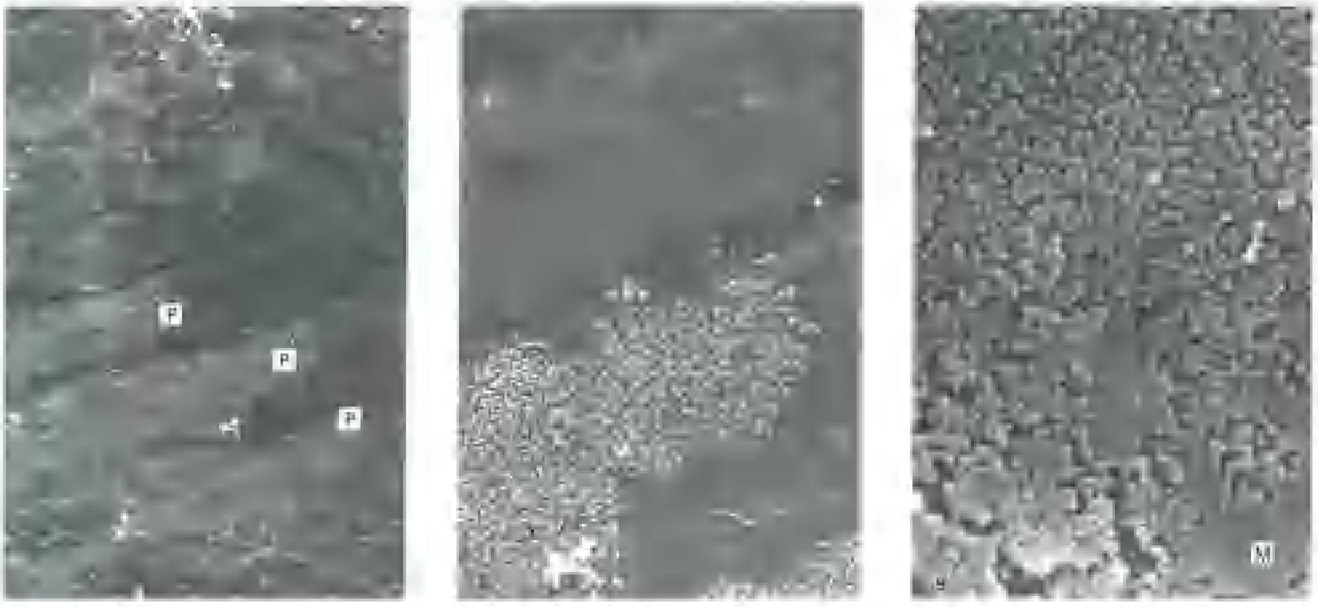


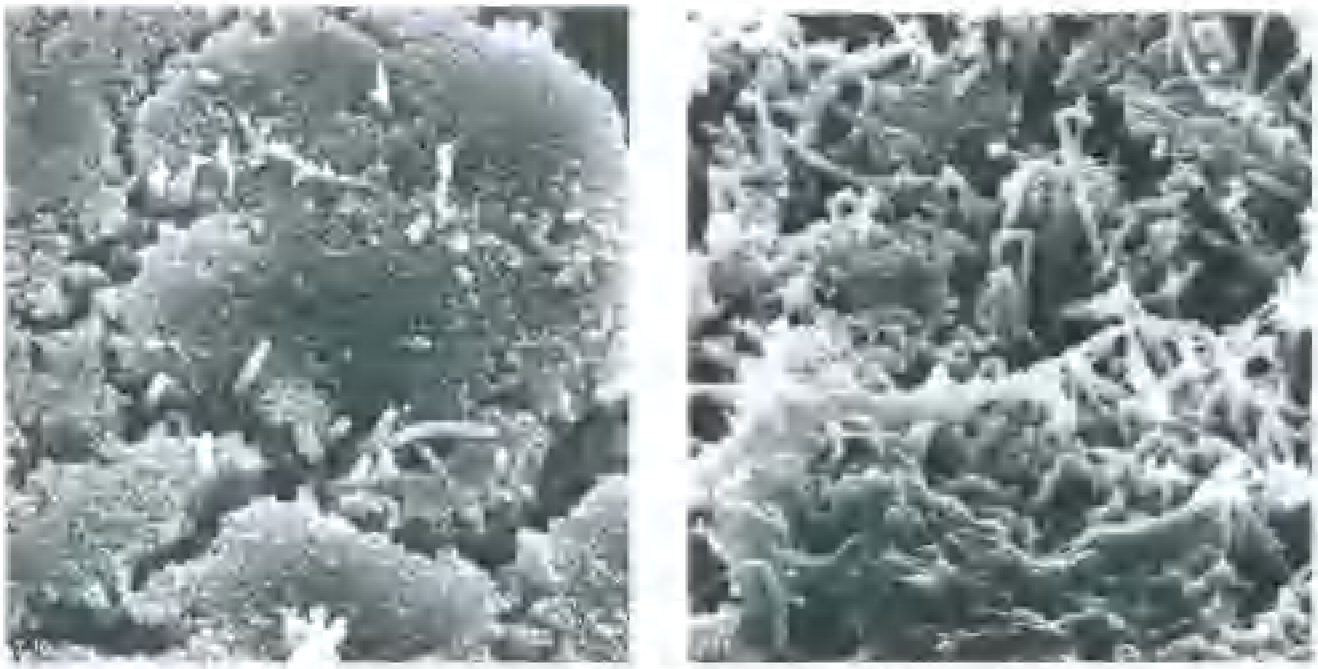
Figure 7.6 Simplified explanation of the principle of selective adherence of bacteria to enamel. Successful irreversible attachment is achieved when adhesins on the surface of a bacterium bind to a receptor in the pellicle (P).

After 8 h only a few groups of microorganisms are found on the surface, sheltered by the perikymata. Numerous bacteria, many of which occur in a stage of division, spread across the surface as a monolayer (Figs 7.7 and 7.8). A rapid increase in the number of bacteria is only observed after 8–12 h. In some areas, multiplying microorganisms form multilayers (Fig. 7.9) in which the individual organisms are embedded in an intermicrobial matrix. Within 1 day the tooth surface is almost completely covered by a blanket of microorganisms. However, the microbial deposits are not uniform in thickness. Areas of monolayers are intermingled with multilayers, and some uncolonized areas are still covered by a thick, bacteria-free pellicle. At this early stage of colonization, Gram-positive and Gram-negative bacteria are not organized according to any particular pattern.

After 1 day the surface of the biofilm is mainly made up of coccoid bacteria with scattered filaments (Fig. 7.10). However, during the course of the second day the biofilm becomes colonized by multiple filamentous organisms with a perpendicular orientation to the surface (Fig. 7.11).



Figures 7.7–7.9 Scanning electron micrographs demonstrating microbial colonization of human enamel 12 h after cleaning [28]. Figures 7.7 and 7.8: In 12-h-old biofilms the microorganisms spread in a monolayer along the perikymata (P). Figure 7.9: The monolayer of bacteria (upper part) is gradually replaced by a multilayer of cells (lower part) which is embedded in an intermicrobial matrix (M). Reproduced with permission of John Wiley & Sons.



Figures 7.10 and 7.11 Distinct morphological changes may be recorded on the surface of the biofilms when comparing the microflora on teeth after 24 h (Fig. 7.10) and 48 h (Fig. 7.11). Whereas the 24-h-old biofilm comprises a mass of coccoid bacteria from which a few filaments extend, the 48-h-old microflora is almost entirely dominated by filamentous organisms [70]. Reproduced with permission of John Wiley & Sons.

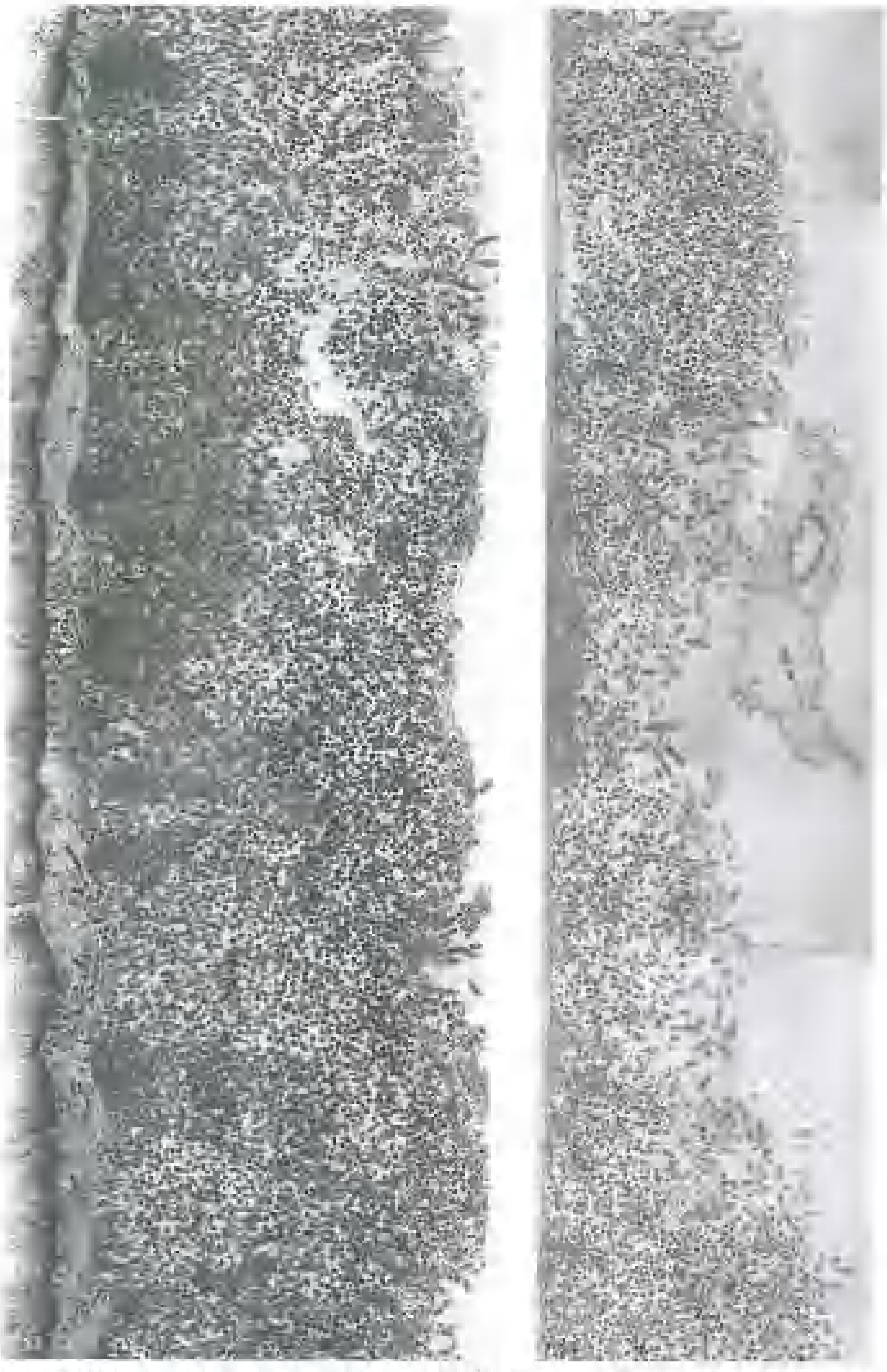
Colonization of root surfaces follows similar principles to those outlined for enamel surfaces, but growth of the microflora proceeds more rapidly on root surfaces because of the uneven surface topography. After 2 days the thickness of the microbial deposits varies distinctly across enamel surfaces, probably reflecting the undulating pattern of the perikymata, whereas on root surface the biofilm exhibits a more homogeneous thickness (Figs 7.12 and 7.13).

Irrespective of the type of tooth surface (enamel or root), the initial colonizers constitute a highly selected part of the oral microflora, and are mainly *S. sanguinis*, *S. oralis* and *S. mitis* biovar 1 (Fig. 7.14) [46, 73, 74]. Together, these three streptococcal species may account for 95% of the streptococci and 56% of the total initial microflora. In addition, the initial microflora includes *Actinomyces* spp. and Gram-negative bacteria; for example, *Haemophilus* spp. and *Neisseria* spp. Interestingly, mutans streptococci do not contribute significantly to the early biofilm formation *in vivo*, in spite of these species being able to form thick adherent biofilms in test tubes *in vitro*. The early colonizers start to multiply and form microcolonies that will eventually coalesce to form a confluent biofilm. The early colonizers use endogenous molecules (e.g., the proteins, peptides, amino acids, and glycoproteins found in saliva) as their main source of nutrients, and the growth rate of oral bacteria is fastest during the early stages of colonization. The metabolism of the early colonizers changes the environment in the developing biofilm, making conditions suitable for the growth of later colonizers.

Microbial succession

As the biofilm matures, the most striking change is a shift from a *Streptococcus*-dominated community to a plaque dominated by *Actinomyces* [86]. Thus, the initial establishment of a streptococcal microbial community appears to be a necessary antecedent for the subsequent proliferation of other organisms. Such population shifts are known as microbial succession.

The principle of microbial succession is, briefly, that pioneer bacteria create an environment that is either more attractive to secondary invaders or increasingly unfavorable to themselves because of a lack of nutrients, accumulation of inhibitory metabolic products, and/or increase in anaerobiosis, and so on. In this way the resident microbial community is gradually replaced by other species more suited to the modified habitat. The secondary colonizers also attach to the established pioneer species via adhesin–receptor interactions (*co-adhesion*) [42]. For example, type-2 fimbriae on *A. naeslundii* are involved in co-adhesion with other oral bacteria by lectin-like interactions (i.e., carbohydrate–protein interactions). *Fusobacterium nucleatum* can co-adhere to all of the early colonizing bacteria, while many later colonizers (especially some of the anaerobic species) can co-adhere to *F. nucleatum*. This organism is described as being an important 'bridging organism' between early and later colonizers. During the initial days, biofilm growth occurs predominantly as a result of cell division, as evidenced by the development of columnar microcolonies perpendicular to the tooth surface [22].



Figures 7.12 and 7.13 Forty-eight-hour old biofilms on root cementum (Fig. 7.12) and enamel (Fig. 7.13) surfaces from the same individual. Note that the microbial biofilms are thicker and more densely packed on root cementum [67].

However, continuous adsorption of single microorganisms from saliva (co-adhesion) also contributes to the expansion of the biofilm. In the surface layer, characterized by high species diversity, some microorganisms co-aggregate with other species to form 'bristle brushes' or 'corn cob' structures (Fig. 7.15). The 'corn cobs' are composed of a central filament coated with spherical organisms and appear to have a direct interspecies relationship mediated by surface fibrils (Fig. 7.16).

As dental biofilms develop, some of the bacteria produce polysaccharides, especially from the metabolism of sucrose (Fig. 7.3), and these contribute to the biofilm matrix. The biofilm matrix is not just a physical scaffold that helps to support the structure of the biofilm; the matrix is also biologically active and is involved in retaining nutrients, water (thereby preventing desiccation), and key enzymes within the biofilm [11]. As the composition of the developing biofilm becomes more diverse, the bacteria can interact both in a conventional biochemical manner and via specific signaling molecules. These will be described in more detail in a later section.

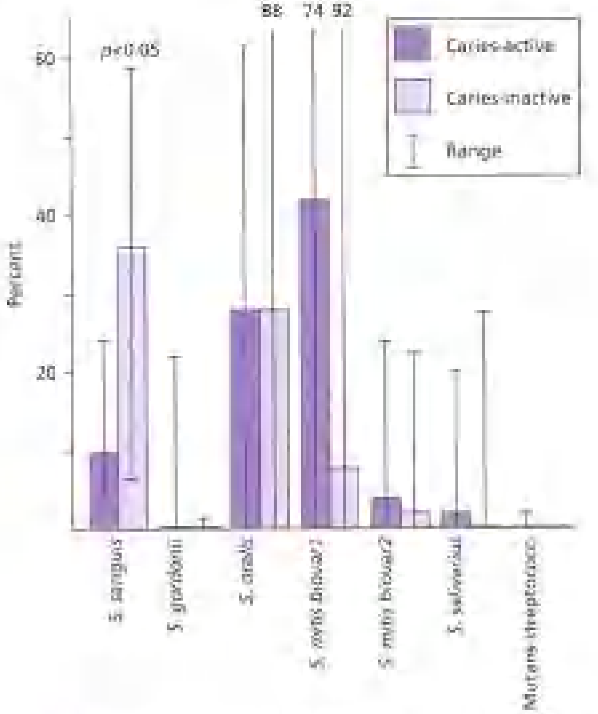


Figure 7.14 Proportions of various streptococci (%) from 4 h dental biofilm in caries-active and caries-inactive individuals [74]. Reproduced with permission of Karger Publishers.

As the biofilm become thicker, a lowering of the oxygen concentration (increased anaerobiosis) is one of the factors that helps to drive microbial succession. Thus, in developing coronal plaque, a progressive shift is observed from mainly aerobic and facultatively anaerobic species in the early stages, to a situation in which facultatively and obligately anaerobic organisms predominate after 9 days (Fig. 7.17) [81].

Microbial composition and structure of the climax community (mature biofilm)

Environmental conditions on teeth are not uniform. Differences exist in the degree of protection from oral removal forces and in the gradients of many biological and chemical factors (e.g., salivary film velocity, glucose- and

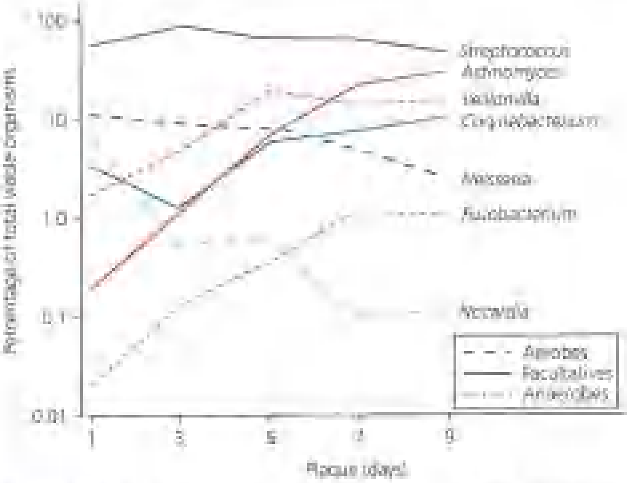


Figure 7.17 Relative proportions of selected microorganisms in developing coronal biofilms (days 1–9) in relation to the atmospheric requirement. Data adapted from [81].

Figures 7.15 and 7.16 Some bacteria in the surface of dental biofilms co-aggregate to form 'corn cob' structures (Fig. 7.15). Individual 'corn cobs' are composed of a central filament covered by spherical microorganisms (Fig. 7.16, cross-section) [72]. Reproduced with permission of John Wiley & Sons.

Table 7.1 Composition of biofilms at distinct surfaces on sound teeth.

	Percentage viable count (range)		
Bacterium	Fissures	Approximal surfaces	Gingival crevice
Streptococcus	8–86	<1–70	2–73
Actinomyces	0–46	4–81	10–63
An G+R	0–21	0–6	0–37
Neisseria	–*	0–44	0–2
Veillonella	0–44	0–59	0–5
An G-R	±*	0–66	8–20
Treponema	—	—	+
Environment:			
Nutrient source	Saliva & diet	Saliva, diet, & GCF	GCF
pH	Neutral–low	Neutral–low	Neutral–high
Eh	Positive	Slight negative	Negative

An G+R, An G-R: obligately anaerobic Gram-positive and anaerobic Gram-negative rods, respectively; GCF: gingival crevicular fluid; Eh: redox potential (a measure of the extent of anaerobiosis).
*Detected occasionally.

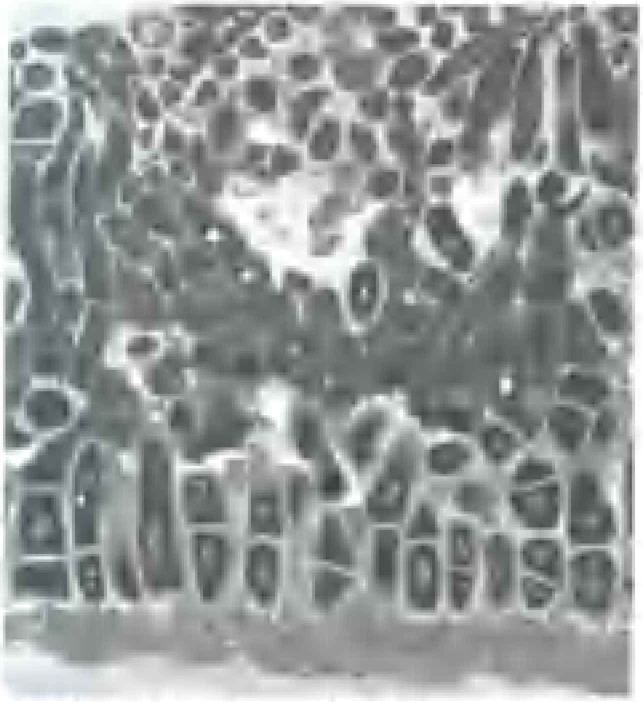


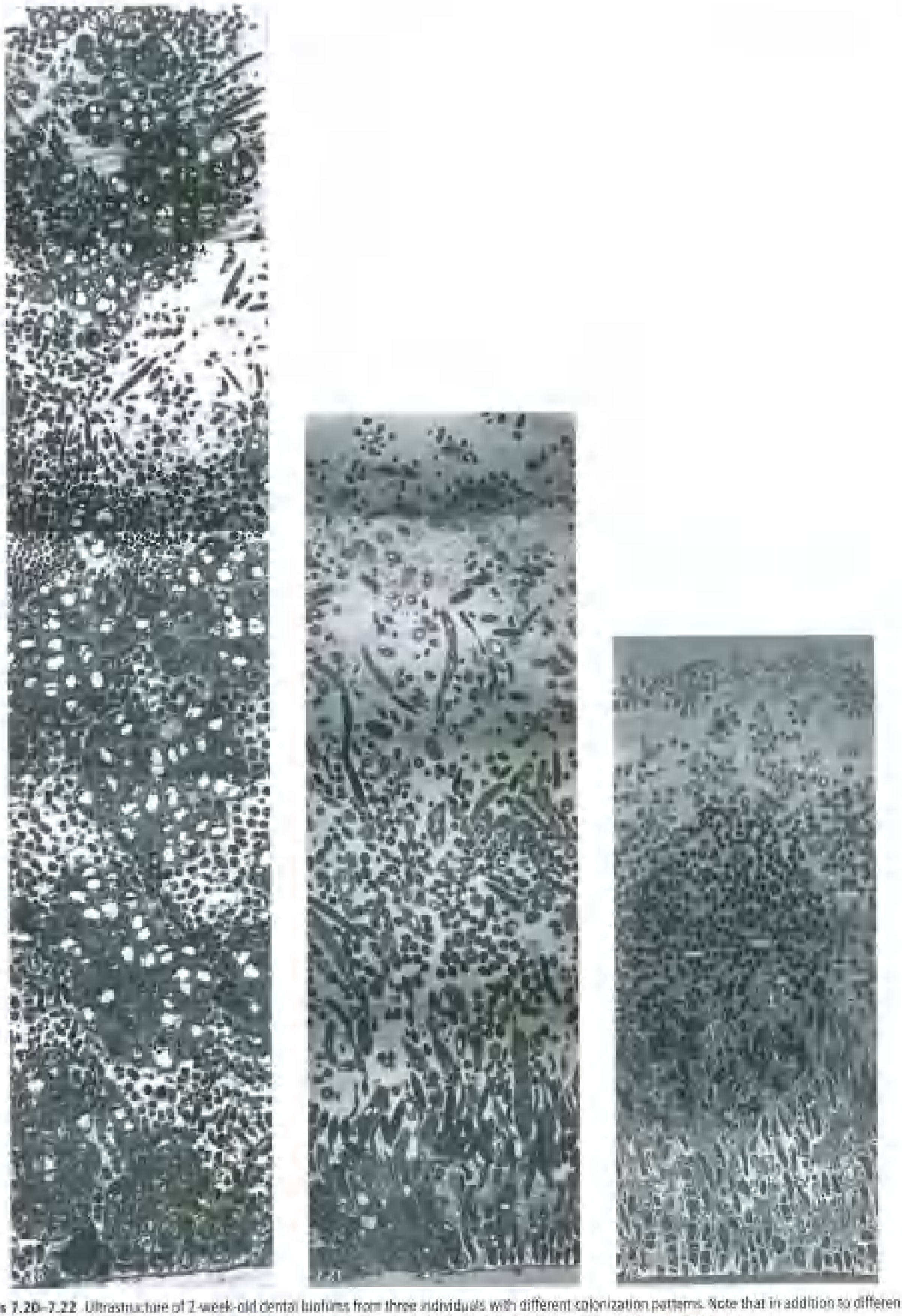
Figure 7.18 Densely packed pleomorphic bacteria resembling *Actinomyces* form palisades along the tooth surface in 3-week-old dental biofilms [71]. Reproduced with permission of Karger Publishers.

hydrogen-ion concentrations, pH) that influence the growth of the resident oral microflora on particular surfaces [27]. These differences will be reflected in the composition of dental biofilms, particularly at sites so obviously distinct as approximal surfaces, occlusal fissures, and gingival crevice. The predominant bacterial genera at these sites is shown in Table 7.1, but a full description of the dental microflora at specific sites is beyond the scope of this chapter, and readers will be referred to specialized papers, or a more general text book; for example, Marsh and Martin [60].

The composition of dental biofilms is diverse, and includes a range of Gram-positive and Gram-negative bacteria, most of which are facultatively or obligately anaerobic. Of relevance to dental caries is the presence in dental biofilms of high numbers of acid-producing Gram-positive cocci, such as low-pH, non-mutans streptococci, and mutans streptococci (*Streptococcus mutans*, *Streptococcus sobrinus*; see later), and Gram-positive rods, such as *Actinomyces* spp. and lactobacilli. However, as pointed out previously, the acidogenic potential of these bacteria can be reduced by other organisms in plaque, such as *Veillonella* spp., which convert lactic acid to weaker acids as part of a food chain, or by bacteria generating alkali from arginine (*S. sanguinis*) or urea (*S. salivarius*, *A. naeslundii*) (Fig. 7.3). This demonstrates the complexity of the challenge when attempting to find correlations between the microbial composition of dental biofilms and the development of caries (see later), and illustrates how disease may be due to the outcome of many interactions among different types of bacteria.

As the biofilm becomes older, characteristic structural changes are noted at the bottom of the biofilm. The most striking change is the formation of an inner layer of densely packed Gram-positive pleomorphic bacteria next to the tooth surface (Fig. 7.18). These bacteria, which have now been identified as *Actinomyces* (Fig. 7.19) [23], are found in close connection with both enamel and root surfaces. *Actinomyces* colonization in this particular niche might help to support homeostasis of the biofilm by converting lactate into weaker acids. The outer part of mature biofilms is usually more loosely structured and varies in composition (Figs 7.20–7.22) [71]. In some individuals the outer microflora may be organized in spheres of one particular type of organism (Fig. 7.20) whereas, in others layers different bacterial species are organized roughly parallel to the tooth surface

Figure 7.19 Fluorescence in-situ hybridization of two-dimensional dental biofilm showing *Actinomyces* (blue), streptococci (green), and other bacteria (red). Note preferential colonization of *Actinomyces* in the inner layer of the biofilm. Courtesy of Irene Dige [21].



Figures 7.20–7.22 Ultrastructure of 2-week-old dental biofilms from three individuals with different colonization patterns. Note that in addition to differences in thickness, the outer part of the biofilms varies in composition and structure [71]. Reproduced with permission of Karger Publishers.

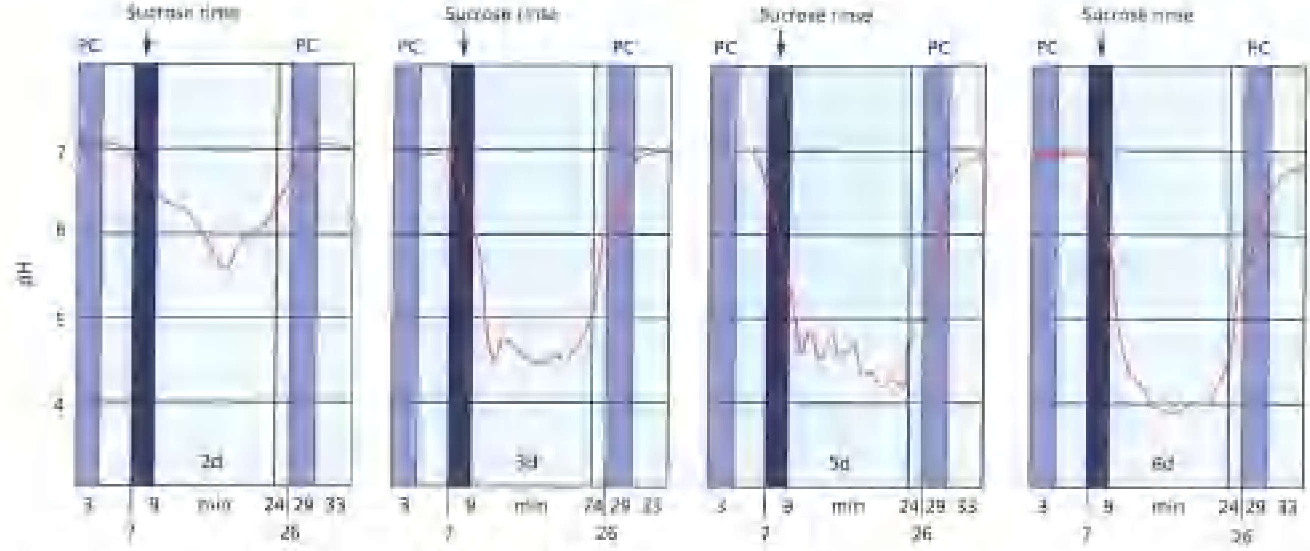


Figure 7.23 Telemetrically recorded pH changes of 2-, 3-, 5-, and 6-day-old interdental biofilms in a 62-year-old male volunteer during and after 2-min rinses with 10% sucrose solution. PC: paraffin chewing. Note that the rate and amount of acid formation increase with the age of the biofilm. Adapted from [36]. Reproduced with permission of the American Academy of Pediatric Dentistry.

(Fig. 7.22). In some cases the outer biofilm is loosely structured and does not show any characteristic pattern (Fig. 7.21).

Irrespective of the dominating pattern of colonization, the bacteria are embedded in an intermicrobial matrix of highly varying amount and electron density. This heterogeneous composition, combined with the observation that young dental biofilms contain fluid-filled channels and voids [99], is believed to create concentration gradients and influence the diffusion properties of biofilms. For example it has been shown that short-term exposures to fluoride solutions (1 000 ppm F⁻) for 30 or 120 s (equivalent to toothbrushing) result in restricted penetration of fluoride into 7-day-old dental biofilms [97]. Thus, the caries-controlling effect of fluoride delivery from toothbrushing may be reduced where oral hygiene is poor.

Dental biofilms must be up to 2 days old before the acid formation in response to a sucrose challenge is sufficient to cause demineralization of the enamel (Fig. 7.23) [36]. However, this does not mean that people should refrain from cleaning their teeth every day. Most individuals are not able to clean their teeth perfectly every time they brush, and bacteria left on the teeth at inaccessible sites may contribute to continued biofilm growth and acid production when toothbrushing is insufficient.

Properties of dental biofilms

Novel imaging and molecular techniques have confirmed that dental biofilms display properties that are consistent with those of biofilms present in other natural habitats (Table 7.2). Thus, the free movement of molecules can be reduced in oral biofilms which, coupled with bacterial metabolism, leads to gradients in key factors (oxygen, nutrients, pH, etc.) over short distances throughout the depth of the biofilm. The use of live/dead stains has shown that bacterial vitality varies, with the greatest concentration of viable microorganisms present in the central parts of the biofilm, and lining any voids or channels.

Table 7.2 Properties of biofilms and microbial communities.

General property	Dental biofilm example
Open architecture	Presence of channels in dental plaque
Protection from host defenses, desiccation, etc.	Production of extracellular polymers to form a functional matrix; physical protection from phagocytosis
Enhanced tolerance to antimicrobials	Reduced sensitivity to chlorhexidine and antibiotics; transfer of resistance genes; microbial community effects provide mutual protection (see below)
Neutralization of inhibitors	Catalase production by neighboring cells to protect sensitive organisms from hydrogen peroxide
Novel gene expression[a]	Synthesis of novel proteins upon attachment; upregulation of glucosyltransferases in mature plaque
Cell–cell signaling	Production of bacterial cell–cell signaling molecules (e.g., competence stimulating peptide) to coordinate gene expression
Spatial and environmental heterogeneity	pH & O_2 gradients; co-adhesion between distinct bacterial species
Broader habitat range	Oral obligate anaerobes grow in an overtly aerobic environment; acid-sensitive species survive
More efficient metabolism	Complete catabolism of complex host macromolecules (e.g., mucins) by consortia; development of microbial food webs
Enhanced virulence	Pathogenic synergism in abscesses

[a] A consequence of altered gene expression can also be an increased tolerance to antimicrobial agents.

Culture-independent approaches (e.g., 16S rRNA gene amplification; fluorescent in-situ hybridization) have also demonstrated an increased richness in bacterial diversity in dental biofilms, with many novel and currently unculturable bacteria being described for the first time; for examples, see Paster *et al.* [77], Becker *et al.* [12], and Dewhirst *et al.* [20].

There are direct- and indirect-mediated changes in bacterial gene expression during biofilm development. For example, the binding of oral bacteria to salivary proteins can induce genes encoding adhesins. During the initial stages of *in vitro* biofilm formation by *S. mutans* (first 2 h following attachment), 33 proteins were differentially expressed (25 proteins upregulated; eight proteins down-regulated; i.e., this is a direct effect following attachment to a surface), and there was an increase in the relative synthesis of enzymes involved in carbohydrate catabolism [98]. In contrast, some glycolytic enzymes were down-regulated in older (3 days) *S. mutans* biofilms, while proteins associated with other biochemical functions were upregulated [85]. Expression of glucosyltransferases by *S. mutans* was markedly upregulated in older biofilms, but this was assumed to be due to indirect effects of biofilm formation (e.g., nutrient limitation, reduced pH) [17]. As biofilms develop, there are increasing opportunities for cells to interact both with each other via cell signaling systems and with other species in a range of conventional synergistic and antagonistic biochemical interactions (Table 7.3).

It is clear from the above statements that the behavior of microorganisms on a surface as part of a biofilm can be very different to that observed in the laboratory in conventional homogeneous liquid culture growth systems (planktonic culture). Of particular clinical relevance is the finding that the sensitivity of oral bacteria to antimicrobials is reduced during growth on a surface, particularly in mature biofilms. Thus, four times the concentration of chlorhexidine was necessary to kill older compared with younger biofilms of *S. sanguinis*. Similarly, biofilms of diverse mixed cultures of oral bacteria were unaffected by concentrations of chlorhexidine that were equivalent to the minimum inhibitory concentration (MIC) of the component species (as determined in liquid culture). Tenfold higher concentrations were needed to demonstrate some effectiveness, but even at these elevated levels some species were unaffected [40]. Similar findings have been reported with other antimicrobial agents used in toothpastes and mouthrinses, while up to 500 times the MIC of amoxicillin and doxycycline (as determined for liquid cultures) was required to eliminate *S. sanguinis* biofilms [44]. Studies of natural plaque biofilms showed that chlorhexidine only affected the outer layers of cells in 24 h and 48 h biofilms, suggesting either quenching of the agent at the biofilm surface or a lack of penetration [101]. Such observations may partly explain why antimicrobial treatment has so far not been a totally successful approach to the control of dental caries.

Table 7.3 *Microbial interactions in dental plaque*

Beneficial	Antagonistic
Enzyme complementation	Nutrient competition
Food chains/food webs	Production of:
Coadhesion	• bacteriocins
Inactivation of inhibitors	• hydrogen peroxide
Subversion of host defenses	• organic acids
	Low pH generation

Dental plaque is not only an example of a biofilm, but it also functions as a microbial community; that is, as a consortium of interacting microorganisms [58]. The significance of this is that the properties of a microbial community are more than the sum of those of the constituent species (Table 7.2). In a complex biofilm such as dental plaque, populations of bacteria are in close proximity to one another and interact as a consequence. These interactions can be beneficial to one or more of the interacting species, while others can be antagonistic (Table 7.3). As stated earlier, the production of antagonistic compounds is a mechanism by which exogenous microbial species can be excluded from the mouth (colonization resistance). In addition, the production of inhibitors can provide an organism with a competitive advantage when interacting with other community members. Although competition for nutrients will be a highly significant factor in determining the prevalence of a species within a habitat such as the mouth, it has been proven that bacteria also have to collaborate in order to completely catabolize host-derived, biochemically complex nutrients such as salivary mucins. The concerted and sequential actions of individual species with complementary patterns of glycosidase and protease activity are required to fully metabolize such glycoproteins. Likewise, a primary feeder (an organism that initially metabolizes a substrate) generates products that can be metabolized to even simpler products by secondary feeders (organisms that utilize the products generated by the metabolism of primary feeders), thereby generating food chains [15]. A classic example is the utilization of lactate by *Veillonella* spp. produced from the metabolism of sugars by saccharolytic bacteria (Fig. 7.3). Such metabolic interdependencies are likely to make a major contribution to the maintenance of microbial homeostasis in dental plaque.

Some dental biofilm bacteria can secrete small, diffusible signaling molecules that enable them to coordinate their activities. Gram-positive bacteria use small peptides, and *S. mutans* synthesizes a competence stimulating peptide. This peptide is believed to enhance acid tolerance and induce genetic competence in neighboring cells of *S. mutans*, so that the ability to take up DNA (transformation) was greater for biofilm-grown cells. Thus, bacteria may be able to transfer genetic material more readily in biofilms, including virulence or antibiotic resistance traits. Different communication systems operate among Gram-negative bacteria (e.g., they use auto-inducer-2; AI-2), and these may operate among many genera of bacteria to coordinate gene expression, emphasizing the need to view plaque as a consortium of microorganisms working in a partnership. Biofilms also facilitate communication via horizontal gene transfer (see [58]). Evidence of horizontal gene transfer between resident oral bacteria (*S. mitis*, *S. oralis*) and opportunistic pathogens (*Streptococcus pneumoniae*) has come from the identification of penicillin resistance genes with a common mosaic structure, which also emphasizes the need for caution if prescribing antibiotics.

Microbial metabolism within plaque produces localized gradients in factors affecting the growth of other species (e.g., pH, dissolved oxygen, essential nutrients, and the accumulation of products of metabolism and inhibitors) [55]. In this way, bacteria are able to modify their local environment. These gradients lead to the development of environmental heterogeneity, and ensure the coexistence of species that would be incompatible with one another in a homogeneous habitat, enabling a more diverse microbial community to establish. Microbial communities display a wider habitat range and demonstrate an increased metabolic efficiency than might be predicted from laboratory data generated from pure culture studies [59]. Microbial communities are also better able to cope with minor environmental perturbations and stresses, and, in some instances, the component bacteria demonstrate an enhanced pathogenic potential ('pathogenic synergism'), which is often seen in dental abscesses, which generally have a polymicrobial etiology.

Caries microbiology: a brief historical perspective

Over a century ago, Dr W.D. Miller [43] recognized the role of the resident oral microflora in caries. Miller introduced the so called 'chemico-parasitic' theory of caries by suggesting that in order for caries to develop 'two factors always have to be in operation: the action of acids and the action of germs'. However, unlike his contemporary colleagues (G.V. Black and J.L. Williams), Miller was not aware of the crucial etiological role of the dental biofilm and believed that the bacteria producing organic acids were mainly living in saliva. It was not until after the end of the 1940s, with the development of antibiotics, that experimental studies using germ-free animals provided a further insight into the microbiology of caries. Experiments showed that rodents developed caries when infected with specific bacteria, and that caries could be transmitted from animal to animal, while other studies proved the essential role of fermentable sugars in the diet [29, 39]. Bacteria could be ranked in terms of their cariogenicity, and the most cariogenic group were the mutans streptococci, especially *S. mutans* and *S. sobrinus*. The role of bacteria was also confirmed in treatment studies. Antibiotics and immunization against the inoculated strain caused a decrease in the numbers of both bacteria in plaque and in caries lesions compared with control animals. It is important to understand, however, that the experimental conditions applied in the above studies were highly artificial as in most studies the animals were inoculated with only a single bacterial strain. This experimental setup is very different from the human oral cavity that contains a community of interacting bacteria. Nevertheless, in spite of these limitations, such observations were taken to indicate by leading scientists that dental caries is a specific infection with mutans streptococci as the main 'pathogens' [48, 93], a view that is still prevalent in many countries today.

However, dental caries does not fulfill the classical principles of a specific infectious disease [26]. Historically, for a microorganism to be considered responsible as an etiological agent for a disease, it would need to satisfy Koch's postulates. Thus, the microorganism should be:

- found in all cases of the disease, with a distribution corresponding to the observed lesions;
- the organism should be grown on artificial media for several subcultures; and
- a pure subculture should produce the disease in a susceptible animal.

As stated previously, the relationship between mutans streptococci and caries is not absolute. Relatively high proportions of mutans streptococci may survive on tooth surfaces without caries developing, while the opposite is also true; that is, caries may arise in the apparent absence of these organisms [60, 68]. Therefore, rather than necessarily initiating the caries process, an outgrowth of mutans streptococci may reflect a disturbance in the homeostasis of the dental biofilm. If the homeostatic balance is disrupted, changes in the relative proportions of the microorganisms making up the microbial community can occur, and this could predispose a site to disease (an 'opportunistic infection'). Hence, it may be more appropriate to think about dental caries as an 'endogenous infection' or as an example of a (minor) 'ecological catastrophe' (see later) [56].

Methodological problems in microbiological studies of dental caries

The high species diversity of dental biofilms makes it rather laborious to perform microbiological studies of caries. Therefore, for many years, with an easy access to selective culture media, some researchers studied only the primary suspects of caries: mutans streptococci and lactobacilli. In view of the discussion above, it should be clear, however, that such a simplified microbiological approach could be very misleading when trying to understand the etiology of caries.

Traditionally, the composition of dental biofilms has been determined by growing the constituent organisms on a range of selective and nonselective agar plates incubated under appropriate conditions, for various lengths of time. The identity of the resultant microbial colonies is achieved by the application of physiological, biochemical, and serological tests. However, recent comparisons of total viable versus total microscopic counts have demonstrated that only about 40–50% of the oral microflora can be cultivated, and that many groups of microorganisms are being underestimated. Many contemporary studies are now using culture-independent (molecular) approaches in which DNA (mainly 16S rRNA gene sequences) is amplified from a specimen of dental plaque using universal primers, partially sequenced, and compared with known sequences in international databases. Novel organisms, and organisms previously found only in low numbers using culture, have been identified, particularly from advanced lesions (see later).

Attention should also be given to the study design when evaluating the results of microbiological investigations of caries. Evidence for the role of plaque bacteria in dental caries in humans has come from both cross-sectional and longitudinal studies in which the microbial composition of plaque is related to the integrity of the underlying tooth surface (Fig. 7.24). In cross-sectional studies, tooth surfaces are sampled at a single time point, and the microbial composition of plaque is related to the caries status of the tooth surface at that time. A limitation of this type of study is that it cannot be established whether the species that are isolated at the time of lesion diagnosis caused the decay or are present as a result of the lesion; thus, these studies only demonstrate *associations*. In contrast, longitudinal studies regularly sample, over a set period, surfaces that are initially clinically sound but a proportion of which will develop caries over the course of the study. The microflora can then be compared (i) at the same site before and after the diagnosis of a lesion and (ii) between those surfaces that decayed and those that remained caries free throughout the study. This type of study design is more expensive and difficult to conduct, but is more likely to establish *cause-and-effect relationships*. Both the cross-sectional and the longitudinal study designs suffer from the fact that it is often difficult to determine exactly when a noncavitated lesion may be detected clinically, as this is essentially a question about the refinement of the diagnostic method (Chapter 10). Likewise, in longitudinal studies of lesion development, the clinical caries diagnostic criteria applied should be sensitive enough to reflect changes in lesion activity (Chapter 11). Alternatively, lesion development may be evaluated by using an experimental in-situ model in which the mineral content of natural tooth surfaces, worn in intra-oral appliances of human volunteers, is monitored in parallel with changes in the composition of the biofilm [75].

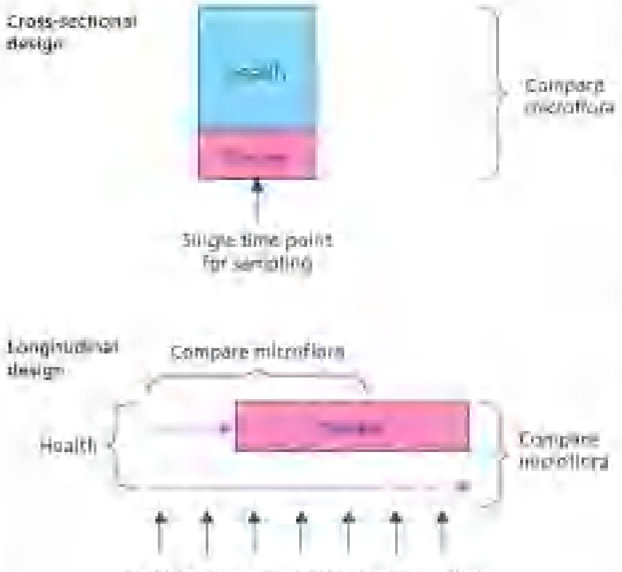


Figure 7.24 Distinction between cross-sectional and longitudinal study designs to investigate the role of dental biofilm bacteria in caries. Cross-sectional studies are relatively quick and easy to perform on different population groups, but they only show associations between the microflora and caries because each site is sampled only at a single time point. Longitudinal studies provide more insights into the microbial ecology of dental caries because the microflora can be compared (a) before and after the diagnosis of a lesion and (b) between sites that developed caries and those that remained caries free. All sites to be investigated are clinically caries free at the start of sampling.

Most studies still rely on conventional culture of the biofilm, with some only focusing on the detection of the main suspected pathogens (i.e., mutans streptococci and lactobacilli), with the risk that this can become a *self-fulfilling prophecy*. The recent development of an appropriate growth medium for the recovery and culture of oral bifidobacteria has led to several studies that now implicate this group of acid-producing and acid-tolerating bacteria with caries in both children [52] and older adults [6]. Some contemporary studies are now deploying culture-independent molecular approaches, which have provided additional insights into the diversity of the microflora from advanced lesions. However, some of these studies ignore the fact that dental caries is a localized disease of the teeth [76]. Thus, in order to obtain a sufficient amount of bacteria for molecular analyses, biofilm has been collected by pooling plaque or collecting saliva as proxy variables for caries. However, sampling strategies that do not reflect precisely defined environmental niches on the teeth are unlikely to give a detailed insight into the ecology of caries.

Microbiology of caries

Enamel caries

Fissures are the most caries-prone sites of the dentition, and the strongest correlation between the biofilm levels of mutans streptococci and caries has been found at these sites.

Table 7.4 Mean proportions of mutans streptococci (MS) and lactobacilli (L) on teeth in schoolchildren (7–8 years old) who remained caries free or who developed a caries lesion during a longitudinal study [51].

Time (months) before caries diagnosis	Mean proportions in fissure plaque					
	Caries sites		Filled sites		Caries free sites	
	MS	L	MS	L	MS	L
0	29	6	—	—	4	2
6	25	8	15	3	17	1
12	16	1	20	2	9	3
18	9	<1	10	1	11	1

Numerous cross-sectional and longitudinal studies have shown a strong relationship between the proportions of mutans streptococci in the biofilm and the detection of a caries lesion, but the relationship is not absolute; and there are lesions from which these organisms have not been detected in the overlying biofilm and cases of mutans streptococci persisting in the absence of a lesion: for examples, see [43, 49–51] (Table 7.4). One of the challenges with these studies is that the composition of the biofilm varies at different parts of the fissure [62], and the early signs of fissure caries develop along the fissure entrance rather than within the fissure proper (see Chapter 5).

A similar problem exists with studies of approximal surfaces; it is difficult to accurately diagnose early lesions, but biofilm is inevitably removed from the whole interproximal area during sampling, including that overlying sound as well as carious enamel. Early cross-sectional studies reported a positive correlation between elevated mutans streptococci levels and lesion development (e.g., [35]), although a less clear-cut association was found in a longitudinal study of English children. At some sites, mutans streptococci could be found in high numbers before the radiographic detection of demineralization, while some lesions developed in the apparent absence of these bacteria [33]. Again, mutans streptococci could also be present at some sites for prolonged periods in high numbers without any evidence of caries.

Several studies have shown an association between high levels of mutans streptococci and rapidly progressing caries in young infants fed from bottles containing formulae with a high content of carbohydrates [48]. However, a recent study of severe early childhood caries of different tooth surfaces at various stages of caries formation using a combination of anaerobic culture and molecular-based techniques found that disease was associated with a diverse microflora, including some previously uncultivated species. The species most closely associated with this severe form of caries included *S. mutans*, *Scardovia wiggsiae*, *Veillonella parvula*, *Streptococcus cristatus*, and *Actinomyces gerencseriae* [82]. Similar findings were reported in a previous study of early childhood caries using culture-independent approaches, but with the limitation that samples of dental biofilms were pooled prior to analysis: *S. sanguinis* was associated with sound enamel, while *A. gerencseriae*, *Bifidobacterium* spp., *S. mutans*, *S. salivarius*, *Streptococcus constellatus*, *Streptococcus parasanguinis*, *Lactobacillus fermentum*, and *Veillonella* spp. were associated with caries [4]. The data suggested that some *Actinomyces* spp. may be significant in caries initiation, while *Bifidobacterium* spp. may play a role in more advanced lesions. Likewise, in a molecular-based study of pooled plaque of caries in primary and permanent teeth in children, a number of species in addition to *S. mutans* were shown to play a role in caries progression; these bacteria included members of the genera *Veillonella*, *Lactobacillus*, *Bifidobacterium*, *Propionibacterium*, *Actinomyces* and *Atopobium*, plus low-pH non-*S. mutans* streptococci [2].

Rampant caries can also occur in people who experience an exceptional change in the oral environment, such as those with markedly reduced salivary flow rates due to radiation therapy or medication. In a classical study, radiation-induced xerostomia produced marked increases in the proportions of *S. mutans*, lactobacilli, and *Candida* spp. in pooled dental plaque at the expense of '*S. sanguis*', *Neisseria*, and *Fusobacterium*. *S. mutans* gained prominence in the biofilm within the first weeks of radiation, before the onset of caries, whereas the growth of lactobacilli was slower, possibly reflecting the aciduric properties of this genus. However, after 6 months the level of lactobacilli in plaque surpassed that of *S. mutans*, demonstrating the profound impact of saliva shutdown on the microbial ecology and caries [13].

Collectively, the data from numerous surveys of various tooth surfaces, of different patient age groups from numerous countries, and populations with different dietary habits, and so on have shown a strong positive association between increased levels of mutans streptococci and the initiation of demineralization. However, not every study identified all of the bacteria present in the clinical samples, and some focused only on organisms already implicated in disease (e.g., mutans streptococci and lactobacilli). Several bacterial species may contribute to demineralization, while others may reduce the impact of acid production by either utilizing the lactate produced from sugar metabolism (e.g., *Veillonella* spp.) or by producing alkali from saliva components (*S. salivarius*, *S. sanguinis*, *A. naeslundii*) (Fig. 7.3). Also, 'mutans streptococci' is a general term for several closely related species of *Streptococcus* originally described as different serotypes of *S. mutans*. The specific name *S. mutans* is now limited to human isolates previously belonging to serotypes *c*, *e*, and *f*. This is the most common species isolated from human dental biofilms. The next most prevalent species is *S. sobrinus* (previously *S. mutans* serotypes *d* and *g*). Some of these strains produce more acid from sucrose than *S. mutans* does [19], and it is preferable, therefore, that mutans streptococci be identified to the species level.

Root-surface caries and infected dentin

Early studies using animal models, and epidemiological surveys in humans, suggested a key role for Gram-positive filamentous bacteria, especially *Actinomyces* spp., in root-surface caries. Subsequent studies failed to confirm such an association, possibly because the early studies focused exclusively on infected root dentin. In cross-sectional studies of biofilm overlying carious root surfaces, mutans streptococci, alone or in combination with lactobacilli, were isolated more frequently or in higher proportions than on sound root surfaces [7, 9, 14, 29, 38, 95]. However, as with enamel caries, this relationship is not absolute. Mutans streptococci can be isolated from sound surfaces [14, 38], and in some studies it has not been possible to detect any differences in the proportion of mutans streptococci between sound and carious surfaces [24, 25]. In one study it was not possible to detect clear differences in the microbial composition of dental plaque on sound and carious root surfaces [82].

More recent studies using a new selective agar, or nonselective media together with novel sampling techniques, have shown that the microflora of root caries is diverse and, in addition to mutans streptococci and lactobacilli, *Actinomyces*, non-mutans streptococci, *Bifidobacterium*, *Rothia*, *Veillonella*, *Candida*, enterococci, and anaerobic Gram-negative species such as *Prevotella intermedia* and *Capnocytophaga* spp. are common [8, 10, 53, 75, 83] (Table 7.5). The presence of the Gram-negative anaerobic organisms may be significant since root caries involves both demineralization of the tissues due to acid production and proteolysis of the dentin collagen matrix.

As pointed out before, a crucial problem with most microbiological studies of caries is the lack of an accurate definition of the onset of lesion formation and/or the demineralization activity of the lesions studied. Because of the dynamic nature of caries, the mineral loss varies over time, not only between different lesions, but also within the individual lesion, depending on the metabolic activity of the microflora. Studies of associations between the microflora and caries should, therefore, preferably be performed on lesions with known age and history. One study that applied this approach suggested that lesions presenting with the highest mineral loss (as assessed by microradiography of root caries lesions developed during 3 months in situ) were dominated by a few acidogenic species, such as *Actinomyces* spp., or a combination of mutans streptococci and lactobacilli [73]. Lesions that lost only a small amount of mineral were associated with a more diverse microflora, including various acidogenic (mutans streptococci, *Actinomyces* spp., *Lactobacillus* spp., and *S. mitis* biovar 1) and lactate-metabolizing species (*Veillonella* spp.). Such differences in the pattern and acidogenic potential of the microflora are likely to reflect differences in the ecology of the lesions and imply that in order to understand the ecology of caries it may be necessary to recover the total microflora of a site.

Table 7.5 Mean proportions of selected bacteria from biofilms developing on root surfaces with and without caries [9].

Bacterium	Sound	Root surface caries	
		Initial (soft)	Advanced (hard)
Mutans streptococci	2	34	0
Streptococcus sanguinis	19	11	46
Actinomyces naeslundii	17	13	15
Lactobacilli	ND	1	1
Veillonella	ND	4	2

A range of other *Actinomyces* species have been isolated from infected dentin of active root caries lesions, including *A. gerencseriae*, *A. israelii*, *A. odontolyticus*, and *A. meyeri* [10].
ND, not determined.

In advanced cavitated lesions of root caries, notably higher levels of *S. mutans* were reported, possibly at the expense of *Actinomyces* spp., while lactobacilli were more common from sites with soft and necrotic dentin [84]. Other studies have also reported high proportions of lactobacilli and other Gram-positive rods from infected dentin [5], including several species of *Actinomyces* such as *A. israelii* and *A. gerencseriae* [10]. Obligately anaerobic Gram-negative bacteria are also present, but in lower levels than in the plaque overlying the lesion. Their role would still be important in contributing to the proteolytic and collagenolytic activities associated with tissue breakdown.

Recently, molecular analyses have been performed on biofilms from carious dentin so as to more fully describe the microbial diversity of lesions. A range of lactobacilli, comprising 50% of the species detected, were identified with novel *Prevotella* spp. Other taxa present included those more commonly seen in subgingival plaque, such as *Selenomonas* spp., *Dialister* spp., *Eubacterium* spp., and *Fusobacterium* spp. [16, 65]; a novel *Propionibacterium* sp. has also been reported [64]. Thus, it is plausible that the diversity and proportions of the organisms within the microflora change as the lesion progresses through the dental tissues, probably in direct response to alterations in critical environmental conditions. These include shifts in pH, the degree of anaerobiosis, and changes to the primary sources of nutrients.

In summary, many studies have shown that mutans streptococci can be isolated more often and in higher numbers from a range of caries lesions, although some advanced dentin lesions generally yield a more diverse microflora, including acidogenic and proteolytic species working in concert. A consistent feature of clinical studies has been the finding that the association of mutans streptococci with caries is not absolute. Thus, mutans streptococci can persist at sites without demineralization, while they cannot be recovered from a proportion of lesions, implying a role for other bacteria. The involvement of other species should not be unexpected when the features that are associated with the cariogenic potential of an organism are considered; these will be described in the 'Cariogenic features of dental biofilm bacteria' section. It may be comforting for the dental student to know that it is less important to remember the specific names of the bacteria than to understand their potential role in the biofilm community in health and disease.

Cariogenic features of dental biofilm bacteria

In order for bacteria to play a role in caries they must possess certain caries-promoting characteristics, which include the following.

- The ability to rapidly transport fermentable sugars when in competition with other plaque bacteria, and the conversion of such sugars to acid. Most saccharolytic bacteria in dental plaque, including mutans streptococci, possess several sugar transport systems, including high-affinity PEP–PTS systems, which are able to scavenge sugars even when they are present in the oral environment only in low concentrations. The incorporated sugars are readily converted to acids through the glycolysis-based pathways (Fig. 7.3).
- The ability to maintain sugar metabolism under extreme environmental conditions, such as at a low pH. Several oral bacteria are able to tolerate acidic conditions for prolonged periods. For example, mutans streptococci, lactobacilli, and bifidobacteria not only remain viable at a low pH but manage to continue to grow and metabolize; that is, they are both acidogenic and aciduric. This ability relies on a series of biochemical properties: (i) the activity of proton translocating ATPase (proton exclusion inside to outside of bacterial cells, see Fig 7.3, reaction 12); (ii) alkali production, due to the activity of bacterial ureases, arginine deiminase, and other alkali-producing systems (see Fig 7.3, reactions 3 and 4); (iii) proton impermeability of the bacterial cell membrane; and (iv) the production of stress proteins (protection of cellular structural and functional proteins from acid denaturation) [89].
- The production of extracellular polysaccharides (EPSs) and IPSs. EPSs include glucans and fructans, both of which contribute to the biofilm matrix. In addition to supporting the structure of the biofilm, the matrix may help to concentrate acids in distinct regions of the biofilm. Furthermore, fructans are labile and can be metabolized by biofilm bacteria under carbohydrate-restricted conditions. IPSs are glycogen-like storage compounds that can be used for energy production and converted to acid when free sugars are not available in the mouth. Thus, the metabolism of IPSs can prolong periods over which biofilms can generate acids (and, therefore, create a low pH in the biofilm).

Mutans streptococci are known to have all these properties and are thus considered as one of the most cariogenic bacteria [48]. However, these properties are not specific to mutans streptococci in the same way that the possession of some virulence factors (e.g., cholera toxin for *Vibrio cholerae*, pertussis toxin for *Bordetella pertussis*) help to define certain classical medical pathogens. Indeed, the acidogenic and aciduric profiles of particular species lie along a continuum, with increasing evidence of considerable overlap. Strains of non-mutans streptococcal species [94, 96] – for example, *S. mitis*, *S. gordonii*, *S. anginosus* and *S. oralis* [19] – have been isolated that can be as acidogenic and acid tolerating as some mutans streptococci (Fig. 7.25). As these species are prevalent among the early colonizers of teeth [74], they could play an important role in preparing the environment to make it suitable for the outgrowth of more aciduric species such as mutans streptococci and lactobacilli. Hence, the importance of the three caries-promoting properties described above may vary depending on the stage and activity of lesion formation. Therefore, it is not surprising that mutans streptococci and bacteria with similar caries-promoting traits are found in elevated proportions at caries sites. However, it should be appreciated that other bacteria may also contribute to the cariogenic potential of the biofilm. Some of these issues are developed further in the following section.

The 'ecological plaque hypothesis' to explain the role of dental biofilm bacteria in the etiology of dental caries

For many years there were two main schools of thought on the role of plaque bacteria in the etiology of caries. The specific plaque hypothesis proposed that, out of the diverse collection of organisms comprising the resident microflora, only a single or very small number of species were actively involved in disease. This proposal has been easy to promote because it focused efforts on controlling disease by targeting preventive measures and treatment against a limited number of organisms, such as by vaccination or gene therapy, or by antimicrobial treatment (Chapter 16). In contrast, the non-specific plaque hypothesis considered that disease is the outcome of the overall activity of the total plaque microflora, so that not just those species that make acid but also those that produce alkali or consume lactate need to be considered. Thus, a heterogeneous mixture of microorganisms could play a role in disease. In some respects, the arguments about the relative merits of these hypotheses may be about semantics, since biofilm-mediated diseases are essentially mixed culture (polymicrobial) infections, but in which only certain (perhaps a limited number) species are able to predominate. The arguments then center about the definitions of the terms specific and nonspecific. Subsequently, an alternative hypothesis was proposed (the 'ecological plaque'

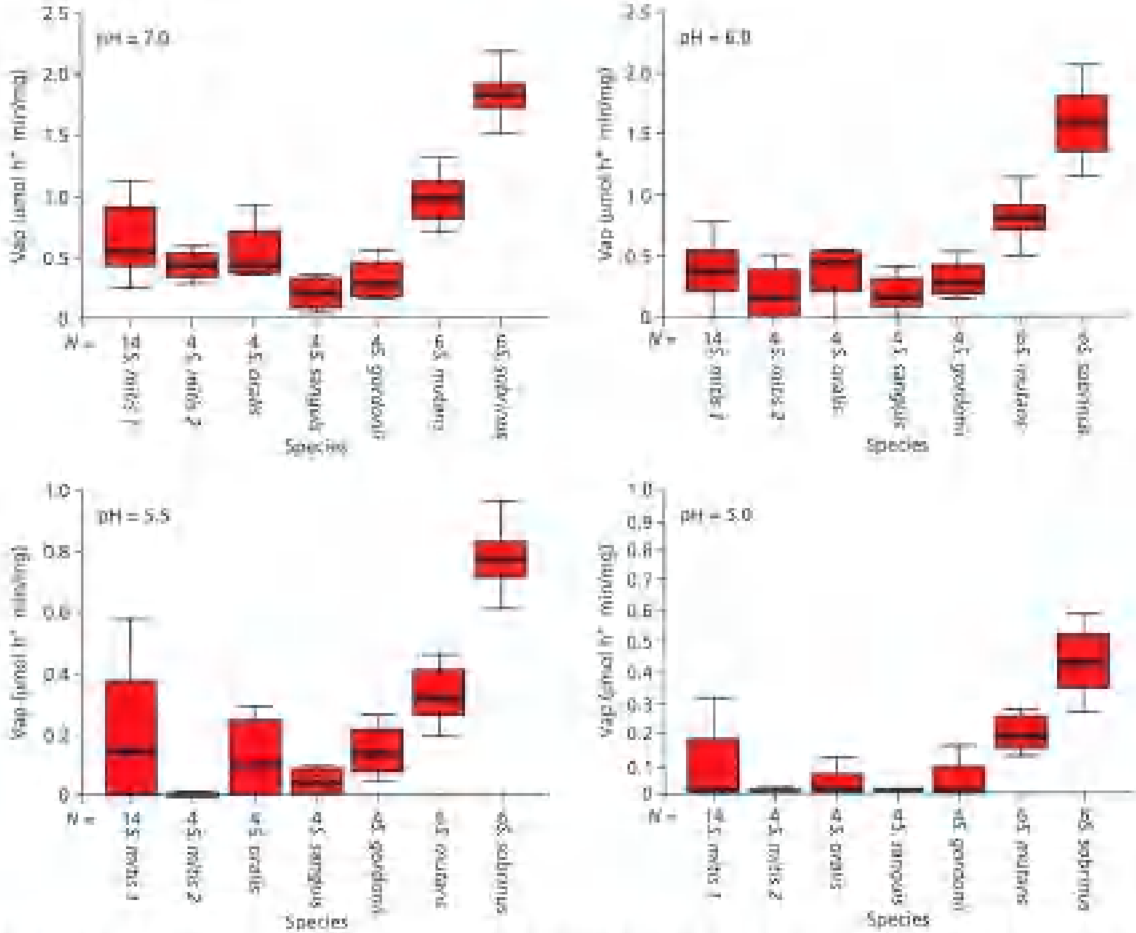


Figure 7.25 Velocity of acid production by six oral streptococcal species at different pH values. The bold line represents the median, and the box and error bars the 95% and 75% confidence intervals respectively [79]. Reproduced with permission of Karger Publishers.

hypothesis) that reconciled key elements of the earlier two hypotheses [56]. In brief, the ecological plaque hypothesis proposes that the organisms associated with disease may also be present at sound sites but at levels too low to be clinically relevant. *Disease is a result of a shift in the balance of the resident microflora driven by a change in local environmental conditions.* In the case of dental caries, repeated conditions of low pH in plaque following frequent sugar intake (or decreased sugar clearance following low salivary secretion) will favor the growth of acidogenic and aciduric species, and thereby predispose a site to caries (Fig. 7.26).

A consistent feature of most of the clinical studies described earlier has been the occasional but regular finding of carious sites from which no mutans streptococci can be isolated. As discussed previously, this suggests that acidogenic bacteria other than mutans streptococci can make a biologically significant contribution to the strength of the cariogenic challenge at a site [94, 96]. The converse situation is also not uncommon, where mutans streptococci are found in high numbers in plaque but in the apparent absence of any demineralization of the underlying enamel. This may be due to

- the structure of the biofilm and the localization of mutans streptococci in the biofilm;
- the presence of lactate-consuming species (e.g., *Veillonella*); or
- the production of alkali to raise the local pH (e.g., by ammonia production from urea or arginine by *S. salivarius* and *S. sanguinis*, respectively).

Other factors will also be significant, and these include the influence of the diet and the chemistry of enamel. These observations serve to emphasize the multifactorial nature of caries (Chapter 4), which involves the interaction of an acidogenic/aciduric microflora on a tooth surface, fueled by a diet consisting of frequent intakes of rapidly fermentable carbohydrates.

Figure 7.26 The ecological plaque hypothesis and the etiology of dental caries. The diagram depicts a dynamic relationship whereby an environmental change in the biofilm (e.g., low pH) drives a shift in the balance of the resident microflora, thereby shifting the balance towards enamel demineralization. Caries could be controlled by inhibiting the putative pathogens (MS or other acid producers) or by interfering with the environmental changes driving the ecological shift, for example, by reducing the acid challenge by the use of sugar control, saliva stimulation, and/or biofilm removal. MS: mutans streptococci. Adapted from Marsh PD 2003 [56].

Collectively, these findings allow a dynamic model to be constructed to explain the changes in the ecology of dental plaque that lead to the development of a caries lesion (Fig. 7.26). Potentially acidogenic/aciduric bacteria may be found naturally in a dental biofilm, but at neutral pH these organisms are weakly competitive and may be present only as a small proportion of the total plaque community. In this situation the acid production by such bacteria is clinically insignificant or may be counteracted by other bacteria, and the processes of demineralization and remineralization are in equilibrium. If the frequency of fermentable carbohydrate intake increases and/or salivary flow is impaired, then the biofilm spends more time below the critical pH for enamel demineralization (approximately pH 5.5). The effect of this on the microbial ecology would be twofold. Conditions of low pH favor the proliferation of aciduric (and acidogenic) bacteria (especially mutans streptococci and lactobacilli, but not exclusively so) [94], while tipping the balance towards demineralization. Greater numbers of aciduric bacteria such as mutans streptococci and lactobacilli in plaque would result in more acid being produced at even faster rates, thereby enhancing demineralization still further. Other bacteria could also make acid under similar conditions, but at a slower rate, or could initiate lesions in the absence of other (more overt) aciduric species in a more susceptible host. If highly aciduric species were not present initially, then the repeated conditions of low pH coupled with the inhibition of competing organisms might increase the likelihood of colonization by mutans streptococci or lactobacilli. This sequence of events would account for the lack of specificity in the microbial etiology of caries and explain the pattern of bacterial succession observed in many clinical studies. This model forms the basis of the ecological plaque hypothesis (Fig. 7.26) [56]. In this hypothesis, caries is a consequence of changes in the natural balance of the resident plaque microflora brought about by an alteration in local environmental conditions (e.g., repeated conditions of high sugar and low biofilm pH). The hypothesis also acknowledges the dynamic relationship that exists between the microflora and the host, so that the impact of alterations in key host factors (such as diet and saliva flow) on plaque composition is also taken into account. This has a great significance for caries prevention, since implicit in the hypothesis is the concept that *disease can be controlled by targeting the putative pathogens (mutans streptococci and other acidogenic/aciduric species) through interference with the factors that are driving the deleterious shifts in the balance of the microflora.* Identification of such critical control points (e.g., mechanical biofilm removal, saliva stimulation and/or dietary control) can lead to the selection of appropriate caries-preventive strategies that are tailored to the needs of individual patients (see Chapter 17). In this way, the clinician not only treats the symptoms of the disease, but also attempts to identify and interfere with the factors that, if left unaltered, will inevitably lead to more disease.

Recently, the ecological plaque hypothesis for dental caries has been extended, based on a further understanding of microbial biochemical responses to acid stress in the biofilm (acid-induced adaptation and selection) and an updated knowledge about the dynamic demineralization and remineralization processes in caries. In the 'extended caries ecological hypothesis' [87, 88], the caries process is subdivided into three reversible stages as follows (Fig. 7.27). In young supragingival biofilms, composed primarily of mitis streptococci and *Actinomyces*, bacteria produce acids by microbial sugar fermentation during meals; however, homeostasis is maintained because the acids are rapidly neutralized by saliva and microbial alkali production

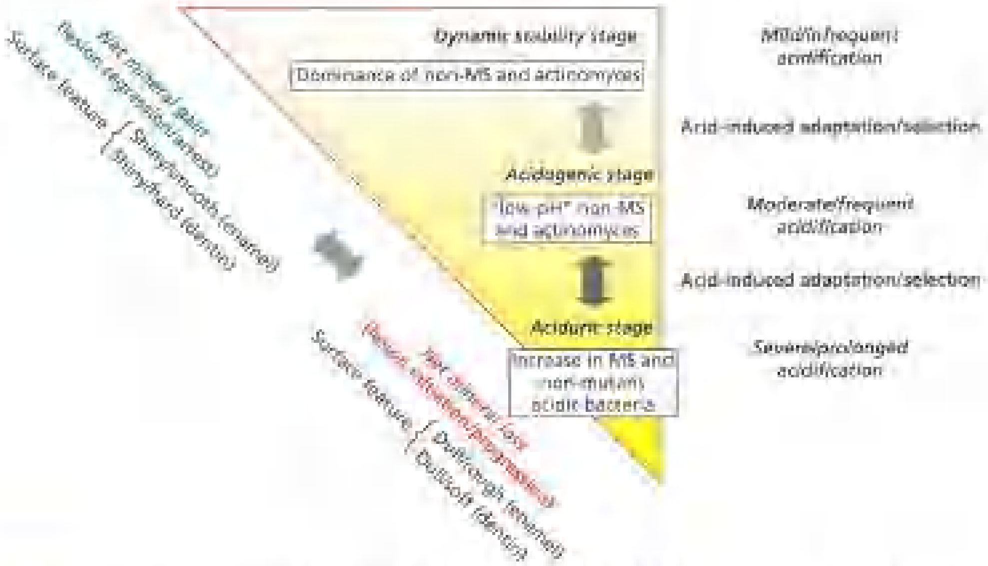


Figure 7.27 The caries process according to the extended ecological caries hypothesis Adapted from Takahashi and Nyvad, 2008 and 2011 [87, 88]. In this hypothesis environmental acidification acts as the main driving force for acid-induced adaptation and acid-induced selection of the microbial community as it passes form the dynamic stability stage via the acidogenic stage to the aciduric stage. Concurrently, caries lesion dynamics shifts towards net mineral loss. Note that reactions may be reversed by elimination of the acid stress.

(dynamic stability stage). At this stage, demineralization and remineralization are balanced and the dental hard tissues do not suffer a clinically detectable mineral loss, in spite of alternating periods of acid and alkali production. Frequent sugar intake and subsequent acid production induce microbial acid-induced adaptation in which a variety of biochemical responses against environmental acidification are enhanced. This series of biochemical reactions increases the microbial acidogenicity (Fig. 7.28), leading to environmental acidification and shifting the mineral balance towards demineralization (acidogenic stage) (Fig. 7.27). At the same time, more acidogenic and aciduric strains of non-mutans streptococci and *Actinomyces* (known as "low-pH" strains of non-mutans streptococci and *Actinomyces*) increase selectively in the biofilm. At this stage, established caries lesions often maintain a low environmental pH and subsequently select for more aciduric bacteria such as mutans streptococci, lactobacilli, and bifidobacteria due to the competitive advantage of these bacteria for growth and survival at low pH [34, 66] (Fig. 7.29) (aciduric stage) (Fig. 7.27). These aciduric bacteria can also increase their acidogenicity by acid-induced adaptation. The resultant severe and prolonged acidification further disturbs the de- and remineralization balance, thereby accelerating the progression of caries. *In the extended ecological caries hypothesis, environmental acidification acts as the main driving force for both acid-induced adaptation and selection of the microflora in the dental biofilm.* It is important to realize, however, that this detrimental (for the tooth!) and tough (for the bacteria!) cascade of events in the biochemical and microbiological profile of the biofilm can be reversed at any stage of development by normalization of the acidic

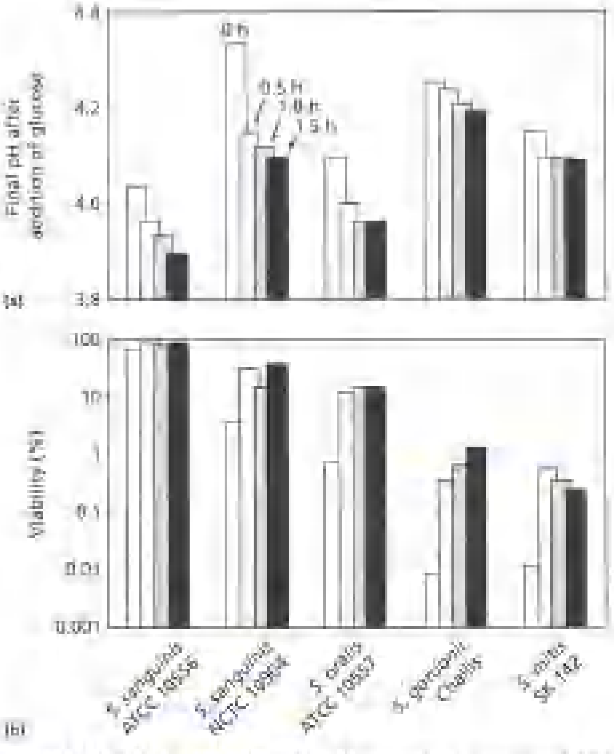


Figure 7.28 Acid-induced adaptation of non-mutans streptococci (data adapted from [89]). (*a*) Acidogenicity (final pH values) after the glucose addition at pH7.0. The bacteria were grown at pH7.0 until the logarithmic phase of growth and further grown at pH5.5 for 0, 0.5, 1.0, and 1.5 h. (*b*) Aciduance (survival rate) after 1 h at pH4.0. The bacteria were grown at pH7.0 until the logarithmic phase of growth and further grown at pH5.5 for 0, 0.5, 1.0, and 1.5 h. The treated bacterial cells were plated on blood agar and counted for colony-forming units after anaerobic incubation.

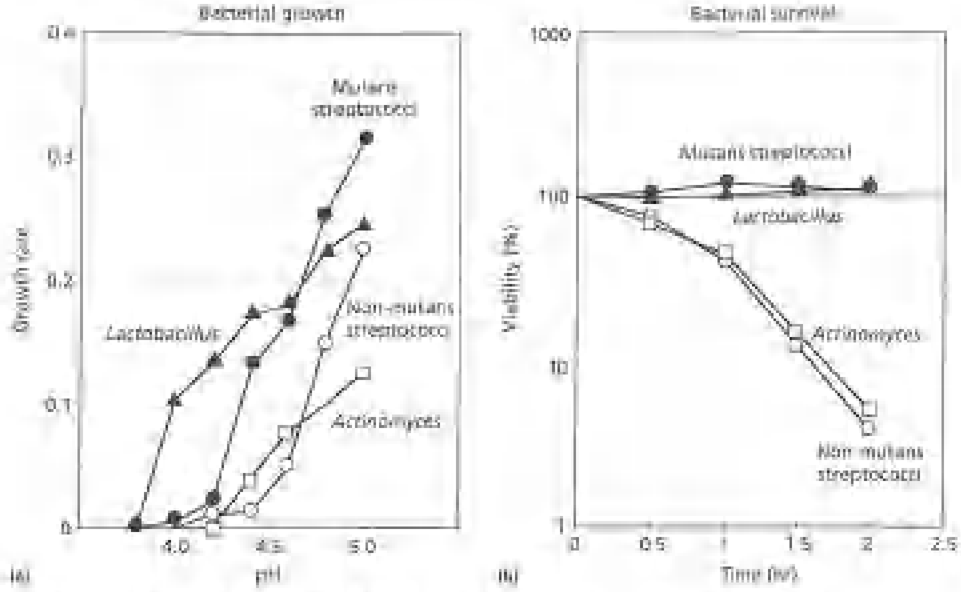


Figure 7.29 Acid-induced selection of oral bacteria. (a) Bacterial growth rate at acidic pH (data adapted from [34]). Bacteria were grown at various pH values with pH control by periodic addition of alkali, and bacterial growth rates were calculated from the logarithmic growth phase. Data are the means of two strains of mutans streptococci, two strains of non-mutans streptococci, and two strains of *Actinomyces*. (b) Bacterial survival at pH4.0 (data adapted from [66]). The bacterial cells grown at pH7.0 were exposed to pH4.0 for 0, 0.5, 1, 1.5, and 2 h in buffer solution. The treated bacterial cells were plated on blood agar and counted for colony-forming units after anaerobic incubation.

environment, for example, by sugar restriction or sugar substitution, in cases where sugar consumption is excessive. Such an approach would also have an effect on the mineral balance and reverse lesion dynamics towards remineralization.

Concluding remarks

In this chapter we have presented evidence for a hypothesis by which it may be possible to explain the etiology of dental caries: the (extended) ecological plaque hypothesis of caries. According to this hypothesis, it is postulated that dental caries is a naturally occurring biological phenomenon that takes place in the dental biofilm as a result of ecological disturbances to the biofilm community. Such imbalances in the biofilm community may originate in the host's own microflora in response to various external factors. For example, increased sugar exposure or impaired salivary clearance may lead to an outgrowth of mutans streptococci and other aciduric bacterial species. This hypothesis is compatible with previous clinical observations of increased proportions of aciduric species in caries lesions, while at the same time acknowledging the lack of absolute specificity of the microflora involved. The ecological hypothesis may also help to explain why tooth surfaces that are constantly covered by biofilm do not always develop caries lesions. Hence, because of the many interactions among different types of bacteria in the biofilm, the outcome may not necessarily end up with a net mineral loss over time (Chapter 2).

Knowledge about the role of bacteria in caries is not merely a theoretical issue. The way by which we interpret the microbiological features in caries has strong implications for our choice of strategy for caries control. If we believe that dental caries results from an ecological disturbance in the biofilm then we should focus our preventive strategies on such methods that restore the ecological balance of the microbial community, such as mechanical plaque removal (Chapter 15), sugar control (Chapter 8) and/or salivary stimulation (Chapter 6).

Background literature

Beighton D. Can the ecology of the dental biofilm be beneficially altered? *Adv Dent Res* 2009; 21: 69–73.

Dewhirst FE, Chen T, Izard J, Paster BJ, Tanner ACR, Yu W-H, Lakshmanan A, Wade WG. The human oral microbiome. *J Bacteriol* 2010; **192**: 5002–17.

Jakubovics NS, Kolenbrander PE. The road to ruin: the formation of disease-associated oral biofilms. *Oral Dis* 2010; **16**: 729–39.

Lemos JA, Burne RA. A model of efficiency: stress tolerance by *Streptococcus mutans*. *Microbiol* 2008; **154**: 3247–55.

Marsh PD, Martin MV. *Oral microbiology*, 5th ed. Oxford: Churchill Livingstone, 2009.

Takahashi N, Nyvad B. The role of bacteria in the caries process: ecological perspectives. *J Dent Res* 2011; **90**: 294–303.

Wade WG. The oral microbiome in health and disease. *Pharmacol Res* 2013; **69**: 137–43.

Zijnge V, van Leeuwen MB, Degener JE, Abbas F, Thurnheer T, Gmür R, Harmsen HJ. Oral biofilm architecture on natural teeth. *PLoS One* 2010; 5: e9321.

References

1. Aas JA, Paster BJ, Stokes LN, Olsen I, Dewhirst FE. Defining the normal bacterial flora of the oral cavity. *J Clin Microbiol* 2005; **43**: 5721–32.
2. Aas JA, Griffen AL, Dardis SR, Lee AM, Olsen I, Dewhirst FE, Leys EJ, Paster BJ. Bacteria of dental caries in primary and permanent teeth in children and young adults. *J Clin Microbiol* 2008; **46**: 1407–17.

3. Aizawa S, Miyasawa-Hori H, Nakajo K, Washio J, Mayanagi H, Fukumoto S, Takahashi N. Effects of alpha-amylase and its inhibitors on acid production from cooked starch by oral streptococci. *Caries Res* 2009; 43: 17–24.
4. Becker MR, Paster BJ, Leys EJ, Moeschberger ML, Kenyon SG, Galvin JL, Boches SK, Dewhirst FE, Griffen AL. Molecular analysis of bacterial species associated with childhood caries. *J Clin Microbiol* 2002; 40: 1001–9.
5. Beighton D, Lynch E, Heath MR. A microbiological study of primary root-caries lesions with different treatment needs. *J Dent Res* 1993; 72: 623–9.
6. Beighton D, Al-Haboubi M, Mantzourani M, Gilbert SC, Clark D, Zoitopoulos L, Gallagher JE. Oral bifidobacteria: caries associated bacteria in older adults. *J Dent Res* 2010; **89**: 970–4.
7. Billings RJ, Brown LR, Kaster AG. Contemporary treatment strategies for root surface dental caries. *Gerodontics* 1985; 1: 20–7.
8. Bowden GHW. Microbiology of root surface caries in humans. *J Dent Res* 1990; **69**: 1205–10.
9. Bowden GHW, Ekstrand J, McNaughton B, Challacombe SJ. The association of selected bacteria with the lesions of root surface caries. *Oral Microbiol Immunol* 1990; 5: 346–51.
10. Brailsford SR, Tregaskis RB, Leftwich HS, Beighton D. The predominant *Actinomyces* spp. isolated from infected dentin of active root caries lesions. *J Dent Res* 1999; 78: 1525–34.
11. Branda SS, Vik S, Friedman L, Kolter R. Biofilms: the matrix revisited. *Trends Microbiol* 2005; 13: 20–6.
12. Brinig MM, Lepp PW, Ouverney CC, Armitage GC, Relman DA. Prevalence of bacteria of division TM7 in human subgingival plaque and their association with disease. *Appl Environ Microbiol* 2003; 69: 1687–94.
13. Brown LR, Dreizen S, Handler S, Johnston DA. Effect of radiation-induced xerostomia on human oral microflora. *J Dent Res* 1975; 54: 740–50.
14. Brown LR, Billings RJ, Kaster AG. Quantitative comparisons of potentially cariogenic microorganisms cultured from noncarious and carious root and coronal tooth surfaces. *Infect Immun* 1986; 51: 765–70.
15. Carlsson J. Growth and nutrition as ecological factors. In: Kuramitsu HK, Ellen RP, eds. *Oral bacterial ecology: the molecular basis*. Wymondham: Horizon Scientific Press, 2000: 67–130.
16. Chhour K-L, Nadkarni MA, Byun R, Martin FE, Jacques NA, Hunter N. Molecular analysis of microbial diversity in advanced caries. *J Clin Microbiol* 2005; 43: 843–9.
17. Cosseau C, Devine DA, Dullaghan E, Gardy JL, Chikatamarla A, Gellatly S, Yu LL, Pistolic J, Falsafi R, Tagg J, Hancock RE. The commensal *Streptococcus salivarius* K12 downregulates the innate immune responses of human epithelial cells and promotes host–microbe homeostasis. *Infect Immun* 2008; 76: 4163–75.
18. Costerton JW, Lewandowski Z, Caldwell DE, Korber DR, Lappin-Scott HM. Microbial biofilms. *Annu Rev Microbiol* 1995; 49: 711–45.
19. De Soet JJ, Nyvad B, Kilian M. Strain-related acid production by oral streptococci. *Caries Res* 2000; 34: 486–90.
20. Dewhirst FE, Chen T, Izard J, Paster BJ, Tanner ACR, Yu W-H, Lakshmanan A, Wade WG. The human oral microbiome. *J Bacteriol* 2010; 192: 5002–17.
21. Dige I. Initial biofilm formation studied by confocal laser scanning microscopy and fluorescence in situ hybridization. PhD Thesis. Faculty of Health Sciences, Aarhus University, Denmark, 2008.
22. Dige I, Nilsson H, Kilian M, Nyvad B. In situ identification of streptococci and other bacteria in initial dental biofilm by confocal laser scanning microscopy and fluorescence in situ hybridization. *Eur J Oral Sci* 2007; 115: 459–67.
23. Dige I, Raarup MK, Nyengaard JR, Kilian M, Nyvad B. *Actinomyces naeslundii* in initial dental biofilm formation. *Microbiology* 2009; 155: 2116–26.
24. Ellen RP, Banting DW, Fillery ED. *Streptococcus mutans* and *Lactobacillus* detection in the assessment of dental root surface caries risk. *J Dent Res* 1985; 64: 1245–9.
25. Emilson CG, Klock B, Sanford CB. Microbial flora associated with presence of root surface caries in periodontally treated patients. *Scand J Dent Res* 1988; 96: 40–9.
26. Fejerskov O, Nyvad B. Is dental caries an infectious disease? Diagnostic and treatment consequences for the practitioner. In: Schou L, ed. *Nordic dentistry 2003 yearbook*. Copenhagen: Quintessence, 2003: 141–51.
27. Fejerskov O, Nyvad B, Larsen MJ. Human experimental caries models: intra-oral environmental variability. *Adv Dent Res* 1994; 8: 134–43.
28. Fitzgerald RJ, Keyes PH. Demonstration of the etiologic role of streptococci in experimental caries in the hamster. *J Am Dent Assoc* 1960; 61: 9–19.
29. Fure S, Romaniec M, Emilson CG, Krasse B. Proportions of *Streptococcus mutans*, lactobacilli, and *Actinomyces* spp in root surface plaque. *Scand J Dent Res* 1987; 95: 119–23.
30. Gibbons RJ. Bacterial adhesion to oral tissues: a model for infectious diseases. *J Dent Res* 1989; 68: 750–60.
31. Gibbons RJ, Hay DI, Childs WC III, Davis G. Role of cryptic receptors (cryptitopes) in bacterial adhesion to oral surfaces. *Arch Oral Biol* 1990; 35: 107S–14S.
32. Govoni M, Jansson EA, Weitzberg E, Lundberg JO. The increase in plasma nitrite after a dietary nitrate load is markedly attenuated by an antibacterial mouthwash. *Nitric Oxide* 2008; 19: 333–7.
33. Hardie JM, Thomson PL, South RJ, Marsh PD, Bowden GH, McKee AS, Fillery ED, Slack GL. A longitudinal epidemiological study on dental plaque and the development of dental caries—interim results after two years. *J Dent Res* 1977; 56 Special Issue C: C90–8.
34. Horiuchi M, Washio J, Mayanagi H, Takahashi N. Transient acid-impairment of growth ability of oral *Streptococcus*, *Actinomyces*, and *Lactobacillus*: a possible ecological determinant in dental plaque. *Oral Microbiol Immunol* 2009; 24: 319–24.
35. Huis in't Veld JHJ, van Palenstein Helderman WH, Backer Dirks O. *Streptococcus mutans* and dental caries in humans: a bacteriological and immunological study. *Antonie van Leeuwenhoek* 1979; 45: 25–33.
36. Imfeld TN, Lutz F. Intraplaque acid formation assessed in vivo in children and young adults. *Pediatr Dent* 1980; 2: 87–93.
37. Kaplan JB. Therapeutic potential of biofilm-dispersing enzymes. *Int J Artif Organs* 2009; 32: 545–54.
38. Keltjens HMAM, Schaeken MJM, van der Hoeven JS, Hendriks JCM. Microflora of plaque from sound and carious root surfaces. *Caries Res* 1987; 21: 193–9.
39. Keyes PH. The infectious and transmissible nature of experimental dental caries. Findings and implications. *Arch Oral Biol* 1960; 1: 304–20.
40. Kinniment SL, Wimpenny JWT, Adams D, Marsh PD. The effect of chlorhexidine on defined, mixed culture oral biofilms grown in a novel model system. *J Appl Bacteriol* 1996; 81: 120–5.
41. Köhler B, Andréen I, Jonsson B. The effect of caries-preventive measures in mothers on dental caries and the oral presence of the bacteria *Streptococcus mutans* and lactobacilli in their children. *Arch Oral Biol* 1984; 29: 879–83.
42. Kolenbrander PE, Andersen RN, Kazmerzak KM, Palmer RJ. Coaggregation and coadhesion in oral biofilms. In: Allison DG, Gilbert P, Lappin-Scott HM, Wilson M, eds. *Community structure and co-operation in biofilms*. Cambridge: Cambridge University Press, 2000: 65–85.
43. Lang NP, Hotz PR, Gusberti FA, Joss A. Longitudinal clinical and microbiological study on the relationship between infection with *Streptococcus mutans* and the development of caries in humans. *Oral Microbiol Immunol* 1987; 2: 39–47.
44. Larsen T, Fiehn N-E. Resistance of *Streptococcus sanguis* biofilms to antimicrobial agents. *APMIS* 1996; 104: 280–4.
45. Levine MJ, Tabak LA, Reddy M, Mandel ID. Nature of salivary pellicles in microbial adherence: role of salivary mucins. In: Mergenhagen SE, Rosan B, eds. *Molecular basis of oral microbial adhesion*. Washington, DC: American Society of Microbiology, 1985: 125–30.
46. Li J, Helmerhorst EJ, Leone CW, Troxler RF, Yaskell T, Haffajee AD, Socransky SS, Oppenheim FG. Identification of early microbial colonizers in human dental biofilm. *J Appl Microbiol* 2004; 97: 1311–18.
47. Li Y, Burne RA. Regulation of the *gtfBC* and *ftf* genes of *Streptococcus mutans* in biofilms in response to pH and carbohydrate. *Microbiology* 2001; 147: 2841–8.
48. Loesche WJ. Role of *Streptococcus mutans* in human dental decay. *Microbiol Rev* 1986; 50: 353–80.
49. Loesche WJ, Straffon LH. Longitudinal investigation of the role of *Streptococcus mutans* in human fissure decay. *Infect Immun* 1979; 26: 498–507.
50. Loesche WJ, Rowan J, Straffon LH, Loos PJ. Association of *Streptococcus mutans* with human dental decay. *Infect Immun* 1975; 11: 1252–60.
51. Loesche WJ, Eklund S, Earnest R, Burt B. Longitudinal investigation of bacteriology of human fissure decay: epidemiological studies in molars shortly after eruption. *Infect Immun* 1984; 46: 765–72.

52. Mantzourani M, Gilbert SC, Sulong HN, Sheehy EC, Tank S, Fenlon M, Beighton D. The isolation of bifidobacteria from occlusal carious lesions in children and adults. *Caries Res* 2009; **43**: 308–13.
53. Mantzourani M, Fenlon M, Beighton D. Association between Bifidobacteriaceae and the clinical severity of root caries lesions. *Oral Microbiol Immunol* 2009; **24**: 32–7.
54. Marsh PD. Role of the oral microflora in health. *Microb Ecol Health Dis* 2000; **12**: 130–7.
55. Marsh PD. Oral ecology and its impact on oral microbial diversity. In: Kuramitsu HK, Ellen RP, eds. *Oral bacterial ecology: the molecular basis*. Wymondham: Horizon Scientific Press, 2000; 11–65.
56. Marsh PD. Are dental diseases examples of ecological catastrophes? *Microbiology* 2003; **149**: 279–94.
57. Marsh PD. Dental plaque as a microbial biofilm. *Caries Res* 2004; **38**: 204–11.
58. Marsh PD. Dental plaque – biological significance of a biofilm and community life-style. *J Clin Periodontol* 2005; **32** (Suppl 6): 7–15.
59. Marsh PD, Bowden GHW. Microbial community interactions in biofilms. In: Allison DG, Gilbert P, Lappin-Scott HM, Wilson M, eds. *Community structure and co-operation in biofilms*. Cambridge: Cambridge University Press, 2000; 167–98.
60. Marsh PD, Martin MV. *Oral microbiology*, 5th ed. Oxford: Churchill Livingstone, 2009.
61. McNamara TF, Friedman BK, Kleinberg I. The microbial composition of human incisor tooth plaque. *Arch Oral Biol* 1979; **24**: 91–5.
62. Meiers JC, Schachtele CF. Fissure removal and needle scraping for evaluation of the bacteria in occlusal fissures of human teeth. *J Dent Res* 1984; **63**: 1051–5.
63. Miller WD. *The micro-organisms of the human mouth: the local and general diseases which are caused by them*. Unaltered reprint of the original work by Willoughby D Miller (1853–1907) published in 1890 in Philadelphia. Karger: Basel, 1973[1890].
64. Munson MA, Banerjee A, Watson TF, Wade WG. Molecular analysis of the microflora associated with dental caries. *J Clin Microbiol* 2004; **42**: 3023–9.
65. Nadkarni MA, Caldon CE, Chhour KL, Fisher IP, Martin FE, Jacques NA, Hunter N. Carious dentine provides a habitat for a complex array of novel *Prevotella*-like bacteria. *J Clin Microbiol* 2004; **42**: 5238–44.
66. Nakajo K, Takahashi N, Beighton D. Resistance to acidic environments of caries-associated bacteria: *Bifidobacterium dentium* and *Bifidobacterium longum*. *Caries Res* 2010; **44**: 431–7.
67. Nyvad B. *Tidlig bakteriekolonisation på emalje og rodoverflader in vivo*. PhD Thesis. Aarhus: Royal Dental College, 1983.
68. Nyvad B. Microbial colonization of human tooth surfaces. *APMIS* 1993; **101** (Suppl 32): 1–45.
69. Nyvad B, Fejerskov O. Experimentally induced changes in ultrastructure of pellicle on enamel in vivo. In: ten Cate JM, Leach SA, Arends J, eds. *Bacterial adhesion and preventive dentistry*. Oxford: IRL Press, 1984; 143–51.
70. Nyvad B, Fejerskov O. Scanning electron microscopy of early microbial colonization of human enamel and root surfaces in vivo. *Scand J Dent Res* 1987; **95**: 287–96.
71. Nyvad B, Fejerskov O. Structure of dental plaque and the plaque-enamel interface in human experimental caries. *Caries Res* 1989; **23**: 151–8.
72. Nyvad B, Fejerskov O. Development, structure and pH of dental plaque. In: Thylstrup A, Fejerskov O, eds. *Textbook of clinical cariology*. Copenhagen: Munksgaard, 1994; 89–110.
73. Nyvad B, Kilian M. Microbiology of the early microbial colonization of human enamel and root surfaces in vivo. *Scand J Dent Res* 1987; **95**: 369–80.
74. Nyvad B, Kilian M. Comparison of the initial streptococcal microflora on dental enamel in caries-active and in caries-inactive individuals. *Caries Res* 1990; **24**: 267–72.
75. Nyvad B, Kilian M. Microflora associated with experimental root surface caries in humans. *Infect Immun* 1990; **58**: 1628–33.
76. Nyvad B, Crielaard W, Mira A, Takahashi N, Beighton D. Dental caries from a molecular microbiological perspective. *Caries Res* 2013; **47**: 89–102.
77. Paster BJ, Boches SK, Galvin JL, Ericson RE, Lau CN, Levanos VA, Sahasrabudhe A, Dewhirst FE. Bacterial diversity in human subgingival plaque. *J Bacteriol* 2001; **183**: 3770–83.
78. Percival RS. Changes in oral microflora and host defences with advanced age. In: Percival S, Hart A, eds. *Microbiology and aging: clinical manifestations*. New York: Springer, 2009; 131–52.
79. Petersson J, Carlström M, Schreiber O, Phillipson M, Christoffersson G, Jägare A, Roos S, Jansson EA, Persson AE, Lundberg JO, Holm L. Gastroprotective and blood pressure lowering effects of dietary nitrate are abolished by an antiseptic mouthwash. *Free Radic Biol Med* 2009; **46**: 1068–75.
80. Rateitschak-Plüss EM, Guggenheim B. Effects of a carbohydrate-free diet and sugar substitutes on dental plaque accumulation. *J Clin Periodontol* 1982; **9**: 239–51.
81. Ritz HL. Microbial population shifts in developing human dental plaque. *Arch Oral Biol* 1967; **12**: 1561–8.
82. Scheie AA, Luan W-M, Dahlén G, Fejerskov O. Plaque pH and microflora of dental plaque on sound and carious root surfaces. *J Dent Res* 1996; **75**: 1901–8.
83. Schüpbach P, Osterwalder V, Guggenheim B. Human root caries: microbiota in plaque covering sound, carious and arrested carious root surfaces. *Caries Res* 1995; **29**: 382–95.
84. Schüpbach P, Osterwalder V, Guggenheim B. Human root caries: microbiota of a limited number of root caries lesions. *Caries Res* 1996; **30**: 52–64.
85. Svensäter G, Welin J, Wilkins JC, Beighton D, Hamilton IR. Protein expression by planktonic and biofilm cells of *Streptococcus mutans*. *FEMS Microbiology Letters* 2001; **205**: 139–46.
86. Syed SA, Loesche WJ. Bacteriology of human experimental gingivitis: effect of plaque age. *Infect Immun* 1978; **21**: 821–9.
87. Takahashi N, Nyvad B. Caries ecology revisited: microbial dynamics and the caries process. *Caries Res* 2008; **42**: 409–18.
88. Takahashi N, Nyvad B. The role of bacteria in the caries process: ecological perspectives. *J Dent Res* 2011; **90**: 294–303.
89. Takahashi N, Yamada T. Acid-induced acid tolerance and acidogenicity of non-mutans streptococci. *Oral Microbiol Immunol* 1999; **14**: 43–8.
90. Takahashi N, Yamada T. Glucose and lactate metabolism by *Actinomyces naeslundii*. *Crit Rev Oral Biol Med* 1999; **10**: 504–18.
91. Takahashi N, Washio J, Mayanagi G. Metabolomic approach to oral biofilm characterization – a future direction of biofilm research. *J Oral Biosci* 2012; **54**: 138–43.
92. Tanner AC, Mathney JM, Kent RL, Chalmers NI, Hughes CV, Loo CY, Pradhan N, Kanasi E, Hwang J, Dahlan MA, Papadopolou E, Dewhirst FE. Cultivable anaerobic microbiota of severe early childhood caries. *J Clin Microbiol* 2011; **49**: 1464–74.
93. Tanzer JM. On changing the cariogenic chemistry of coronal plaque. *J Dent Res* 1989; **68** (spec iss): 1576–87.
94. van Houte J. Role of micro-organisms in caries etiology. *J Dent Res* 1994; **73**: 672–81.
95. van Houte J, Jordan HV, Laraway R, Kent R, Soparkar PM, DePaola PF. Association of the microbial flora of dental plaque and saliva with human root surface caries. *J Dent Res* 1990; **69**: 1463–8.
96. van Ruyven FOJ, Lingström P, van Houte J, Kent R. Relationship among mutans streptococci, "low-pH" bacteria, and iodophilic polysaccharide-producing bacteria in dental plaque and early enamel caries in humans. *J Dent Res* 2000; **79**: 778–84.
97. Watson PS, Pontefract HA, Devine DA, Shore RC, Nattress BR, Kirkham J, Robinson C. Penetration of fluoride into natural plaque biofilms. *J Dent Res* 2005; **84**: 451–5.
98. Welin J, Wilkins JC, Beighton D, Svensäter G. Protein expression by *Streptococcus mutans* during initial stage of biofilm formation. *Appl Environ Microbiol* 2004; **70**: 3736–41.
99. Wood SR, Kirkham J, Marsh PD, Shore RC, Nattress B, Robinson C. Architecture of intact natural human plaque biofilms studied by confocal laser scanning microscopy. *J Dent Res* 2000; **79**: 21–7.
100. Zahradnik RT, Moreno EC, Burke EJ. Effect of salivary pellicle on enamel subsurface demineralization in vitro. *J Dent Res* 1976; **55**: 664–70.
101. Zaura-Arite E, van Marle J, ten Cate JM. Confocal microscopy study of undisturbed and chlorhexidine-treated dental plaque. *J Dent Res* 2001; **80**: 1436–40.

8

Diet and dental caries

C. van Loveren and P. Lingström

History

In ancient times, when both sugar and processed starch were almost completely absent from the diet, which consisted of raw grains, berries, roots, and herbs, dental caries was only found to a low degree. In recent excavations in northern Morocco, however, significant numbers of carious teeth have been found in skulls of hunter gatherers of the Middle Stone Age and Later Stone Age (15 000 to 13 700 years ago) consuming a diet comprising pistacios, acorns, pine nuts, and wild oats [48]. In the late Middle Ages diet changed for some when sugar from sugar cane (*Saccharum officinarum*) was introduced in Europe. Sugar cane is a large, strong-growing species of grass that may contain 13% sucrose. When introduced, sugar was an exclusive and expensive product available for the rich. Historically, the black and rotten teeth of Queen Elisabeth I (1533–1603) were recounted by foreign ambassadors. She also had some teeth missing, which made understanding her words difficult at times (http://www.elizabethi.org/contents/myths/).

In the 18th century the sugar consumption in the UK rose from 2 kg per capita to 5.5 kg in 1780. There are very early references to sugar or sweet foods and dental caries by Fauchard [27] in 1746 and shortly afterwards by Berdmore [9] in 1769, who wrote that 'where sugar, tea, coffee and sweetmeats are used in excess, the people even at an early age are remarkable for the badness of their teeth.' Miller [95], who postulated the chemicoparasitic theory for caries, was the first to show experimentally the relationship between carbohydrates and caries. He demonstrated *in vitro* that incubation of carbohydrate-containing foods with human

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd

saliva may result in the formation of lactic acid that could cause demineralization. The acid formation was greater from cooked carbohydrates, such as potatoes and bread, than from sugar; consequently, he considered starch to be more detrimental to the teeth than sugar. Although he was well aware of the presence of microbes on the tooth surface and in carious lesions, he did not identify the important role of dental plaque in caries unlike G.V. Black (see Chapter 7).

Early ecological studies

In the 1930s, ecological studies were reported on the relationship between the prevalence of dental caries and diet. Comparison between two tribes in Kenya, the Masai and the Kikuyu, revealed better oral health for the Masai than for the Kikuyu [111]. This difference was related to their diets being protein rich for the Masai and carbohydrate rich for the Kikuyu. In the East Greenland Eskimos (Inuit) the dental status was worse when people lived close to the trading posts, where lifestyle recently had changed from a diet dominated by meat and fat to one of starches and sugars [114, 119]. At Tristan da Cunha, a remote island in the Atlantic Ocean, caries prevalence increased when western dietary habits were introduced after the settlement of a meteorological institute and a canned fish company [46, 138]. Another increase in caries, related to a higher consumption of refined carbohydrates, was observed after the inhabitants were evacuated to England, between 1961 and 1963, following a volcanic eruption on the island [29]. A comparable effect of the introduction of 'western civilization' was observed in Goms in Switzerland after the opening of this remote area by the construction of a highway [123]. A distinct reduction in caries prevalence in children during and after both World Wars has been noticed in several Scandinavian countries and Japan [137, 144, 148]. A common dietary change was a reduction in consumption of foods and concomitantly of refined carbohydrates, especially sugar and sweets. In Basel, Switzerland, wartime restriction during World War II reduced sugar supply from about 40 to 16 kg per person per year, resulting in an increase in the percentage of caries-free children from about 2% to 15%. This improvement of oral health disappeared when sugar became freely available after the war ended. Similar data have been presented from Denmark, Finland, and Norway [148]. In a reflection of the Swiss data, it was concluded that the improvement was impressive at that time but it was dwarfed with the start of fluoride supplies, oral hygiene instructions at school, and water fluoridation [63]. This observation gave further ammunition to the discussion of the relative importance of sugar restriction versus the appropriate use of fluoride as a caries preventive measure.

In 1960, prior to the introduction of fluoride toothpaste, the effect of between-meal eating was given special attention [151]. Children with little between meal eating exhibited 3.3 decayed, missing, or filled primary teeth (dmft), while those eating more than four times between meals had on average 9.8 dmft. In another study, children aged 6–13 years living in an Australian children's home, Hopewood House, consuming a mainly lactovegetarian diet with minimal amounts of sugar and refined flour, showed a low caries prevalence compared with a control group. However, caries levels rose to those found in the general population when the children left the home [87]. The relation between sugar consumption and the prevalence of dental caries has also been studied in subjects with hereditary fructose intolerance who have to avoid eating fructose and sucrose. In 17 subjects with fructose intolerance, the daily sugar intake was 2.5 g, while it was 48.2 g for the controls. The corresponding decayed, missing, or filled permanent teeth (DMFT) levels were 2.1 and 14.3 [87, 107].

Experimental human studies

Apart from the historical data, knowledge on the relationship between diet and dental caries is based on a limited number of experimental human studies. This is because it is not ethical to alter diet experimentally in a way that is expected to cause caries. The Vipeholm study was a human experiment on adults living in a mental hospital in Sweden where sugar consumption was increased and the relationship between a variety of sugar intakes and caries increment was recorded [49]. The main findings of the 5-year study (1946–1951) were as follows (Fig. 8.1):

- A low caries incidence was found when the diet was almost free of sugar.
- The caries progression rate increased with the addition of sugar to the diet, but to a varying degree depending on the manner of consumption.
- Sugar intake with meals, such as sweet drinks (nonsticky form) or sweet bread (sticky form), resulted in a minor increase in the caries progression rate.
- The frequency of sugar intake influenced the caries progression rates: a moderate caries increase was observed for the groups receiving chocolate four times daily, and a dramatic increase for the groups receiving 22 caramels, 24 toffees, or 8 toffees at and between meals.
- Sugar consumed between meals in a highly retentive (sticky) form resulted in the highest caries progression rate.

Unfortunately, the consumption of sugar in a nonsticky form between meals was not studied. Thus, the latter conclusion does not exclude that sugar in a nonsticky form might be as cariogenic as a sticky form!

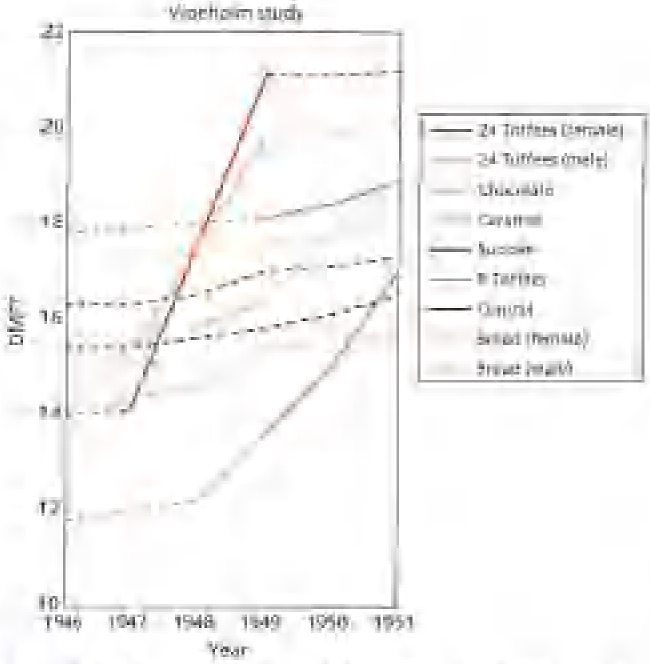


Figure 8.1 Information from the Vipeholm study: average DMFT per person relative to the type and time of eating various sugars and sugar-containing products. Solid lines represent experimental periods with increased consumption between meals; dashed lines represent control periods or increased consumption only during the meals. Data source: [39].

Although a classic, The Vipeholm study has some serious drawbacks, including a complex design where numerous modifications were made during the course of the study. It was carried out in an institution in a population that was not representative of its era or of today's modern society. The participants had bad oral hygiene habits and the use of fluoride was absent. Today, the ethics of the Vipeholm study would be unacceptable, but it is important to bear in mind that the link between sugar and caries was not definitely established at the time the study was carried out.

In clinical studies, where different sugar substitutes have been evaluated, caries development in the control group can be used as indirect evidence for the impact of sugars on caries. The Turku sugar study, a controlled longitudinal human study, involved three groups of adult subjects who during 25 months consumed a diet sweetened with either sucrose, fructose, or xylitol [129]. An 85% reduction in caries increment (noncavitated and cavitated lesions taken together) was found for the individuals in the xylitol group and a 32% reduction for the fructose group, compared with the sucrose group (Fig. 8.2). Caries development was not observed in the xylitol group, suggesting effectiveness of removal of sucrose from the diet in caries control. When analyzing the noncavitated and cavitated lesions separately, it was found that subjects in the sucrose group developed more noncavitated lesions than the subjects in the fructose group, while the subjects in the fructose group developed more cavitated lesions. There is no good biological explanation for these findings. Therefore, from the Turku sugar studies it cannot be concluded that substitution of sucrose by fructose is a worthwhile caries-preventive measure.

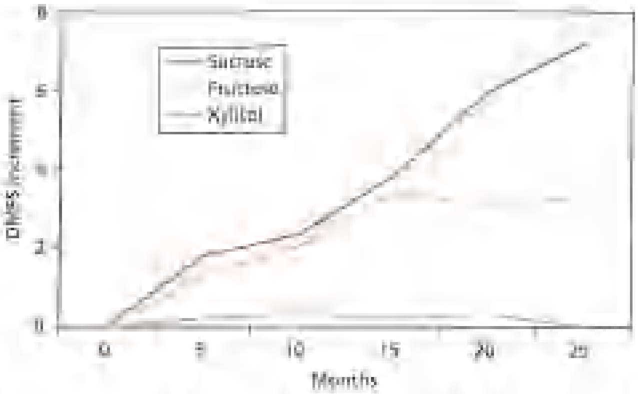


Figure 8.2 Increase in decayed missing, filled tooth surfaces (DMFS) in the three groups in the Turku experiment based on clinical and radiographic findings including white spots. Data source: [129].

Influence of fluoride on the diet–caries relationship

In the late 1970s, before fluoride was widely used and when the quality of oral hygiene was still generally poor, the impact of diet on caries could be well established. When the caries prevalence among 12-year-old children in 47 nations was related with the sugar (mono- and disaccharides) supply per capita [139], the mean DMFT of 21 countries with a sugar supply below 18 kg per person per year was 1.2 (±0.6). For nine countries, with an average sugar supply between 18 and 44 kg per person per year, the mean DMFT was 2.0 (±0.7), while for 10 other countries the mean DMFT was 4.0 (±0.9). In seven countries where the sugar supply exceeded 44 kg per person per year, the mean DMFT was as high as 8.0 (±2.4). Sreebny considered that approximately 18 kg per person per year may represent an upper limit of 'safe' sugar consumption [139].

Some 10 years later the relationship between sugar consumption and caries was less clear. In a study of 61 developing and 29 industrialized countries [158], approximately 26% of the variation in caries in the developing countries was explained by the estimated sugar consumption. In the industrialized countries, however, less than 1% was explained. This suggests that, when fluoride is used regularly (e.g., in industrialized countries), variations in sugar intake may be of lesser importance in caries prevalence and subsequently that restrictions in sugar intake may be of lesser efficacy in caries prevention. A recent evaluation [89] also showed that amongst high-income countries there is a negative correlation between sugar availability

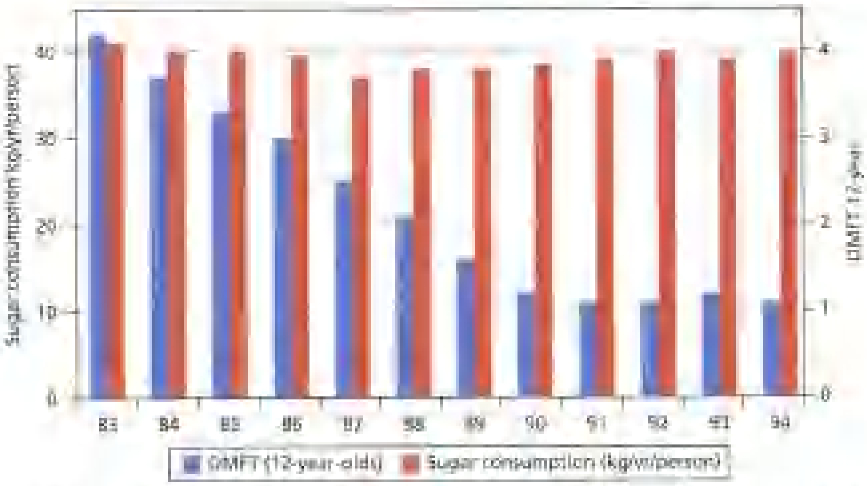


Figure 8.3 Sugar consumption (kilograms per year per person) in Denmark and caries experience (DMFT) in 12-year-old schoolchildren between 1974 and 1997. Data source: [109].

and caries levels, while a positive correlation was still seen in low-income countries.

In many western societies the consumption of sugars over the past 30 years has remained more or less stable at approximately 40 kg per person per year. Therefore, the dramatic decline in dental caries prevalence that occurred in this period in most western industrialized countries cannot primarily be attributed to changes in diet but is mainly due to the widespread use of toothbrushing with fluoride. Ecological observations in many countries confirm that sugar consumption remained high in this period of caries decline (Fig. 8.3). In a large sample of 1450 British preschool children, sugar-containing food and drinks were not associated with caries experience unless children brushed with fluoridated toothpaste only once a day or less [35].

Experimentally, the relationship between the frequency of carbohydrate consumption, the use of fluoridated toothpaste, and enamel demineralization was studied using an in-situ caries model [24]. Demineralization developed only after seven or more sucrose intakes per day when the subjects used a fluoride-containing toothpaste, while with a fluoride-free toothpaste demineralization occurred already after three sucrose intakes per day.

König and Navia [64] discussed that the relationship between diet and dental caries is difficult to measure for a variety of reasons:

- variability in patterns of consumption affects the duration of exposure of the teeth to sugars;
- national supply data, dietary recalls, and food diaries only provide an approximation of actual food consumption and sugars consumption patterns;
- patterns of sugars consumption are reported on a short term basis, but caries formation normally takes several years;
- caries prevalence is influenced by several factors that are difficult to control for, including protective factors in food, oral health, oral hygiene habits, including fluoride exposure, and education level.

Thus, the studies mentioned above must be considered in light of these concerns. Nevertheless, it is clear that only a smaller percentage of the variation in caries experience in individuals may be explained by dietary components since the introduction and use of fluoridated toothpaste. Sugar consumption is probably only a risk indicator of caries in persons that do not have regular exposure to fluoride [13] and with those patients who have dry mouth.

Measuring cariogenicity

Food claims towards cariogenicity can be estimated from the composition of a food, or tested *in vitro*, in animal experiments, in situ and *in vivo*. The limitations of these methods become clear when one realizes the cascades of processes resulting in acid production in the dental biofilm. First of all, the sugars or fermentable carbohydrates have to be transferred from the food to the dental plaque. Factors influencing this process are the consistency of the food (solid versus fluid), the chewing efficiency of the individual, the temperature (influences diffusion), the clearance of the food from the mouth (sticky versus nonsticky), the hydrolysis into monosaccharides, and the location, composition, consistency, and pH of the dental biofilm. Once the sugar has reached the plaque the production of a variety of acids, primarily lactic and acetic, starts to decrease the local pH (see Chapter 7). The end point of the induced pH drop depends on the numbers and types of bacteria present, and the acid production may be counteracted by environmental factors such as buffers or antimicrobial components of the food that are transferred concomitantly. Sufficient acids have to be produced during a certain time interval to demineralize the mineral. Finally, the food will be cleared and the acids buffered by saliva, the production of which is an attribute of the individual but which is also provoked by the food, depending on the consistency and taste. The result of all the processes will be different if the food is taken as a single unit or in combinations with other foods. The effect of a candy bar taken between meals will be different from the effect of the same bar taken as dessert after a meal.

It follows from the above that it is very difficult to assess the cariogenicity of a food. In the following subsections we describe current methodologies that can be used to evaluate food acidogenicity and cariogenicity.

Plaque pH measurements

All common mono- and disaccharides, together with hydrolysed polysaccharide starch, can be fermented by oral bacteria, and these carbohydrates are therefore potentially cariogenic. Plaque pH was first measured *in vivo* by Stephan and Miller in 1940 [141]. They demonstrated that the pH in the plaque on the upper front teeth dropped from about 6.5 (resting pH) to pH 5 within 3 min after rinsing with a glucose rinse and that it took approximately 40 min for the pH to restore to pre-rinse levels (Fig. 8.4). Subsequently, they cleaned the surface of the left tooth and observed that the pH on this tooth did not drop after another sucrose rinse while pH on the right tooth dropped again. Since then, the course of a pH curve in dental plaque following a carbohydrate challenge has been referred to as the 'Stephan curve'. The classical Stephan curve typically consists of three phases:

- a steep and immediate drop in pH due to bacterial acid production;
- a period of low pH where there is a balance between acid production, buffering, and clearance by saliva [76];
- a slow increase of pH to the pre-experimental value when buffering and salivary clearance gradually supersede acid production.

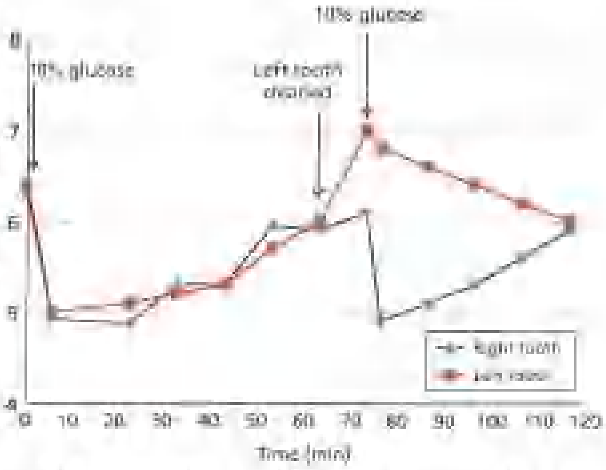


Figure 8.4 Stephan and Miller, in 1943, measured the course of the pH on buccal surfaces of the first permanent incisors after a glucose rinse. They repeated the experiment after the left tooth had been cleaned. Data source [141].

At pH values below the so-called 'critical' pH value for enamel (around pH 5.5; see Chapter 9) tooth mineral tends to demineralize, whereas 'remineralization' may occur above this value.

Figure 8.5 is a typical representation of the Stephan curve and is useful in educational material for the patient. Such simple information may help the caries-active patient better to understand the deleterious effects of dietary sugars and make the patient appreciate why a pattern of frequent sugar consumption can lead to high caries progression. At the same time, it is easy to explain why a diet without frequent sugar exposures can facilitate 'healing' of already established caries lesions.

Sucrose is often claimed to be the most potent acid-generating substrate for oral bacteria. However, based on numerous *in vitro* and *in vivo* studies, there is little or no evidence to support a difference in the potential acidogenicity between sucrose, glucose, fructose, or maltose. Lactose and galactose may be less acidogenic [30, 65, 127, 147] (Fig. 8.6).

Today, there are three possible methods of plaque pH measurement:

- the plaque sampling method (plaque is collected *in vivo* and pH is measured *in vitro*);
- the microtouch electrode (a thin needle-like pH-electrode is inserted into the plaque *in vivo*);
- the (interproximal) telemetry method (pH is measured in plaque on indwelling pH-electrodes *in vivo*).

Each of the three methods can satisfactorily identify nonacidogenic foods when used properly with appropriate positive (10% sucrose) and negative (10% sorbitol) controls [73, 128]. However, there are differences in the level of the pH curve when comparing results after a sucrose challenge, with the telemetric method yielding the most pronounced pH drops. Owing to the technical complexity of the telemetric method and difficulties in identifying suitable test subjects, the microtouch method is now the most commonly used technique. Figure 8.7 shows the typical plaque pH response from clinically sound occlusal surfaces compared with plaque pH of active and inactive occlusal caries lesions following a sucrose rinse using the microtouch electrode [28]. It is obvious that the acidogenic response of the active cavitated lesions is much more severe than for the inactive lesions and sound surfaces, thus supporting the clinical concept of caries lesion activity assessment (see Chapter 11).

Figure 8.8a–f gives examples of various pH telemetry experiments measuring the acidogenicity in undisturbed interproximal biofilm following the intake of different test foods [50]. Typically, the experiments start with 3-min paraffin chewing to clean the mouth and neutralize pH. Then the test food will be eaten for 2 min. After another

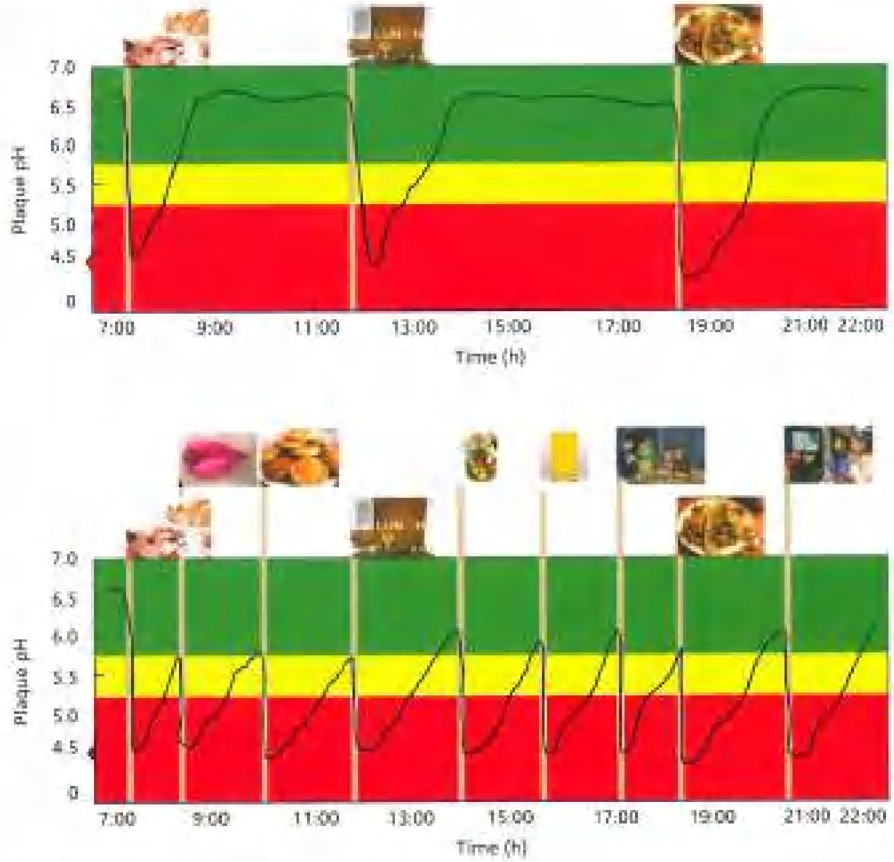


Figure 8.5 An example of the Stephan curve as used in health promotion materials.

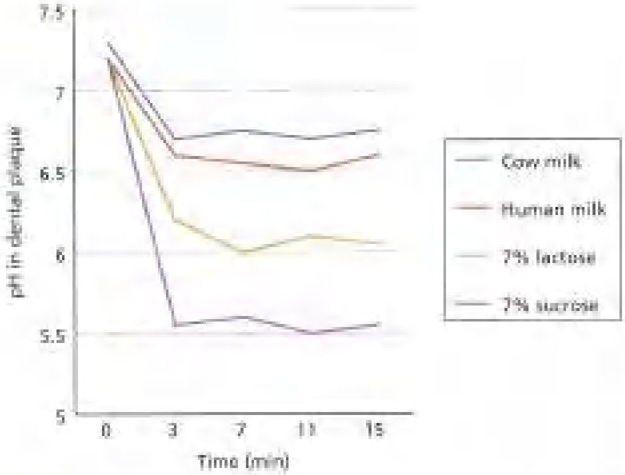


Figure 8.6 pH course in dental plaque up to 15 min rinsing with human milk, cow milk, 7% lactose, and 7% sucrose. Data source: [127].

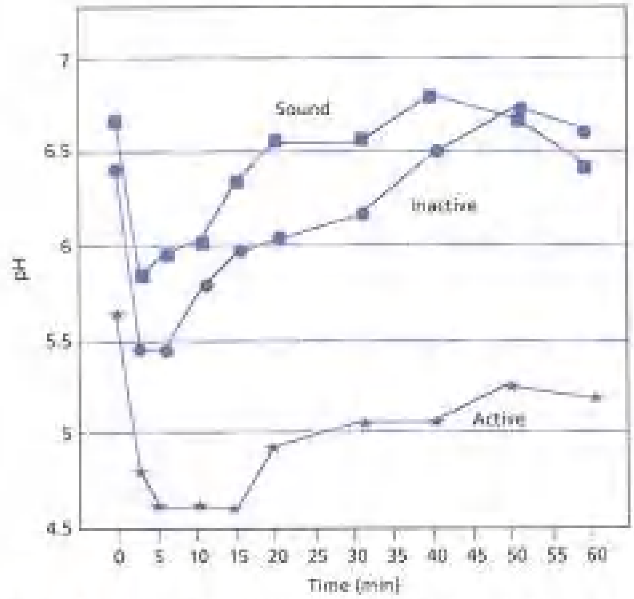


Figure 8.7 The Stephan response curves obtained from sound occlusal surfaces, inactive occlusal caries lesions, and deep, active occlusal caries lesions following a sucrose rinse. Mean values. Data source: [28].

15 min the test persons rinse their mouths with water or urea solution, followed by paraffin chewing again to clear foods and restore the pH. In all examples the experimental plaque was 5 days old. Figure 8.8a illustrates pH drops following oral rinses with various concentrations of sucrose. As little as 1.25% sucrose can lower the pH to levels where tooth mineral dissolves. Figure 8.8b shows that the pH drop caused by either glucose, maltose, or sucrose is comparable. Figure 8.8c and d shows that when the pH-neutralizing rinse and chew intervention are postponed the pH remains low till the acids are cleared by a stimulated salivary flow or by removal of impacted food. Figure 8.8e demonstrates

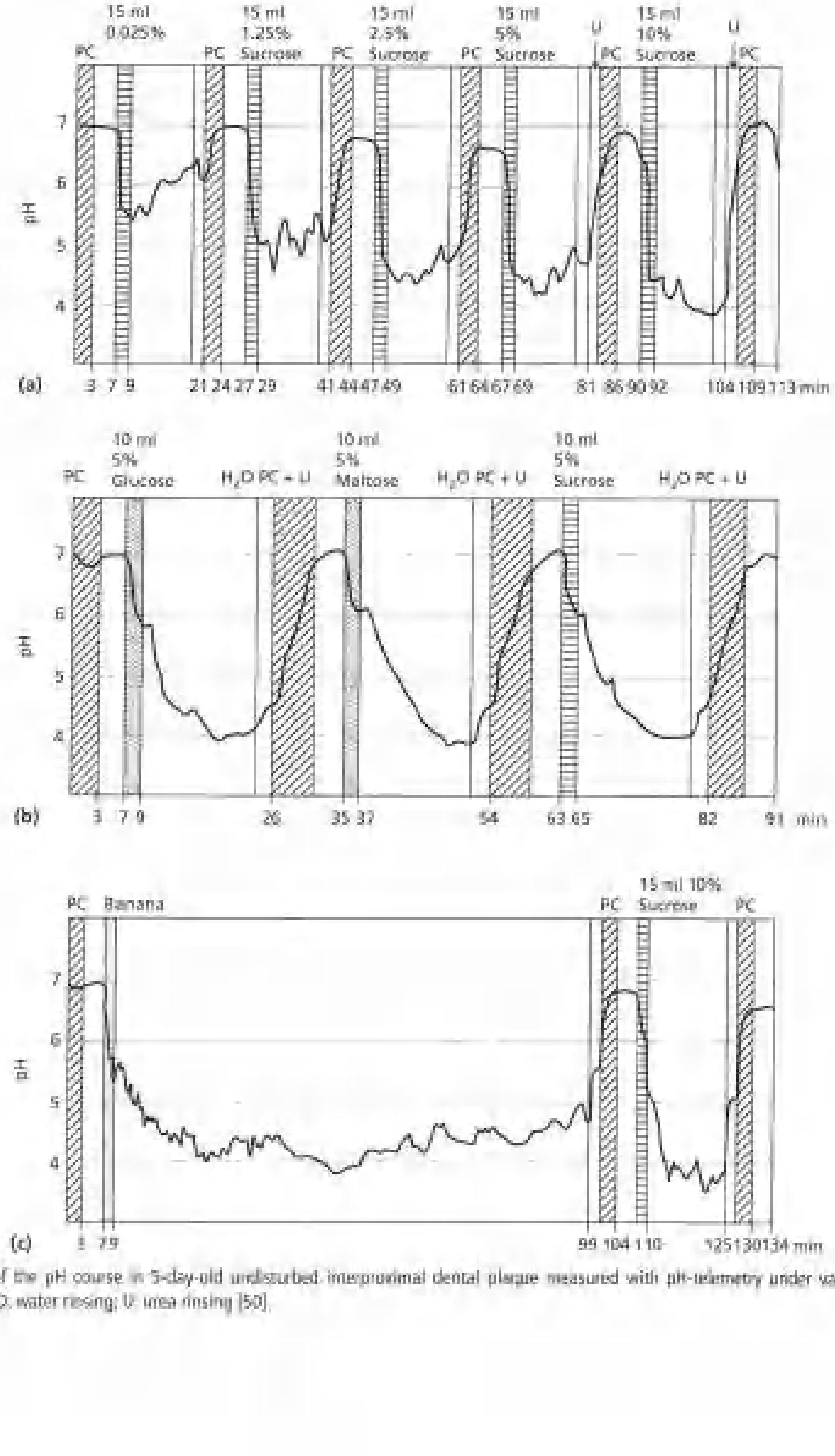


Figure 8.8 Examples of the pH course in 5-day-old undisturbed interproximal dental plaque measured with pH-telemetry under various rinsing conditions. PC: paraffin chewing; H_2O: water rinsing; U: urea rinsing [50].

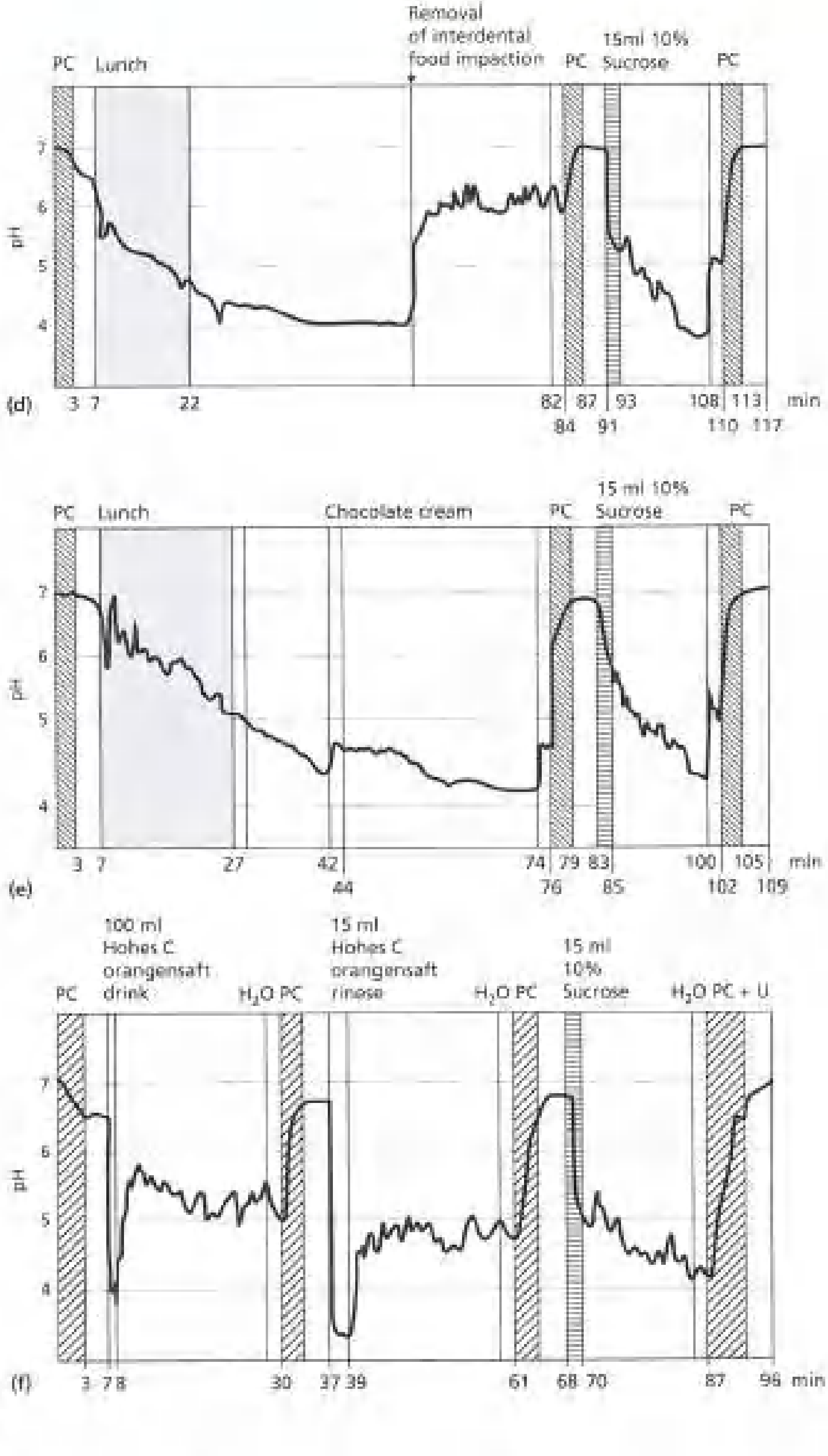


Figure 8.8 (Continued)

what happens when chocolate cream is taken when the pH is still low after a previous sugar exposure. Figure 8.8c–e indicates that the educational models based on 30 min duration of a pH drop may not always tell the truth, as the pH drop may continue for a much longer period of time. Figure 8.8f shows the course of the pH curve induced by an acidic fruit juice. The initial low pH related to the acidic content of the drink is quickly neutralized by the plaque buffer system, but subsequently the pH remains at a low level for a long time due to the fermentation of the sugar in the drink. A second rinse with fruit juice depressed pH to the same low level as a 10% sucrose rinse.

As stressed at the beginning of this section, it is important to realize that plaque pH methods can only indicate acidogenic potential of a product and not the true cariogenic potential. If the plaque pH profile of a product does not differ statistically significantly from that of a 10% sorbitol rinse, then the food can be considered as noncariogenic [21]. When the plaque pH profile falls below that of sorbitol, but not below pH 5.7, an in-situ cariogenicity test is required to further evaluate the food.

In-situ caries models

In-situ caries models, or the intraoral cariogenicity testing method, involve the use of appliances or other devices that carry enamel or dentin samples and are worn intra-orally by participants [145]. The strength of these models is that all the multifactorial aspects of natural caries development are generally included. Foods and beverages can be tested under clinically relevant conditions and the effect of the foods on the tooth samples can be evaluated in the laboratory. Issa *et al.* [55] compared the effect on enamel demineralization in situ of both whole and juiced fruits and vegetables consumed seven times a day for 10 days. The mineral profile of the pre-demineralized enamel slabs was studied before and after the test period using transverse microradiography and showed progressive demineralization for all test foods. No significant differences were found between the solid and juiced foods. The authors concluded that sugars present intrinsically in a food had a similar demineralizing potential as free sugars and could not be considered less cariogenic.

Clinical experiments

Eventually, foods could be tested in clinical experiments using randomized controlled trials. Clinical studies with appropriate controls allow local caries risk factors to be assessed and clinical assessment of caries increment. For ethical reasons it is clear that long-term clinical studies can only be used for studies of foods that are expected not to be cariogenic or to have a beneficial effect. Clinical studies are expensive and complicated by the fact that the study design would ideally require a sugar-containing control group, which would now be deemed unethical.

Sweeteners

Noncariogenic sweeteners may play a significant role in caries control when the caries-active patient with a 'sweet tooth' does not master proper plaque control (see Chapter 17). Therefore, dentists should have a significant knowledge of the potential cariogenicity of the sweeteners that are currently used in foods, drinks, and confectionary in modern diets.

There has been a steep rise in the use of convenience foods over the past few decades. The shift towards reliance on convenience foods away from home food preparation means that the consumer has little control over how much of sugars is added; therefore, people might be unaware of how much sugar they are consuming. It is not obvious to many people that sugar may be a major constituent in products such as breakfast cereals, flavored crisps (chips), ketchup, and bread. Thus, just focusing on confectioneries in caries control may have little impact on reducing caries activity if an individual is exposed to many other sugary products per day. A misleading annotation is 'no sugar added'. Often, such products contain the sugar of the original component (e.g., the fruit), which may give the product a 10% sugar content.

Table 8.1 presents an overview of the different carbohydrates and sweeteners that the dentists should be familiar with in order to guide their patients in choosing a tooth-friendly substitute for sugars.

Cariogenic sweeteners

Monosaccharides and disaccharides

The monosaccharides (glucose, fructose, galactose, rhamnose, and xylose) and the disaccharides (sucrose, maltose, and lactose; Table 8.2) are commonly referred to as sugars, while the term sugar is used synonymously for sucrose. In addition to imparting a sweet taste, sugars have functions that are important to safety and quality of foods. The functions include [30]:

- inhibition of microbial growth by binding water in jams and jellies (osmotic effect),
- adding texture, bulk, flavor, and color to (baked) goods,
- supporting growth of yeast for leavening or fermentation,
- balancing acidity in salad dressings, sauces, and condiments.

When replacing sugars these functions have to be ensured, in addition to the taste replacement.

High-fructose corn syrup

High-fructose corn syrup (HFCS) is a cariogenic sweetener that is produced mainly for economic reasons for use in beverages in the USA. HFCS is made by enzymatic degradation of corn starch. It is chemically similar to invert sugar, which consists of 50% fructose plus 50% glucose. As fructose is sweeter than sucrose, both invert sugar and HCFS are sweeter than sucrose as well. The percentage fructose in HFCS may range from 42%, which is most often used in baked goods, to 55%, which is found only in beverages. HFCS, as well as invert sugar, may have slight advantages from a cariological point of view. Bacteria do not produce extracellular polysaccharides from these sugars, but the cariogenicity of invert sugar has been found to be only marginally less than that of sucrose [31].

Table 8.1 Different types of carbohydrates and sugar substitutes grouped according to potential cariogenicity and type and number of saccharides.

Cariogenic sweeteners		
Mono- and disaccharides		
High-fructose corn syrup (HFCS)		
Starches		
Noncariogenic bulking agents		
Fructose polymers		
Inulin		
Polydextrose		
Nutriose		
Sucrose substitutes		
Cariogenic oligosaccharides		
Glucose polymers and maltodextrins		
Isomaltooligosaccharides (IMOs)		
Sucromalt		
Fructooligosaccharides (FOSs)		
(Likely) low or noncariogenic mono- and disaccharides		
Tagatose		
Trehalose		
Sucrose isomers: palatinose, trehalulose, turanose, maltulose and leucrose		
Noncariogenic sucrose substitutes		
Noncaloric intense sweeteners		
	Times sweeter than sucrose	ADI[a] (mg/kg body weight)
Glycyrrhizine, monelline, thaumatine, miraculin, and neohesperidine DC	Thaumatine: 3000	
Acesulfame K	200	15
Aspartame	160–220	40
Advantame	20000	5
Cyclamate	30	7
Saccharin	300	5
Sucralose	600	15
Steviolglycosides: stevioside, rebaudioside	250	4
Caloric sweeteners		
Sugar alcohols	Relative sweetness to sucrose (%)	kcal/g
Hydrogenated monosaccharides		
sorbitol	50–70	2.6
mannitol	50–70	1.8
xylitol	100	2.4
erythritol	60–80	0.2
D-tagatose	75–92	1.5
Hydrogenated disaccharides		
isomalt	45–65	2.0
lactitol	30–40	2.0
maltitol	90	2.1
Hydrogenated starch hydrolysates	25–50	
maltitol syrups/lycasin		
sorbitol syrups		

[a] Accepted daily intake.

Starches

Starches are not direct substrates for bacterial fermentation, but starches are hydrolyzed to maltose, isomaltose, and glucose in the oral cavity. Both salivary and bacterial amylases can accomplish this, and it has been shown that, after chewing crackers, potato chips, and so on, glucose clearance is prolonged due to the intermediate degradation products of starch, maltotriose, and maltose [75]. Acid formation can start surprisingly quickly after starchy food has interacted with the dental plaque. Pollard and coworkers [117, 118] tested the acidogenicity of white bread, cooked spaghetti, cooked long-grain rice, and many other starch products, with and without added sugar. The minimum pH values measured with indwelling electrodes showed that none of

Table 8.2 The composition and relative sweetness of the disaccharides.

Disaccharide	Relative sweetness to sucrose (%)	Unit 1	Unit 2
Sucrose (table sugar, cane sugar, beet sugar or saccharose)	100	Glucose	Fructose
Lactose (milk sugar)	20	Galactose	Glucose
Maltose (a hydrolysis product of starch)	30–50	Glucose	Glucose

the test products were significantly different from 10% sucrose solution. Therefore, there is no doubt that starches are acidogenic in the mouth. The degree of cariogenicity of starch products depends on many factors. Impaction of starchy food in the dentition, especially when the starch has been industrially processed, may give rise to considerable amounts of acid and their cariogenic potential must be considered high. Lingström *et al.* [74] have shown with three different pH measurement systems that acid formation in plaque after chewing soft bread or potato chips is more intense and lasts longer than after intake of sucrose. Starch may also influence the stickiness of products [5, 6], which might be an important co-determinant for the cariogenicity. Therefore, it is questionable whether a recommendation to eat complex carbohydrates in place of sugars would decrease the caries risk.

Noncariogenic carbohydrate bulking agents

Noncariogenic carbohydrate bulking agents are additives to increase the weight or volume of a food material without imparting additional functionality or utility. Food bulking agents usually add little food value and/or few calories to a food material and are often used to produce dietary food. They may be fibrous, which facilitates or increases bowel movements and causes the stool to be bulkier and to retain more water. Because of a wide variety of proposed health-promoting functions [61], these have wide applications in various types of foods, like confectionery, fruit preparations, milk desserts, yogurt and fresh cheese, baked goods, chocolate, ice cream, and sauces. They are regarded as noncariogenic [26, 102]. They include: fructans (e.g., inulin), polydextrose, and Nutriose® (a soluble fiber).

Sucrose substitutes

Commercially produced carbohydrates, including polymers of glucose and oligosaccharides of glucose, fructose, and galactose, are increasingly being used in everyday food products because they are cheaper and it is claimed that their consumption may have potential health benefits. For instance, they may be more fibrous, less digestible, have a lower or higher energy content, or give a lower rise of blood sugar levels. Many of these saccharides pass to the large bowel where they stimulate the growth of lactobacilli and bifidobacteria, which are known to reduce the growth of pathogenic microorganisms [71]. However, many of the species of bacteria found in the colon are also present in dental plaque (e.g., bifidobacteria and lactobacilli, which are not necessarily beneficial in the oral cavity); therefore, the dental health effects of these novel carbohydrates warrants investigation. Ingredients that reach the colon in an intact form producing specific changes in the composition and/or activity of the gastrointestinal flora that confer benefits on host well-being and health, are often referred to as *prebiotics*.

In general, mono-, di-, and oligosaccharide fragments are readily taken up by oral bacteria and fermented to acids. Salivary amylase hydrolyzes α-1,4-glycosidic bonds to break up longer chains into mono- and disaccharides. Other bonds may be hydrolyzed by bacterial enzymes. If sucrose substitutes do not contain mono-, di-, or oligosaccharide, or are these are not formed by hydrolysis in the oral cavity, then it may be presumed that the product has low cariogenicity or is noncariogenic. However, firm conclusions on the acidogenicity and possible cariogenicity of all possible carbohydrates can only be drawn from experimental data.

Cariogenic oligosaccharides

Glucose polymers are produced by acid hydrolysis of starch and comprise a mixture of mono-, di-, tri-, tetra-, penta-, hexa-, and heptasaccharides and alpha limit dextrins. The degree of polymerization is given by the DE value (glucose [dextrose] as percentage dry weight). The DE of starch is close to 0 and that of glucose 100. The DE of dextrins varies between 1 and 13, the DE of maltodextrins between 3 and 20, and glucose syrups contain a minimum of 20% glucose (DE ≥20). Glucose polymers having the same DE may, however, have significantly different compositions and hence different acidogenic responses.

Glucose polymers and maltodextrins are used to increase the energy content of foods. They may be prescribed by health professionals for children with clinical conditions such as renal failure, liver cirrhosis, disaccharide intolerance, disorders of amino acid metabolism, malabsorption status, and conditions requiring high energy intake [101]. Being virtually tasteless and odorless, they may be added to a variety of products without a major influence on the taste and smell of the product. Glucose polymers are frequently added to soft drinks, infant food and drinks, sports drinks, desserts, confectionery, and energy supplements.

As said, the monosaccharides, disaccharides, and smaller oligosaccharides can be fermented directly in dental plaque. The larger oligosaccharides have first to be hydrolyzed by salivary amylase, resulting in shorter chains. The extent of hydrolysis by amylase will be determined by the retention time in the oral cavity. Glucose polymers are potentially cariogenic; however, evidence to demonstrate this is sparse, with most data from animal, plaque pH, and *in vitro* laboratory studies. In the absence of evidence from human clinical trials (and, as explained previously, it is not ethical to perform these), advice for the use of glucose polymers should be the same as that for free sugars. They should not be recommended as sugar substitutes. Glucose syrups replace lactose in soya infant formula, raising concern about the cariogenic potential of these formulae.

IMOs, also known as glucosyloligosaccharides, contain monosaccharides that are mainly α1–6 linked (α1–6 links cannot be hydrolyzed by salivary amylase) and include isomaltose (glucose α1–6-glucose), isomaltulose (glucose α1–6-fructose, also known as palatinose), and panose (glucose α1–6-glucose α1–4-glucose). These oligosaccharides are produced commercially from starch or sucrose. Plaque pH studies have shown that IMOs are less acidogenic than glucose or sucrose, but may nevertheless result in a pH fall to below 5.0 (see [94] for a review).

Sucromalt is a full calorie sweetener syrup. It is considered as a low-glycemic alternative to sugar and HFCS. Sucromalt is a syrup with a moisture content of 20–25%; its dry matter consists of fructose (35–40%), the disaccharide leucrose (7–15%), other disaccharides (≤3%), and higher saccharides (40–60%).

FOSs are resistant to digestion in the upper gastrointestinal tract and increase the growth of bifidobacteria. FOSs are marketed as Neosugar, Meioligo, Actilight and Nutraflora. Raftilose (also known as oligo-fructose) is also widely used in food, especially in Japan. Experimental studies suggest that FOSs are potentially as cariogenic as sucrose; however, further studies in animals and human plaque pH studies are required to confirm this.

Dental health professionals should be aware, and alert their patients, that nondigestible oligosaccharides are fermentable in the oral cavity; but despite this, products that contain them may be labeled as sugar free (e.g., chewable sugar-free vitamin tablets). They should not be considered safe for teeth.

Likely low cariogenic and noncariogenic mono- and disaccharides

Monosaccharides

Tagatose is similar to fructose in structure and is found in many foods, including dairy products. In comparison with sucrose and other sugars, tagatose produces lower glycemic response and zero calories [113]. Tagatose has physical attributes identical to that of sucrose, and the sweetness is comparable as well.

Disaccharides

Trehalose constitutes two glucose molecules (α1–1). Trehalose is found naturally in foods such as honey and unprocessed mushrooms (mushroom sugar). The most widely known effect of trehalose is its ability to stabilize and protect biologically active molecules in many organisms. An example of this protective function is the resurrection plant (*Selaginella lepidophylla*) that can survive several years of dryness in the desert by synthesizing trehalose to a concentration of 12.5% dry weight. Sweetness is approximately 45% of sucrose. It is only used in small quantities.

Sucrose has five structural isomers, varying in the way the glucose molecule and fructose molecule are bound: palatinose (isomaltulose), trehalulose, turanose, maltulose, and leucrose. Some of these isomers have similar organoleptic properties to sucrose. These isomers have been reported to be noncariogenic disaccharides, as they cannot be utilized by mutans streptococci as substrates for acid production or in glucan synthesis. Trehalulose and leucrose have been shown to be noncariogenic in rats [156].

When screening 146 plaque bacteria isolated from plaque of young children for the ability to ferment these isomers it was concluded that 33% of these strains (predominantly *Actinomyces* spp.) fermented palatinose to lower pH below 5.5 in cultures [90]. Among the palatinose fermenting bacteria, all strains fermented trehalulose, 25% of the strains fermented turanose, 70% of the strains fermented maltulose, and 23% of the strains fermented leucrose. The authors concluded that a significant number of the non-streptococcal oral bacteria are able to ferment the sucrose isomers.

Noncariogenic sucrose substitutes

The noncariogenic sugar substitutes can be separated into two major groups: intense sweeteners (noncaloric) and bulk sweeteners (caloric). Except to benefit oral health, health reasons for using these sugar substitutes include reducing overweight and obesity and thereby the risk of type 2 diabetes and prediabetes. In addition, the use of these sweeteners may also benefit oral health.

Noncaloric intense sweeteners

There are many natural and chemically synthesized intense sweeteners on the market. Some are several thousand times as sweet as sucrose. However, they do not have the same functional properties, such as browning, crystallization, and microbial inhibition, as do sucrose and other saccharides, which limits their use. Nor do they provide bulk. Furthermore, the common perception that noncaloric intense sweeteners may promote weight loss may be misplaced because a positive correlation between consumption of noncaloric intensive sweeteners and increased body mass index in children and adolescents has been reported in several observational studies [34].

Glycyrrhizine (obtained from licorice root), monellin, thaumatin, and miraculin are examples of naturally occurring intense sweeteners. The latter three are extracted from various fruits. The sweeteners alitame and aspartame are based on amino acids or peptides, while acesulfame K, cyclamate, and saccharin are all chemically synthesized sweeteners. Neohesperidine DC is a modified glycoside, extracted from lemon peel. Aspartame is 200 times sweeter than sucrose; therefore, very small amounts are required for sweetening foods, thus making its caloric contribution (because it is made from amino acids it provides 4 kcal/g) insignificant. Advantame, derived from aspartame and vanillin, is an artificial sweetener that is thousands of times sweeter than sucrose and 100 times sweeter than aspartame and could be used in small quantities in food and beverages compared with other sweeteners. Advantame has a clean, sweet taste very similar to aspartame with a slightly longer sweetness duration.

Intense sweeteners are used in a variety of food products, including soft drinks, beer, confectionery, desserts, ice cream, marmalade, and jam. They are also used in dentifrices and in sweetening drops and tablets for use in food, coffee, tea, and so on. Currently, about 30% of the carbonated beverages consumed in the USA are sweetened with aspartame.

For safety reasons, there are strict regulations on the use of intense sweeteners, which vary between countries. It should be pointed out, however, that few side effects of intense sweeteners have been reported in humans. Food labels must declare if a product contains a sweetener, and in the case of aspartame the label must also say that the product contains a source of phenylalanine because some individuals are unable to metabolize this amino acid (i.e., those with phenylketonuria).

Intense sweeteners are not metabolized to acids by oral microorganisms; thus, they cannot cause dental caries. However, in some food products intense sweeteners are added along with sugars (e.g., in fruit-flavored soft drinks), and these products may still be cariogenic.

Sucralose, a chlorinated derivative of sucrose, is now widely available as a sugar substitute with a sensory profile very similar to table sugar [17]. Sucralose has been shown to be noncariogenic in rats [13]. Meyerowitz *et al.* [93] compared the effects on plaque pH *in vivo* of sucralose with nonsweetened and sucrose-sweetened tea. The pH course over 60 min did not differ after the consumption of sucralose-sweetened or nonsweetened tea. Owing to its high relative sweetness, sucralose is used in only very small quantities, with typical dosages at or below 0.02% in foods and drinks. Sucralose can be classified as safe for teeth.

Steviolglycosides

Stevia is a genus of about 240 species of herbs and shrubs in the sunflower family, native to subtropical and tropical regions from western North America to South America. The species *Stevia rebaudiana*, commonly known as sweet leaf, sugar leaf, or simply stevia, is widely grown for its sweet leaves. As a sweetener and sugar substitute, the taste of stevia has a slower onset and longer duration than that of sugar, although some of its extracts may have a bitter or licorice-like aftertaste at high concentrations. With its steviol glycoside extracts (stevioside and rebaudioside A) having approximately 250–300 times the sweetness of sugar, stevia has attracted attention with the rise in demand for low-carbohydrate, low-sugar sweeteners. Because stevia has a negligible effect on blood glucose it is attractive to people on carbohydrate-controlled diets. Stevioside and rebaudioside A were tested for cariogenicity in albino Sprague–Dawley rats. It was concluded that neither stevioside nor rebaudioside A were cariogenic [78]. Commercially available stevia containing tablets (15% stevia, 7% sucralose in a 70% lactose tablet) have recently been tested in an *in vitro* *Streptococcus mutans*-biofilm model on top of bovine enamel slabs [34]. Some demineralization of the enamel slabs occurred, but far less than after incubation with sucrose. The authors suggested the slight demineralization was due to the lactose content of the tablets. Stevia is concluded to be safe for teeth.

Caloric sweeteners

Sugar alcohols

Among the caloric sweeteners, sugar alcohols such as sorbitol and xylitol play an important role because of their good technological properties (sweetness, hygroscopicity, and solubility) and their well-established safety and regulatory acceptance. The use of sugar alcohols as a strategy to improve the dental health has been in focus since the 1970s, and these substances are currently used in confectionery, chewing gum, chocolate, jellies, and other sweets. The main routes of manufacturing sugar alcohols are shown in Fig. 8.9. Table 8.3 gives an overview of the main properties and applications of sugar alcohols, indicating that not all sugar alcohols are suitable for all types of products.

Sugar alcohols provide less energy, with an average of 3 kcal/g compared with 4 kcal/g imparted by mono-, disaccharides, and carbohydrates. One of the disadvantages of sugar alcohols is that they are only partially absorbed in the small intestine and pass to the colon, where they may induce osmotic diarrhea. The upper tolerance limit varies between individuals and among the different sugar alcohols. For this reason, food and drinks containing bulk sweeteners are not recommended for children under 3 years of age. Some individuals may experience a laxative effect from a daily consumption of sugar alcohols when exceeding 20 g of mannitol and ≥50 g of sorbitol.

Sorbitol

Sorbitol, a six-carbon sugar alcohol, cannot be utilized by the microorganisms that dominate in dental plaque. However, the majority of the strains of mutans streptococci, lactobacilli, and some other less frequently encountered oral microorganisms do ferment sorbitol. Concern has been expressed that the observed fermentability of sorbitol, in particular by mutans streptococci, may limit its value as

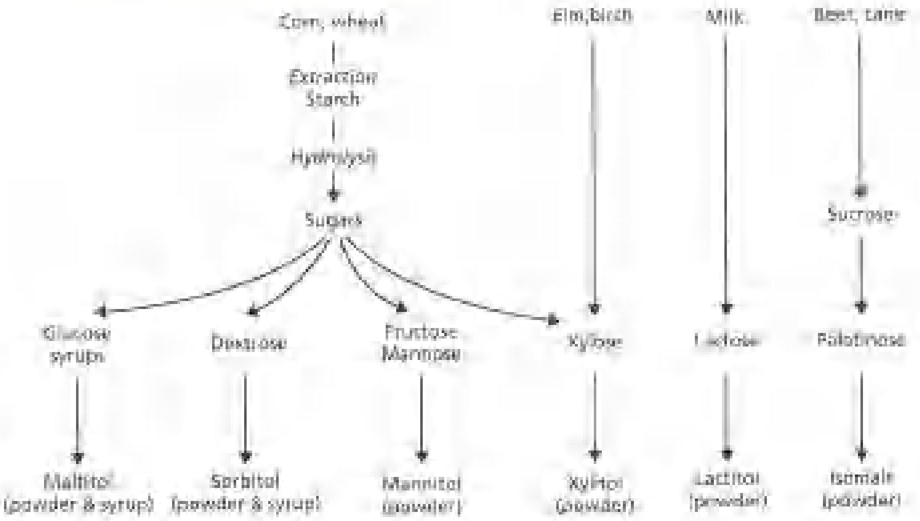


Figure 8.9 The main routes of manufacturing sugar alcohols.

Table 8.3 Properties and applications of various sugar alcohols.

	Properties	Applications
Sorbitol Crystal	Cooling effect Compressible Cryopreservation	Chewing gum Tablet Surimi
Maltitol crystal	High melting point Crystallization	Chocolate Chewing gum, bakery
Sorbitol Liquid	Humectant	Pastry Seasoning
Maltitol Liquid	Anti-crystallizing Plasticizer	Hard-boiled candy Jelly, chewing gum
Xylitol	Cooling effect, crystallization	Chewing gum
Mannitol	Nonhygroscopic	Chewing gum (dusting)
Isomalt	Crystallization Low hygroscopicity	Hard-boiled candy

a noncariogenic sugar substitute. It is essential to bear in mind that there are fundamental differences between the fermentation of sucrose and that of sorbitol by *S. mutans* and other sorbitol-fermenting microorganisms [10]. First, the fermentation of sorbitol proceeds at a rather slow rate, and the final pH in liquid cultures normally does not reach such low levels as are regularly seen with glucose or sucrose. Second, sorbitol is metabolized by inducible enzymes (enzymes that are usually inactive and only activated if exposed to a substrate), which are synthesized only when the bacteria are exposed to sorbitol for a sufficient period. This means that in the presence of glucose the bacterial metabolism is rapidly switched back to the metabolic utilization of this more easily available energy source. The constant presence of low levels of glucose in saliva and the intermittent release of larger amounts of glucose from dietary starch by salivary amylase mean that it is questionable whether dental plaque maintains high sorbitol metabolism. Third, the degradation of sorbitol yields a quantitatively different profile of fermentation end products than the catabolism of sucrose. Under anaerobic conditions, lactic acid is the major product of sucrose fermentation, whereas sorbitol yields considerable amounts of ethanol and formic acid, but a smaller proportion of lactic acid. This observation is relevant because lactic acid exerts a stronger demineralizing effect than the other volatile fermentation end products (see Chapter 7).

Many studies in which changes in plaque pH have been measured after rinsing with sorbitol solution, or after consumption of sorbitol-based sweets, have concluded that plaque pH drops only marginally and that a critical pH of less than 5.7 is very seldom obtained in dental plaque following sorbitol consumption. It has been argued that there may be adaptive changes in dental plaque upon prolonged exposure (e.g., in a person with a dry mouth) and that this may lead to a possible caries risk on exposed root surfaces [59]. Some studies suggest that prolonged or frequent exposure to sorbitol results in changes in plaque ecology in favor of sorbitol-fermenting bacteria. However, there is only anecdotal evidence that these adaptive changes will result in dental plaque that metabolizes sorbitol as rapidly as sucrose or glucose [10]. In relation to potential increases in *S. mutans*, there is no doubt that frequent sucrose exposure provides an ecological advantage to this acidogenic microorganism, whereas frequent exposure to sorbitol has hardly any clinically relevant effect. Therefore, it appears that the potential hypoacidogenic properties of sorbitol do not pose a cariogenic threat to the majority of people.

Xylitol

Xylitol is a pentitol, a sugar alcohol with five carbon atoms. Several studies have shown that most oral streptococci and other microorganisms do not ferment xylitol. In contrast to

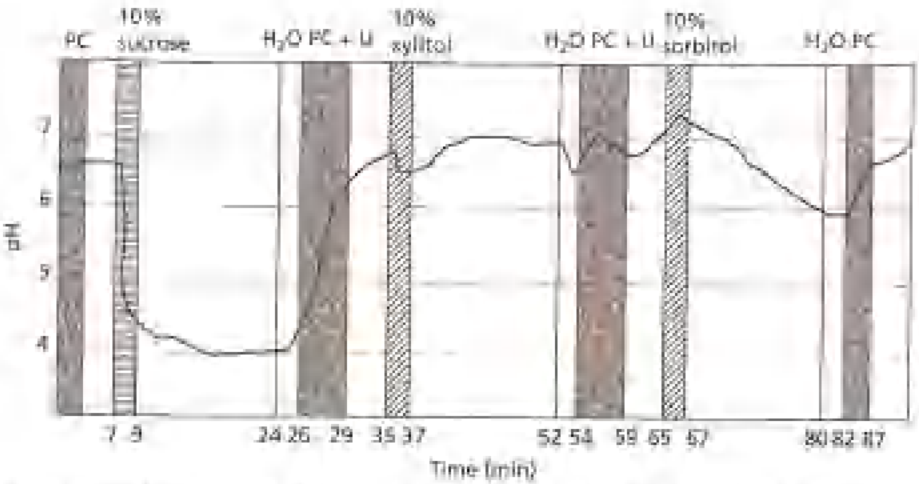


Figure 8.10 The course of pH in interproximal plaque after a 10% sucrose rinse, 10% xylitol rinse, and 10% sorbitol rinse. PC: paraffin chewing; H$_2$O: water rinsing; U: urea rinsing [103].

sorbitol, xylitol exerts a bacteriostatic effect on mutans streptococci *in vitro*. The inhibitory effect is apparently due to the entry of xylitol into the bacterial cell, resulting in an intracellular accumulation of xylitol 5-phosphate. Ultrastructural studies of *S. mutans* and *Streptococcus sobrinus* have shown that the presence of xylitol results in cell degradation, intracellular vacuoles, and other damage to the cell. It is well established that xylitol does not lower the pH of dental plaque *in vivo* or *in vitro* (see Fig. 8.10) [103]. It has been speculated that xylitol may have an inhibitory effect on the acid production from sucrose and glucose in dental plaque. However, the data are conflicting, as some studies *in vitro* have shown such an effect [150], whereas *in vivo* studies have failed to demonstrate a direct inhibitory action of xylitol on the acid production from sugars [103]. This means that it is problematic to mix xylitol with other sugars in the same product and then market them as 'low cariogenic.' Nevertheless, the nonacidogenicity of xylitol in dental plaque is well documented and probably one of the most important factors related to its noncariogenicity. When xylitol is consumed frequently and for a long period, the metabolism of dental plaque has been found to be altered, resulting in less acid formation from sucrose [1]. This may be due to ecological changes in the microflora or reduced production of dental plaque. Another possible mechanism is the accumulation of xylitol 5-phosphate in plaque bacteria after exposure to xylitol.

Xylitol is proposed to reduce the population of mutans streptococci in plaque [53, 80], to make plaque less adherent and to reduce mutans streptococcus binding to the tooth surfaces [134]. This effect was found to depend on the frequency of chewing and the initial level of mutans streptococci [78, 80, 94] and seemed to persist after habitual use of xylitol had stopped [53]. However, other studies on the effect of xylitol did not confirm its inhibitory effect on mutans streptococci [11, 135, 152]. Moreover, the clinical relevance of such bacterial reductions remains to be documented.

Habitual xylitol consumption by mothers over several years may reduce the mother–child transmission of mutans streptococci [136], which may prevent caries in the primary dentition [54]. In a Finnish study carried out in the 1990s, high-caries-risk mothers used xylitol gum on a daily basis when their babies were 3–24 months old. The control high-risk mothers received biannual fluoride or chlorhexidine treatments. The xylitol program reduced colonization of mutans streptococci and early childhood caries in children. A post-trial follow up when the children were 10 years of age revealed that the median caries-free age (dmft =0/DMFT =0) was 8.2 years in the xylitol and 5.8 years in the control group [66]. Thus, while the children in the xylitol group were caries free for longer than children in the control group, they still developed caries over time. These studies are criticized because the evaluation took place after a long period in which the behavior of the participants was not controlled. The preventive behavior of the families might have been quite different.

Other sugar alcohols

Polyols other than sorbitol and xylitol are currently used as bulk sweeteners, especially in confectionery products. These include mannitol, maltitol, lactitol, isomalt, and the product Lycasin®. Although these sweeteners have not been evaluated as extensively as sorbitol and xylitol, animal studies, plaque pH studies *in vivo*, and incubation studies *in vitro* have indicated that they have a non- or low cariogenic potential. Other sugar alcohols are emerging, such as erythritol (a four-carbon polyol) [62, 85]. *In vitro* incubation with a range of *Streptococcus* species has shown that no acids are produced from erythritol [62]. In clinical trials erythritol had similar effects to xylitol on the amount of plaque and the levels of mutans streptococci [86]. The results of a recent clinical trial, however, suggest that in relatively low caries conditions the school-based use of *xylitol/maltitol* or *erythritol/maltitol lozenges* would not have an additional caries-preventive effect above a traditional prevention program involving fluorides [72].

Mannitol, like sorbitol, is a hexitol. It is industrially prepared by hydrogenation of invert sugar, sucrose, or monosaccharides. Lactobacilli and *S. mutans* are unique among the dental plaque microflora in their ability to ferment the two-sugar alcohols mannitol and sorbitol (see 'Sorbitol' section). The enzymes mannitol 6-phosphate dehydrogenase and sorbitol 6-phosphate dehydrogenase involved in hexitol catabolism, however, are inducible (the enzyme is only activated when exposed to a substrate) and their synthesis is inhibited by the presence of glucose in saliva [14]. Accordingly, mannitol is of low acidogenicity [7, 49].

Maltitol is a 12-carbon polyol, which is produced by hydrogenation of maltose. This sugar alcohol cannot be metabolized by most oral microorganisms, but can be fermented at slow rate by mutans streptococci, *Actinomyces*, and some species of lactobacilli [25]. Both animal experiments and plaque pH studies in human volunteers have suggested maltitol as virtually noncariogenic. Maltitol lozenges, when consumed four times a day for 3 months did not affect plaque formation, acid production, or the number of mutans streptococci and lactobacilli in dental plaque [11].

Research on the dental properties of lactitol (12-carbon polyol) as a bulk sweetener to replace dietary sugar revealed that it was not easily metabolized by acidogenic and polysaccharide-forming oral microorganisms. Intra-oral acid development and dental plaque formation from lactitol in humans were substantially lower than from sucrose [38].

Isomalt or palatinit is a 1:1 mixture of two 12-carbon polyols. When evaluating the cariogenicity of isomalt from a bacteriological point of view it was concluded to be comparable to sorbitol, maltitol, and Lycasin® [12].

Lycasin® is produced from potato or corn starch by partial acid or enzymatic hydrolysis and subsequent hydrogenation at high pressure and high temperature. Various types have been manufactured. Animal and bacteriological studies have shown that Lycasin® has a low to medium cariogenic potential depending on which type of Lycasin® has been used. Hard sugared confectionery sweetened with Lycasin®, with a high content of maltitol and a low content of higher saccharides, causes a relatively small decrease in plaque pH [51].

Clinical trials with sorbitol

In the first clinical study with sorbitol, children receiving sorbitol tablets developed 49% less caries than control children that did not get tablets [133]. After this initial study, many studies using sorbitol-sweetened gum [8, 37, 79, 81, 97, 98, 115, 142] and chocolates [7] have been carried out. Most clinical trials with sorbitol-sweetened gums indicate that daily three to five times between- or after-meal consumption of sorbitol-sweetened chewing gum has an anticaries effect in comparison with controls without gum use. In a systematic review, Deshpande and Jadad [33] concluded that the preventive fraction for sorbitol-blended gum was 20% and for sorbitol–mannitol-blended chewing gum it was 11% for the permanent dentition. Chewing sorbitol gum may also be effective in the prevention of caries in the primary dentition, but owing to the limited number of studies, it is impossible to quantify the effect. In 6-year-old children, chewing sorbitol pellet gum resulted in a 55% decrease of the caries increment in the primary dentition when the children were compared with non-gum users after the 2-year evaluation period [83]. When sorbitol stick gums were chewed the reduction was 30%.

Clinical trials with xylitol

In the first clinical xylitol study, the Turku sugar study, dietary sucrose was almost completely replaced by xylitol (Fig. 9.2). After 2 years the sucrose group had developed 7.2 new DMFS and the xylitol group zero [131]. In a parallel 1-year chewing gum study, the group receiving a sucrose-sweetened gum developed approximately three new DMFS, while in the xylitol group (gums were sweetened with 50% xylitol and 6% sorbitol) the number of DMFS (including noncavitated lesions) decreased by one DMFS [130]. The reversal of caries may not be solely attributed to xylitol. Increased salivary flow as a result of chewing may also have accounted for the caries reduction. However, since no control group chewing a placebo gum was included in the study, it was not possible to distinguish between different reasons for the caries reduction.

The Ylivieska studies in Finland evaluated the effect of chewing frequency: ≤1.5 pieces of xylitol gum a day, 1.5–2.5 pieces, or 3 pieces [52]. After 2 years the DMFS increments in the ≤1.5 gum group did not differ from the no-gum control group. In the 1.5–2.5 pieces group there was a nonsignificant difference of approximately 30%, and in the three-pieces group the reduction was significant at approximately 55–60%. Caries reduction after using xylitol chewing gum three to five times a day was confirmed in several later studies in children and adolescents [3, 52, 60, 79, 81] and in elderly individuals where root caries was prevented [84]. When evaluated in an adult population, participants using xylitol lozenges developed 40% fewer root caries lesions than those in the placebo arm [122].

Chewing gum with mixtures of sorbitol and xylitol has also been found effective when chewed five times a day [3, 60, 81]. Altogether, there is a considerable amount of evidence that the use of gum or sweets sweetened with xylitol or a mixture of xylitol and sorbitol prevents dental caries when used daily for several times and minutes a day. Compared with controls without gum use, the prevented fraction varied from 59% for xylitol to 53% for xylitol-sorbitol blend [23].

'Remineralization' as a result of using sugar alcohols has been suggested, but the evidence from clinical trials is not clear. In the Belize chewing gum study, 'rehardening' was observed in 10–37% of the dentinal lesions in the younger children [82]. The use of xylitol chewing gum five times daily tended to be more effective in 'rehardening' than when the gum was chewed less frequently or when it was sweetened with sorbitol. However, the types of lesions shown in the publication were mostly large, open occlusal caries cavities, which are easily subjected to functional attrition and plaque removal by chewing. It is likely, therefore, that the mechanical effect of chewing, and not the sugar alcohol itself, was responsible for these clinical changes. Hence, in spite of what some authors suggest, the present state of the art does not support an active caries 'remineralizing' effect of xylitol.

Chew or polyol effect

To measure the caries preventive effect of the polyols per se, polyol-sweetened gums should be compared with a control gum that does not contain polyols but is sweetened by a nonacidogenic/noncariogenic sweetener. Recently, it was shown that such a control gum was as effective as a sorbitol- or xylitol-sweetened gum, indicating that the caries preventive effect of chewing sugar-free gum is related to the chewing process rather than being an effect of the polyols [79]. The importance of chewing would also explain why gum pellets with a harder texture were more effective in caries prevention than were softer gum sticks, as demonstrated in the Belize study [81, 83]. Chewing stimulates salivary flow [124], as does sucking of lozenges [146]. It is not surprising, therefore, that the caries preventive effect of candies sweetened with xylitol and maltitol or polydextrose has been reported to be similar to that of chewing xylitol chewing gum [3]. If there was an effect of polyols per se it might become visible when subjects rinse with a polyol solution. Giertsen *et al.* [36], however, showed no effect of 4 weeks three times daily rinsing for 1 min with a 40% xylitol solution on salivary flow rate, on the total number of colony-forming units of streptococci or mutans streptococci in saliva, on dental plaque accumulation, gingivitis development, or the acidogenic potential of plaque.

Many of the studies referred to above suggest that a certain amount of xylitol should be consumed to be effective in caries prevention. However, the studies with gums containing different amounts of xylitol do not support this suggestion. For instance, the study of Kandelman and Gagnon [60] indicates that as little as 0.9 g of xylitol in chewing gum was sufficient for caries prevention, while the Ylivieska study suggests that at least 7 g of xylitol would be necessary [52]. Also, when comparing the mixed xylitol/sorbitol groups in the Belize study, those consuming the lowest daily amount of xylitol (2 g versus 6 g a day) had the lowest caries increment, although the difference was not statistically significant [81].

Protective factors in foods

Dairy products

Despite being one of the main sources of sugars in the diet of young children, cow's milk is noncariogenic. The sugar in milk is lactose, which is the least acidogenic and cariogenic sugar, and milk is also known to contain protective factors.

Compared with cow's milk, breast milk contains more lactose (~7% versus 4–5%) and lower concentrations of calcium and phosphate and may in theory be more cariogenic. However, epidemiological evidence indicates that breast feeding is associated with lower dental caries [47, 132]. This could be a secondary effect due to socioeconomic status, which is linked to both breast feeding and lower consumption of sugars. However, there is no opportunity to add additional sugar to breast milk feeds, and breast fed infants are less likely to use reservoir feeders containing sugary liquids [125]. There have been reports of cases of severe dental caries associated with prolonged (usually over 2 years) on-demand breast feeding, often when infants have suckled during the night [40]. However, these cases are rare and associated with unusual feeding practices (see Chapter 17). Breast feeding should be promoted since it provides the best infant nutrition.

Numerous animal and experimental studies have indicated that cheese is anticariogenic (see [100] for a review). It has been speculated that consumption of cheese increases oral pH by stimulating salivary flow and raises plaque calcium concentrations, both of which protect against demineralization. Meals containing cooked cheese have also been shown to increase plaque calcium concentrations, which might be effective in reducing caries [57]. Cheese intake was shown to be higher in children who remained caries free over a 2-year period than in children who developed most caries [126], and children who consumed 5 g of Edam daily following breakfast for a period of 2 years had a significantly lower caries increment compared with controls [32]. A similar relationship has been found in a more recent Swedish study [110].

The dairy components that have anticariogenic properties are calcium, phosphate, casein, and lipids. Casein added to food (e.g., chocolate) reduces cariogenicity, but since it is required in large amounts that cause the product to taste bad its use in a food is precluded [121]. Digestion of casein did not destroy the protein's ability to prevent enamel demineralization in a human oral caries model. Two casein digestives, caseinophosphopeptides (CPP) and glycomacropeptide (GMP), have been patented for use in common personal hygiene products to prevent dental caries. Research has shown that CPP and GMP may inhibit growth of *S. mutans* and other oral species [56, 105, 106]. Additionally, CPP forms nanoclusters with amorphous calcium phosphate at the tooth surface to provide a reservoir of calcium and phosphate ions to maintain a state of supersaturation with respect to tooth enamel. In an in-situ study, greater remineralization was produced by CPP-ACP sugar-free gum, compared with gum without CPP-ACP and a no-gum control [19].

Probiotics

The idea of using bacteria, often administered in food products, to modify plaque virulence has been researched for many years. There have been several approaches. There have been investigations into how the resident oral flora associated with health could be favored over the species associated with disease. Many early studies concentrated on using bacteria known to compete with cariogenic bacteria [45, 143, 149]. Another approach was to replace, for instance, *S. mutans* strains with strains of attenuated virulence (lactate dehydrogenase deficiency) and increased competitiveness [46]. Another study utilized a recombinant strain of *S. mutans* expressing urease, which was shown to reduce the cariogenicity of plaque in an animal model [18]. Recently, there has been focus to maintain a healthy oral flora by modification by nonresident bacteria, the *probiotic* approach. The rationale for this approach in controlling oral health stems from medical studies in which it was shown that probiotic bacteria may confer health benefits by alleviating infections in the gastrointestinal tract (for a review, see [108]).

Probiotic bacteria include a large spectrum of bacteria primarily belonging to the genera *Lactobacillus* and *Bifidobacterium* [112] that are common inhabitants of the oral microbiota. It was shown that such bacteria can adsorb to saliva-coated hydroxyapatite *in vitro* [20, 42]. Furthermore, these bacteria are capable of fermenting a broad range of sugars *in vitro*, which can lead to lowering of pH beyond the 'critical' value for dissolution of dental hard tissues [43, 44]. The acidogenic properties of probiotic bacteria raise concerns that ingestion of probiotics might have a negative side effect by promoting caries lesion development. However, clinical studies have not been able to prove that dental plaque serves as a reservoir of probiotic bacteria *in vivo* [88, 120], neither does short-term consumption (tablets) of probiotic lactobacilli have an effect on acid production in supragingival plaque [88]. With the current state of knowledge, therefore, it is difficult to conceive that probiotic bacteria should have an inhibitory effect on caries, as described in some clinical trials [104, 116, 140]. Well-conducted studies with a proper study design are needed to clarify this question (for reviews, see [91, 92]).

Diet and dental erosion

In addition to being the main driver of dental caries, diet plays an important role in dental erosion, a destructive process that results in the surface dissolution of dental hard tissues. As explained in Chapter 9, caries is defined as chemical dissolution of dental hard tissues caused by acids produced in biofilms covering the tooth surfaces. In contrast, erosion is defined as a dissolution of apatite mineral caused by acids of any other origin (soft drinks, food, fruit, stomach content, airborne, etc.) introduced into the oral environment. Erosion removes mineral layer by layer from the tooth surfaces (compare Fig. 9.8 with Fig. 9.7). Dental erosion is the main driver of pathologic tooth wear by exposure to acidic substances, and along with abrasion and attrition contributes to the multifactorial nature of this condition [68].

The clinical expression of dental erosion is modified by the chemical and physical properties of a food or beverage [69, 77], and biological and behavioral factors [155]. Changes in lifestyle and the increasing availability of acidic beverages and juices are considered to be responsible for an increase in the prevalence of dental erosion, primarily in young children and adolescents [4, 96]. In addition, the improvement in oral hygiene and obsession with 'whiter teeth' may be having an unintended negative consequence by rendering teeth more at risk for acids of intrinsic and extrinsic origin.

The potential of acidic foods and beverages to cause erosion has been known for a long time. A wide range of acidic food substances has been implicated by varying degrees of scientific evidence, including citrus fruit juices and other acidic fruit juices, acidic carbonated beverages, acidic uncarbonated beverages, acidic sport drinks, wines, cider, acidic herbal teas, citrus fruits and other acidic fruits and berries, salad dressing, vinegar conserves, and acidic fruit-flavored candies (for a review, see [154]). Of particular dietary concern is the high and increasing intake of acidic beverages, especially juices and soft drinks [67]. In the USA the consumption by adolescents of fruit juices and soft drinks has more than doubled over the past 30 years, while over the same period the consumption of milk decreased 36% [16].

The ultimate erosive potential of a food or drink depends on an interaction of its chemical properties (pH, total acid content, calcium, and phosphate content, and adhesiveness), biological factors (salivary flow rate, buffering capacity and composition, pellicle formation, tooth composition, and dental and soft tissue anatomy), and behavioral (lifestyle) factors (eating and drinking habits, especially the frequency, duration, and timing of exposure). In particular, drinking habits have, in relation to drink consumption, been found as a factor that may influence the risk for dental erosion [58]. The interplay of all these factors at a given tooth surface determines the degree of saturation in relationship to tooth mineral (see Chapter 9) and whether erosion will occur or not. It is important to stress that fluoride does not reduce dental erosion caused by soft drinks [70] for the reasons presented in Chapter 9.

Conclusion

A diet void of naturally occurring sugars and fermentable carbohydrates is not feasible, and a diet void of added sugars would be difficult to achieve and maintain. However, with diligent practice of oral hygiene with a fluoride-containing toothpaste and a nutritionally sensible diet, most people should be able to enjoy foods considered 'bad' for the teeth without any risk to their dental health. The practical aspects of dietary investigation and advice for the individual patient are dealt with in Chapter 17.

References

1. Aguirre-Zero O, Zero DT, Proskin HM. Effect of chewing xylitol chewing gum on salivary flow rate and the acidogenic potential of dental plaque. *Caries Res* 1993; 27: 55–9.
2. Ahldén ML, Frostell G. Variation in pH of plaque after a mouth rinse with a saturated solution of mannitol. *Odontol Revy* 1975; 26: 1–5.
3. Alanen P, Isokangas P, Gutmann K. Xylitol candies in caries prevention: results of a field study in Estonian children. *Community Dent Oral Epidemiol* 2000; 28: 218–24.
4. Al-Dlaigan YH, Shaw L, Smith A. Dental erosion in a group of British 14-year-old school children. Part II: Influence of dietary intake. *Br Dent J* 2001; 190: 258–61.
5. Al-Khatib GR, Toumba KJ, Duggal MS, Pollard MA, Curzon MEJ. An *in vivo* evaluation of the demineralising potential of maltodextrin using an intra oral cariogenicity testing method. *Caries Res* 1997; 31: 316.
6. Al-Khatib GR, Duggal MS, Toumba KJ. An evaluation of the acidogenic potential of maltodextrins *in vivo*. *J Dent* 2001; 29: 409–14.
7. Bánóczy J, Hadas E, Esztary I, Marosi I, Nemes J. Three-year results with sorbitol in clinical longitudinal experiments. *J Int Assoc Dent Child* 1981; 12: 59–63.
8. Beiswanger BB, Boneta AE, Mau MS, Katz BP, Proskin HM, Stookey GK. The effect of chewing sugar-free gum after meals on clinical caries incidence. *J Am Dent Assoc* 1998; 129: 1623–6.
9. Berdmore T. *A treatise on the disorders of the teeth and gums*. Dublin, 1768.
10. Birkhed D, Bär A. Sorbitol and dental caries. *World Rev Nutr Diet* 1991; 65: 1–37.
11. Birkhed D, Edwardsson S, Ahldén M-L, Frostell G. Effects of 3 months frequent consumption of hydrogenated starch hydrolysate (Lycasin®), maltitol, sorbitol and xylitol on human dental plaque. *Acta Odontol Scand* 1979; 37: 103–15.
12. Birkhed D, Kalfas S, Svensäter G, Edwardsson S. Microbiological aspects of some caloric sugar substitutes. *Int Dent J* 1985; 35: 9–17.
13. Bowen WH, Young DA, Pearson SK. The effects of sucralose on coronal and root-surface caries. *J Dent Res* 1990; 69: 1485–7.
14. Brown AT, Wittenberger CL. Mannitol and sorbitol catabolism in *Streptococcus mutans*. *Arch Oral Biol* 1973; 18: 117–26.
15. Burt BA, Pai S. Is sugar consumption still a major determinant of dental caries? A systematic review. *J Dent Educ* 2001; 65: 1017–23.
16. Cavadini C, Siega-Riz AM, Popkin BM. US adolescent food intake trends from 1965 to 1996. *Arch Dis Child* 2000; 83: 18–24.
17. Cardoso JMP, Bolini HMA. Descriptive profile of peach nectar sweetened with sucrose and different sweeteners. *J Sens Stud* 2008; 23: 804–16.
18. Clancy KA, Pearson S, Bowen WH, Burne RA. Characterization of recombinant, ureolytic *Streptococcus mutans* demonstrates an inverse relationship between dental plaque ureolytic capacity and cariogenicity. *Infect Immun* 2000; 68: 2621–9.
19. Cochrane NJ, Shen P, Byrne SJ, Walker GD, Adams GG, Yuan Y, Reynolds C, Hoffmann B, Dashper SG, Reynolds EC. Remineralisation by chewing sugar-free gums in a randomised, controlled in situ trial including dietary intake and gauze to promote plaque formation. *Caries Res* 2012; 46: 147–55.
20. Comelli EM, Guggenheim B, Stingele F, Neeser JR. Selection of dairy bacterial strains as probiotics for oral health. *Eur J Oral Sci* 2002; 110: 218–24.
21. Curzon MEJ, Hefferren JJ. Modern methods for assessing the cariogenic and erosive potential of foods. *Br Dent J* 2001; 191: 41–6.
22. Das S, Das AK, Murphy RA, Punwani IC, Nasution MP, Kinghorn AD. Evaluation of the cariogenic potential of the intense natural sweeteners stevioside and rebaudioside A. *Caries Res* 1992; 26: 363–6.
23. Deshpande A, Jadad AR. The impact of polyol-containing chewing gums on dental caries: a systematic review of original randomized controlled trials and observational studies. *J Am Dent Assoc* 2008; 139: 1602–14.
24. Duggal MS, Toumba KJ, Amaechi BT, Kowash MB, Higham SM. Enamel demineralization in situ with various frequencies of carbohydrate consumption with and without fluoride toothpaste. *J Dent Res* 2001; 80: 1721–4.
25. Edwardsson S, Birkhed D, Mejàre B. Acid production from Lycasin, maltitol, sorbitol and xylitol by oral streptococci and lactobacilli. *Acta Odontol Scand* 1977; 35: 257–63.
26. EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA). Scientific opinion on the substantiation of a health claim related to "non-fermentable" carbohydrates and maintenance of tooth mineralisation by decreasing tooth demineralisation pursuant to Article 13(5) of Regulation (EC) No 1924/2006. *EFSA J* 2013; 11: 3329.
27. Fauchard P. *Chirurgien dentiste*. Paris: Pierre-Jean Mariette, 1746.
28. Fejerskov O, Scheie AA, Manji F. The effect of sucrose on plaque pH in the primary and permanent dentition of caries-inactive and -active Kenyan children. *J Dent Res* 1992; 71: 25–31.
29. Fisher FJ. A field study of dental caries, periodontal disease and enamel defects in Tristan da Cunha. Part 2. Methods and results. *Br Dent J* 1968; 125: 447–53.
30. Fitch C, Keim KS; Academy of Nutrition and Dietetics. Position of the Academy of Nutrition and Dietetics: use of nutritive and nonnutritive sweeteners. *J Acad Nutr Diet* 2012; 112: 739–58.
31. Frostell G, Birkhed D, Edwardsson S, Goldberg P, Petersson LG, Priwe C, Winholt AS. Effect of partial substitution of invert sugar for sucrose in combination with Duraphat treatment on caries development in preschool children: the Malmö Study. *Caries Res* 1991; 25: 304–10.
32. Gedalia I, Ben Mosheh S, Biton J, Kogan D. Dental caries protection with hard cheese consumption. *Am J Dent* 1994; 7: 331–2.
33. Giacaman RA, Campos P, Muñoz-Sandoval C, Castro RJ. Cariogenic potential of commercial sweeteners in an experimental biofilm caries model on enamel. *Arch Oral Biol* 2013; 58: 1116–22.
34. Giammattei J, Blix G, Marshak HH, Wollitzer AO, Pettitt DJ. Television watching and soft drink consumption: associations with obesity in 11- to 13-year-old schoolchildren. *Arch Pediatr Adolesc Med* 2003; 157: 882–6.
35. Gibson S, Williams S. Dental caries in pre-school children: associations with social class, toothbrushing habit and consumption of sugars and sugar-containing foods. Further analysis of data from the national diet and nutrition survey of children aged 1.5–4.5 years. *Caries Res* 1999; 33: 101–13.
36. Giertsen E, Emberland H, Scheie AA. Effects of mouth rinses with xylitol and fluoride on dental plaque and saliva. *Caries Res* 1999; 33: 23–31.
37. Glass RL. A two-year clinical trial of sorbitol chewing gum. *Caries Res* 1983; 17: 365–8.
38. Grenby TH. Latest state of research on lactitol and dental caries. *Int Dent J* 1989; 39: 25–32.
39. Gustafsson BE, Quensel CE, Swenander Lanke L, Lundqvist C, Grahnén H, Bonow BE, Krasse B. The Vipeholm Dental Caries Study. The effect of different levels of carbohydrate intake on caries activity in 436 individuals observed for five years. *Acta Odontol Scand* 1954; 11: 232–364.

40. Hackett AF, Rugg-Gunn AJ, Murray JJ, Roberts GJ. Can breast feeding cause dental caries? *Hum Nutr Appl Nutr* 1984; 38A: 23–8.
41. Harris R. Biology of the children of Hopewood House, Bowral, Australia. 4. Observations of dental caries experience extending over five years (1957–1961). *J Dent Res* 1963; 42: 1387–99.
42. Haukioja A, Yli-Knuuttila H, Loimaranta V, Kari K, Ouwehand AC, Meurman JH, Tenovuo J. Oral adhesion and survival of probiotic and other lactobacilli and bifidobacteria in vitro. *Oral Microbiol Immunol* 2006; 21: 326–32.
43. Haukioja A, Söderling E, Tenovuo J. Acid production from sugars and sugar alcohols by probiotic lactobacilli and bifidobacteria in vitro. *Caries Res* 2008; 42: 449–53.
44. Hedberg M, Hasslöf P, Sjöström I, Twetman S, Stecksén-Blicks C. Sugar fermentation in probiotic bacteria – an in vitro study. *Oral Microbiol Immunol* 2008; 23: 482–5.
45. Hillman JD. Genetically modified *Streptococcus mutans* for the prevention of dental caries. *Antonie Van Leeuwenhoek* 2002; 82: 361–6.
46. Holloway PJ, James PM, Slack GL. Dental disease of inhabitants of Tristan da Cunha in 1962. *Arch Oral Biol* 1962; 7 (Suppl): 335–40.
47. Holt RD, Joels D, Winter GB. Caries in pre-school children: the Camden study. *Br Dent J* 1982; 153: 107–9.
48. Humphrey LT, de Groote I, Morales J, Barton N, Collcutt S, Bronk Ramsey C, Bouzouggar A. Earliest evidence for caries and exploitation of starchy plant foods in Pleistocene hunter-gatherers from Morocco. *Proc Natl Acad Sci U S A* 2014; 111: 954–9.
49. Imfeld T. Identification of low caries risk dietary components. *Monogr Oral Sci* 1983; 11: 1–198.
50. Imfeld T. *Identification of low caries risk dietary components.* Basel: Karger, 1983.
51. Imfeld T, Mühlemann HR. Addendum to: Acid production from Swedish Lycasin (candy quality) and French Lycasin (80/55) in human dental plaque. *Caries Res* 1978; 12: 256–63.
52. Isokangas P, Alanen P, Tiekso J, Mäkinen KK. Xylitol chewing gum in caries prevention: a field study in children. *J Am Dent Assoc* 1988; 117: 315–20.
53. Isokangas P, Tenovuo J, Söderling E, Männistö H, Mäkinen KK. Dental caries and mutans streptococci in the proximal areas of molars affected by habitual use of xylitol chewing gum. *Caries Res* 1991; 25: 444–8.
54. Isokangas P, Söderling E, Pienihäkkinen K, Alanen P. Occurrence of dental decay in children after maternal consumption of xylitol chewing gum, a follow-up from 0 to 5 years of age. *J Dent Res* 2000; 79: 1885–9.
55. Issa AI, Toumba KJ, Preston AJ, Duggal MS. Comparison of the effects of whole and juiced fruits and vegetables on enamel demineralisation in situ. *Caries Res* 2011; 45: 448–52.
56. Janer C, Rohr LM, Peláez C, Laloi M, Cleusix V, Requena T, Meile L. Hydrolysis of oligofructoses by the recombinant beta-fructofuranosidase from *Bifidobacterium lactis*. *Syst Appl Microbiol* 2004; 27: 279–85.
57. Jenkins GN, Hargreaves JA. Effect of eating cheese on Ca and P concentrations of whole mouth saliva and plaque. *Caries Res* 1989; 23: 159–64.
58. Johansson AK, Lingström P, Imfeld T, Birkhed D. Influence of drinking method on tooth-surface pH in relation to dental erosion. *Eur J Oral Sci* 2004; 112: 484–9.
59. Kalfas S, Svensäter G, Birkhed D, Edwardsson S. Sorbitol adaptation of dental plaque in people with low and normal salivary-secretion rates. *J Dent Res* 1990; 69: 442–6.
60. Kandelman D, Gagnon G. A 24-month clinical study of the incidence and progression of dental caries in relation to consumption of chewing gum containing xylitol in school preventive programs. *J Dent Res* 1990; 69: 1771–5.
61. Kaur N, Gupta AK. Applications of inulin and oligofructose in health and nutrition. *J Biosci* 2002; 27: 703–14.
62. Kawanabe J, Hirasawa M, Takeuchi T, Oda T, Ikeda T. Noncariogenicity of erythritol as a substrate. *Caries Res* 1992; 26: 358–62.
63. König KG. Changes in the prevalence of dental caries: how much can be attributed to changes in diet? *Caries Res* 1990; 24 (Suppl 1): 16–18.
64. König KG, Navia JM. Nutritional role of sugars in oral health. *Am J Clin Nutr* 1995; 62 (Suppl): 275S–283S.
65. Koulourides T, Bodden R, Keller S, Manson-Hing L, Lastra J, Housch T. Cariogenicity of nine sugars tested with an intraoral device in man. *Caries Res* 1976; 10: 427–41.
66. Laitala ML, Alanen P, Isokangas P, Söderling E, Pienihäkkinen K. Long-term effects of maternal prevention on children's dental decay and need for restorative treatment. *Community Dent Oral Epidemiol* 2013; 41: 534–40.
67. Larsen MJ. Degrees of saturation with respect to apatites in fruit juices and acidic drinks. *Scand J Dent Res* 1975; 83: 13–17.
68. Larsen MJ. Erosion of the teeth. In: Fejerskov O, Kidd EAM, eds. *Dental caries. The disease and its clinical management*, 2nd ed. Oxford: Blackwell Munksgaard, 2008: 233–48.
69. Larsen MJ, Nyvad B. Enamel erosion by some soft drinks and orange juices relative to their pH, buffering effect and contents of calcium phosphate. *Caries Res* 1999; 33: 81–7.
70. Larsen MJ, Richards A. Fluoride is unable to reduce dental erosion from soft drinks. *Caries Res* 2002; 36: 75–80.
71. Leeds AR, Rowland IR. *Gut flora and health: past, present and future.* London: Royal Society of Medicine Press, 1996.
72. Lenkkeri AM, Pienihäkkinen K, Hurme S, Alanen P. The caries-preventive effect of xylitol/maltitol and erythritol/maltitol lozenges: results of a double-blinded, cluster-randomized clinical trial in an area of natural fluoridation. *Int J Paediatr Dent* 2012; 22: 180–90.
73. Lingström P, Birkhed D, Granfeldt Y, Björck I. pH measurements of human dental plaque after consumption of starchy foods using the microtouch and the sampling method. *Caries Res* 1993; 27: 394–401.
74. Lingström P, Imfeld T, Birkhed D. Comparison of three different methods for measurement of plaque-pH in humans after consumption of soft bread and potato chips. *J Dent Res* 1993; 72: 865–70.
75. Linke HA, Moss SJ, Arav L, Chiu PM. Intra-oral lactic acid production during clearance of different foods containing various carbohydrates. *Z Ernährungswiss* 1997; 36: 191–7.
76. Lundqvist C. Trans. by Evans CEM. *Oral sugar clearance: its influence on dental caries activity.* Lund: CWK Gleerup, 1952.
77. Lussi A, Jaeggi T, Schärer S. The influence of different factors on in vitro enamel erosion. *Caries Res* 1993; 27: 387–93.
78. Ly KA, Milgrom P, Roberts MC, Yamaguchi DK, Rothen M, Mueller G. Linear response of mutans streptococci to increasing frequency of xylitol chewing gum use: a randomized controlled trial. *BMC Oral Health* 2006; 6: 6–12.
79. Machiulskiene V, Nyvad B, Baelum V. Caries preventive effect of sugar-substituted chewing gum. *Community Dent Oral Epidemiol* 2001; 29: 278–88.
80. Mäkinen KK, Söderling E, Isokangas P, Tenovuo J, Tiekso J. Oral biochemical status and depression of *Streptococcus mutans* in children during 24- to 36-month use of xylitol chewing gum. *Caries Res* 1989; 23: 261–7.
81. Mäkinen KK, Bennett CA, Hujoel PP, Isokangas PJ, Isotupa KP, Pape HR, Mäkinen P-L. Xylitol chewing gums and caries rates: a 40-month cohort study. *J Dent Res* 1995; 74: 1904–13.
82. Mäkinen KK, Mäkinen P-L, Pape HR Jr, Allen P, Bennett CA, Isokangas PJ, Isotupa KP. Stabilisation of rampant caries: polyol gums and arrest of dentine caries in two long-term cohort studies in young subjects. *Int Dent J* 1995; 45: 93–107.
83. Mäkinen KK, Hujoel PP, Bennett CA, Isotupa KP, Mäkinen P-L, Allen P. Polyol chewing gums and caries rates in primary dentition: a 24-month cohort study. *Caries Res* 1996; 30: 408–17.
84. Mäkinen KK, Pemberton D, Mäkinen P-L, Chen C-Y, Cole J, Hujoel PP, Lopatin D, Lambert P. Polyol-combinant saliva stimulants and oral health in Veterans Affairs patients – an exploratory study. *Spec Care Dentist* 1996; 16: 104–15.
85. Mäkinen KK, Isotupa KP, Kivilompolo T, Mäkinen P-L, Toivanen J, Söderling E. Comparison of erythritol and xylitol saliva stimulants in the control of dental plaque and mutans streptococci. *Caries Res* 2001; 35: 129–35.
86. Mäkinen KK, Saag M, Isotupa KP, Olak J, Nõmmela R, Söderling E, Mäkinen P-L. Similarity of the effects of erythritol and xylitol on some risk factors of dental caries. *Caries Res* 2005; 39: 207–15.
87. Marthaler TM. Hereditary fructose intolerance. *Br Dent J* 1967; 123: 597–9.
88. Marttinen A, Haukioja A, Karjalainen S, Nylund L, Satokari R, Öhman C, Holgerson P, Twetman S, Söderling E. Short-term consumption of probiotic lactobacilli has no effect on acid production of supragingival plaque. *Clin Oral Investig* 2012; 16: 797–803.

89. Masood M, Masood Y, Newton T. Impact of national income and inequality on sugar and caries relationship. *Caries Res* 2012; **46**: 581–8.
90. Matsuyama J, Sato T, Hoshino E, Noda T, Takahashi N. Fermentation of five sucrose isomers by human dental plaque bacteria. *Caries Res* 2003; **37**: 410–5.
91. Meurman JH. Probiotics: do they have a role in oral medicine and dentistry? *Eur J Oral Sci* 2005; **113**: 188–96.
92. Meurman JH, Stamatova I. Probiotics: contributions to oral health. *Oral Dis* 2007; **13**: 443–51.
93. Meyerowitz C, Syrrakou EE, Raubertas RF. Effect of sucralose – alone or bulked with maltodextrin and/or dextrose – on plaque pH in humans. *Caries Res* 1996; **30**: 439–44.
94. Milgrom P, Ly KA, Roberts MC, Rothen M, Mueller G, Yamaguchi DK. Mutans streptococci dose response to xylitol chewing gum. *J Dent Res* 2006; **85**: 177–81.
95. Miller WD. *The microorganisms of the human mouth*. Philadelphia, PA: S.S. White; 1890.
96. Millward A, Shaw L, Smith AJ, Rippin JW, Harrington E. The distribution and severity of tooth wear and the relationship between erosion and dietary constituents in a group of children. *Int J Paediatr Dent* 1994; **4**: 152–7.
97. Møller IJ. Sorbitol containing chewing gum and its significance for caries prevention. *Dtsch Zahnarztl Z* 1977; **32** (Suppl 1): 66–70.
98. Møller IJ, Poulsen S. The effect of sorbitol-containing chewing gum on the incidence of dental caries, plaque and gingivitis in Danish schoolchildren. *Community Dent Oral Epidemiol* 1973; **1**: 58–67.
99. Moynihan PJ. Update on the nomenclature of carbohydrates and their dental effects. *J Dent* 1998; **26**: 209–18.
100. Moynihan P. Foods and factors that protect against dental caries. *Nutr Bull* 2000; **25**: 281–6.
101. Moynihan PJ, Gould MEJ, Huntley N, Thorman S. Effect of glucose polymers in water, milk and a milk substitute (Calogen) on plaque pH in vitro. *Int J Paediatr Dent* 1996; **6**: 19–24.
102. Mühlemann HR. *Polydextrose – ein kalorienarmer Zuckerersatz*. Zahnmedizinische Prüfungen. *Swiss Dent* 1980; **1**: 29.
103. Mühlemann HR, Schmid R, Noguchi T, Imfeld T, Hirsch RS. Some dental effects of xylitol under laboratory and *in vivo* conditions. *Caries Res* 1977; **11**: 263–76.
104. Näse L, Hatakka K, Savilahti E, Saxelin M, Pönkä A, Poussa T, Korpela R, Meurman JH. Effect of long-term consumption of a probiotic bacterium, *Lactobacillus rhamnosus* GG, in milk on dental caries and caries risk in children. *Caries Res* 2001; **35**: 412–20.
105. Neeser JR, Chambaz A, Del Vedovo S, Prigent MJ, Guggenheim B. Specific and nonspecific inhibition of adhesion of oral *Actinomyces* and streptococci to erythrocytes and polystyrene by caseinoglycopeptide derivatives. *Infect Immun* 1988; **56**: 3201–8.
106. Neeser JR, Golliard M, Woltz A, Rouvet M, Dillmann ML, Guggenheim B. In vitro modulation of oral bacterial adhesion to saliva-coated hydroxyapatite beads by milk casein derivatives. *Oral Microbiol Immunol* 1994; **9**: 193–201.
107. Newbrun E, Hoover C, Mettraux G, Graf H. Comparison of dietary habits and dental health of subjects with hereditary fructose intolerance and control subjects. *J Am Dent Assoc* 1980; **101**: 619–26.
108. Nomoto K. Prevention of infections by probiotics. *J Biosci Bioeng* 2005; **100**: 583–92.
109. Nyvad B. Sukker og caries. In: Mølgaard C, Lyhne Andersen N, Barkholt V, Grunnet N, Herrmansen K, Pedersen BK, Raben A, Stender S, eds. *Sukkers sundhedsmæssige betydning*. Copenhagen: Danish Board of Nutrition, 2003; 59–67.
110. Öhlund I, Holgerson PL, Bäckman B, Lind T, Hernell O, Johansson I. Diet intake and caries prevalence in four-year-old children living in a low-prevalence country. *Caries Res* 2007; **41**: 26–33.
111. Orr JB, Gilks JL. *Studies of nutrition: the physique and health of two African tribes*. Medical Research Council Special Report Series No 155. London: Medical Research Council; 1931.
112. Ouwehand AC, Salminen S, Isolauri E. Probiotics: an overview of beneficial effects. *Antonie Van Leeuwenhoek* 2002; **82**: 279–89.
113. Patra F, Tomar SK, Arora S. Technological and functional applications of low-calorie sweeteners from lactic acid bacteria. *J Food Sci* 2009; **74**: R16–23.
114. Pedersen PO. Ernährung und Zahnkaries primitiver und urbanisierter Grönländer. *Dtsch Zahn Mund Kieferheilkd* 1938; **5**: 728–53.
115. Petersen PE, Razanamihaja N. Carbamide-containing polyol chewing gum and prevention of dental caries in Madagascar. *Int Dent J* 1999; **49**: 226–30.
116. Petersson LG, Magnusson K, Hakestam U, Baigi A, Twetman S. Reversal of primary root caries lesions after daily intake of milk supplemented with fluoride and probiotic lactobacilli in older adults. *Acta Odontol Scand* 2011; **69**: 321–7.
117. Pollard MA. Potential cariogenicity of starches and fruits as assessed by the plaque-sampling method and an intraoral cariogenicity test. *Caries Res* 1995; **29**: 68–74.
118. Pollard MA, Imfeld T, Gall M, Borgia A, Curzon MEJ. Acidogenicity of cereals and fruit using the indwelling electrode to measure plaque pH. *Caries Res* 1998; **32**: 315.
119. Price WA. Eskimo and Indian field studies in Alaska and Canada. *J Am Dent Assoc* 1936; **23**: 417–37.
120. Ravn I, Dige I, Meyer RL, Nyvad B. Colonization of the oral cavity by probiotic bacteria. *Caries Res* 2012; **46**: 107–12.
121. Reynolds EC, Black CL. Cariogenicity of a confection supplemented with sodium caseinate at a palatable level. *Caries Res* 1989; **23**: 368–70.
122. Ritter AV, Bader JD, Leo MC, Preisser JS, Shugars DA, Vollmer WM, Amaechi BT, Holland JC. Tooth-surface-specific effects of xylitol: randomized trial results. *J Dent Res* 2013; **92**: 512–7.
123. Roos A. *Kulturzerfall und Zahnverderbnis*. Bern: Hans Huber; 1962.
124. Rosenhek M, MacPherson LMD, Dawes C. The effects of chewing-gum stick size and duration of chewing on salivary flow rate and sucrose and bicarbonate concentrations. *Arch Oral Biol* 1993; **38**: 885–91.
125. Rugg-Gunn AJ, Nunn JH. *Nutrition, diet and oral health*. Oxford: Oxford University Press; 1999.
126. Rugg-Gunn AJ, Hackett AF, Appleton DR, Jenkins GN, Eastoe JE. Relationship between dietary habits and caries increment assessed over two years in 405 English adolescent schoolchildren. *Arch Oral Biol* 1984; **29**: 983–92.
127. Rugg-Gunn AJ, Roberts GJ, Wright WG. Effect of human milk on plaque pH in situ and enamel dissolution in vitro compared with bovine milk, lactose, and sucrose. *Caries Res* 1985; **19**: 327–34.
128. Scheie AA, Fejerskov O, Lingström P, Birkhed D, Manji F. Use of palladium touch microelectrodes under field conditions for in vivo assessment of dental plaque pH in children. *Caries Res* 1992; **26**: 44–51.
129. Scheinin A, Mäkinen KK. Turku sugar studies I–XXI. *Acta Odontol Scand* 1975; **33** (Suppl 70): 1–351.
130. Scheinin A, Mäkinen KK, Tammisalo E, Rekola M. Turku sugar studies. XVIII. Incidence of dental caries in relation to 1-year consumption of xylitol chewing gum. *Acta Odontol Scand* 1975; **33** (Suppl 70): 307–16.
131. Scheinin A, Mäkinen KK, Ylitalo K. Turku sugar studies. V. Final report on the effect of sucrose, fructose and xylitol diets on caries incidence in man. *Acta Odontol Scand* 1975; **33** (Suppl 70): 67–104.
132. Silver DH. A longitudinal study of infant feeding practice, diet and caries, related to social class in children aged 3 and 8–10 years. *Br Dent J* 1987; **163**: 296–300.
133. Slack GL, Millward E, Martin WJ. The effect of tablets stimulating salivary flow on the incidence of dental caries: a two-year clinical trial. *Br Dent J* 1964; **116**: 106–8.
134. Söderling E, Isokangas P, Tenovuo J, Mustakallio S, Mäkinen KK. Long-term xylitol consumption and mutans streptococci in plaque and saliva. *Caries Res* 1991; **25**: 153–7.
135. Söderling E, Trahan L, Tammiala-Salonen T, Häkkinen L. Effects of xylitol, xylitol–sorbitol, and placebo chewing gums on the plaque of habitual xylitol consumers. *Eur J Oral Sci* 1997; **105**: 170–7.
136. Söderling E, Isokangas P, Pienihäkkinen K, Tenovuo J, Alanen P. Influence of maternal xylitol consumption on mother–child transmission of mutans streptococci: 6-year follow-up. *Caries Res* 2001; **35**: 173–7.
137. Sognnaes RF. Analysis of wartime reduction of dental caries in European children. *Am J Dis Child* 1948; **75**: 792–821.
138. Sognnaes RF. *Oral health survey of Tristan Da Cunha*. Results of the Norwegian Scientific Expedition to Tristan da Cunha, 1937–1938. No. 24. Oslo: Det Norske Videnskaps-Akademi; 1954.
139. Sreebny LM. Sugar availability, sugar consumption and dental caries. *Community Dent Oral Epidemiol* 1982; **10**: 1–7.

140. Stecksén-Blicks C, Holgerson PL, Twetman S. Effect of xylitol and xylitol–fluoride lozenges on approximal caries development in high-caries-risk children. *Int J Paediatr Dent* 2008; **18**: 170–7.
141. Stephan RM, Miller BF. A quantitative method for evaluating physical and chemical agents which modify production of acids in bacterial plaques on human teeth. *J Dent Res* 1943; **22**: 45–53.
142. Szöke J, Bánóczy J, Proskin HM. Effect of after-meal sucrose-free gum chewing on clinical caries. *J Dent Res* 2001; **80**: 1725–9.
143. Tagg JR, Dierksen KP. Bacterial replacement therapy: adapting 'germ warfare' to infection prevention. *Trends Biotechnol* 2003; **21**: 217–3.
144. Takeuchi M. Epidemiological study on dental caries in Japanese children before, during and after World War II. *Int Dent J* 1961; **11**: 443–57.
145. Ten Cate JM. Patient selection and appliance design in intra-oral models. *J Dent Res.* 1992; 71 (Spec No): 908–10.
146. Tenovuo J, Hurme T, Ahola A, Svedberg C, Ostela I, Lenander-Lumikari M, Neva M. Release of cariostatic agents from a new buffering fluoride- and xylitol-containing lozenge to human whole saliva *in vivo*. *J Oral Rehabil* 1997; **24**: 325–31.
147. Thomson ME, Thomson CW, Chandler NP. *In vitro* and intra-oral investigations into the cariogenic potential of human milk. *Caries Res* 1996; **30**: 434–8.
148. Toverud G. The influence of war and post war conditions on the teeth of Norwegian school children II and III. *Millbank Mem Fund Q* 1957; **35**: 127–96.
149. Van der Hoeven JS, de Jong MH, Rogers AH, Camp PJ. A conceptual model for the co-existence of *Streptococcus* spp. and *Actinomyces* spp. in dental plaque. *J Dent Res* 1984; **63**: 389–92.
150. Wåler SM, Rölla G. Effect of xylitol on dental plaque in vivo during carbohydrate challenge. *Scand J Dent Res* 1983; **91**: 256–9.
151. Weiss RL, Trithart AH. Eating habits and dental caries experience in preschool children. *Am J Public Health Nations Health* 1960; **50**: 1097–104.
152. Wennerholm K, Arends J, Birkhed D, Ruben J, Emilson CG, Dijkman AG. Effect of xylitol and sorbitol in chewing gums on mutans streptococci, plaque pH and mineral loss of enamel. *Caries Res* 1994; **28**: 48–54.
153. Woodward , Walker ARP. Sugar consumption and dental caries: evidence from 90 countries. *Br Dent J* 1994; **176**: 297–302.
154. Zero DT. Etiology of dental erosion – extrinsic factors. *Eur J Oral Sci* 1996; **104**: 162–77.
155. Zero DT, Lussi A. Etiology of enamel erosion – intrinsic and extrinsic factors. In: Addy M, Embery G, Edgar M, Orchardson R, eds. *Tooth wear and sensitivity*. Martin Dunitz, Ltd, 2000: 121–39.
156. Ziesenitz SC, Siebert G, Imfeld T. Cariological assessment of leucrose [D-glucopyranosyl-alpha(1-5)-D-fructopyranose] as a sugar substitute. *Caries Res* 1989; **23**: 351–7.

9

Demineralization and remineralization: the key to understanding clinical manifestations of dental caries

O. Fejerskov and M.J. Larsen

Introduction

It is a common expression that 'the teeth are bathed in saliva.' This gives the erroneous impression of the oral cavity as a closed sink filled with saliva. However, saliva only covers the teeth with a thin film of about 10 μm thickness. This fluid film is constantly moved along the tooth surfaces as we swallow, chew, talk, and so on. The composition of saliva and the velocity of the salivary film play a significant role in maintaining the integrity of the dental hard tissues.

When chemical reactions of the biological apatite in the dental hard tissues are discussed, it should be appreciated that the situation is not as simple as having a pure hydroxyapatite exposed to a surrounding liquid phase of known composition. Proteins of salivary origin will cover any exposed tooth tissue (see Chapter 6). The very thin organic film on tooth surfaces is called the pellicle and is formed as a result of selective adsorption of salivary proteins to tooth surfaces [1, 26]. The surface of hydroxyapatite is amphoteric,

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

which means that it binds acidic and basic proteins equally well. However, acidic proteins can be desorbed by phosphate or other anions, whereas basic proteins can be desorbed by calcium. The hydroxyapatite surface has a net negative charge because the phosphate groups close to the surface of the crystals more or less shield the positively charged calcium groups.

The aim of this chapter is to make the reader appreciate the chemical dynamics of how dental hard tissues dissolve in the oral cavity and interact with saliva and fluid in the biofilm (the plaque fluid). Only by understanding this situation is it possible to appreciate the dynamics of demineralization and remineralization – or 'de- and remin' as often said in the clinic. There has been much 'hype' about remineralization in the last two to three decades, so as a clinician it is important to know what this means and what can be done clinically to promote conditions that favor remineralization.

Enamel mineral

Enamel crystals differ from pure hydroxyapatite in that they contain several foreign inorganic ions. The apatite lattice is particularly 'flexible' and will allow the inclusion of extraneous ions in sites normally reserved for calcium, phosphate, or hydroxyl ions. In enamel crystals some phosphate ions, for example, are replaced by carbonate ions, often with the simultaneous replacement of calcium by sodium. There is, however, a limit to how much carbonate can be accommodated this way without disrupting the lattice. In addition, some hydroxyl ions are replaced by fluoride ions, but there is no limit to the possible extent of this substitution; 100% replacement results in fluorapatite, but this mineral is rarely found in biological tissues (an exception is shark enameloid). One can tell that carbonate and fluoride are part of the crystal because they change the lattice dimensions. Enamel apatite and most other biological apatites, therefore, are a carbonated fluor-hydroxyapatite. Other ions that are normally incorporated in biological apatite, but to a smaller extent, are chloride and magnesium. Yet other substitutions are possible (e.g., strontium for calcium), but are not quantitatively important.

Enamel crystals have a very large surface area, allowing great opportunity for the adsorption of foreign ions. It is likely that all the previously mentioned ions are adsorbed at the surface in a bound water layer, the 'hydration shell', including HPO_4^{2-} and Ca^{2+} ions (Fig. 9.1). These ions are readily exchangeable, unlike ions in the lattice. Also adsorbed on the crystal surface are enamel trace elements such as potassium, zinc, lead, and copper [3]. In Fig. 9.1b we assume that the apatite surface is negatively charged, which then attracts positively charged ions, which in turn attract negatively charged ions and so on. After a short distance of three to five layers of ions these binding effects are very weak and disorganized. In such a system water molecules are easily trapped because of their stereologically separated positive and negative charges. Water comprises the major part of the environment of each crystal, and, as pointed out above, this is designated the 'hydration shell.' This shell can only be removed if crystals are heated to temperatures of about 500 °C for prolonged periods of time. The final diffusion and ion substitution into the crystal interior is an extremely slow process.

In addition to variations on the crystal surface due to adsorption, the bulk of the enamel crystal is not homogeneous. There is reason to believe that enamel crystals are covered with an indistinct layer of apatitic mineral that has a greater stability; for example, less carbonate and/or more fluoride. Thus, the extent of the substitutions is not constant throughout the crystal.

Stability of calcium phosphates

Above pH 4.3, hydroxyapatite is the most stable calcium phosphate mineral, and it is understandable why it is the form laid down during tissue development. However, after eruption of the tooth the apatite of outer enamel and dentin

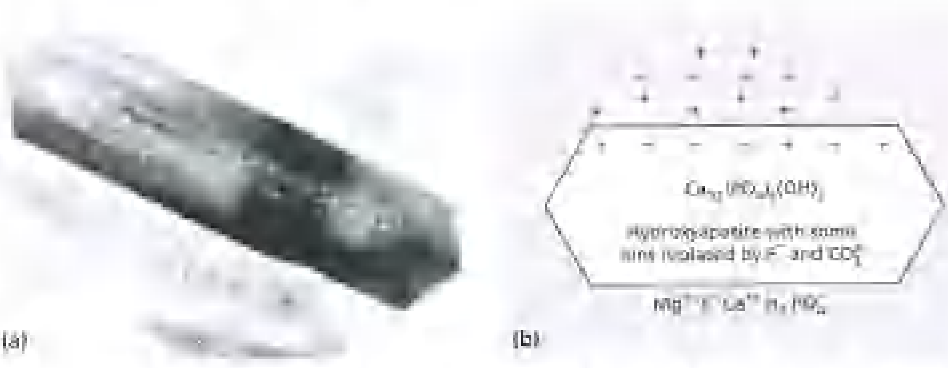


Figure 9.1 (a) Cross-cut enamel crystal from outermost highly mineralized human enamel. The hexagonal crystal exhibits a dark central line and a lattice striation with an interval of 0.817 nm (~8.2 Å) between the lines which intersect each other at an angle of 60° reflecting the unit cell of hydroxyapatite. From [12]. Reproduced with permission of Oxford University Press. (b) Schematic drawing of a 'typical' enamel crystal. These crystals are about 350 Å in thickness and 1000 Å in width. Ions in the hydration shell can easily be exchanged. Other ions are bound in the hydroxyapatite lattice (e.g., fluoride); it is not easily exchanged unless the crystal is dissolved. For an explanation of the drawing, please see the text.

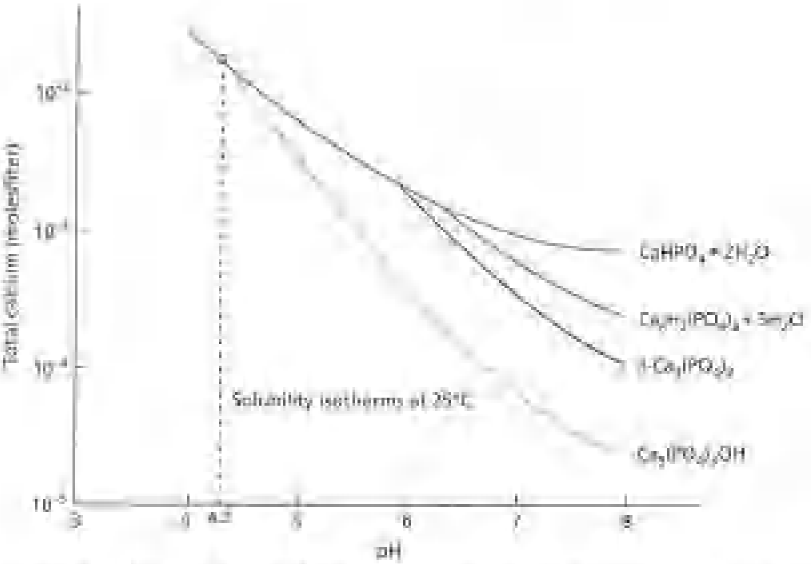


Figure 9.2 Phase solubility diagram at 25 °C for salts of calcium phosphates that may form under physiological conditions. Adapted from [2]. Reproduced with permission of the US Department of Commerce.

is exposed to a wide variation in pH through diets, soft drinks, and plaque metabolism. A phase diagram (Fig. 9.2) can be used to predict that, below pH 4.3, brushite is more stable than hydroxyapatite and that brushite may precipitate as separate crystals or cover existing enamel crystals. However, above pH 4.3 hydroxyapatite is more stable than any of the other three calcium phosphates shown. Moreover, the presence of additional ions, fluoride or magnesium, can result in other stable calcium phosphate minerals, such as fluorapatite and whitlockite, precipitating in preference to hydroxyapatite.

Crystal dissolution

All minerals have an inherent and fixed solubility in water at any given temperature. Dissolution in pure water is relatively fast at first, but then slows as ions from the crystals accumulate in solution. Eventually, net dissolution ceases and the solution is said to be saturated with respect to that mineral, although there remains a slow exchange of ions between crystals and solution. Water is almost unique in its ability to dissolve inorganic crystals. Water molecules work their way into the crystal surface and dislodge ions from the lattice by virtue of their ability to reduce the attractive forces between oppositely charged ions, a function of water's high dielectric constant. In addition, water molecules surround the newly released ions, and this energy of hydration overcomes the lattice energy holding the crystal together.

Whether or not a solution is saturated with respect to hydroxyapatite can be determined from the solubility product principle. This theory is derived from the law of mass action, which states that the velocity of a reaction is proportional to the product of the masses of the reacting substances, each raised to a power equal to the number of molecules taking part. By convention, when one unit mass of solid hydroxyapatite dissolves, five calcium ions, three trivalent phosphate ions, and one hydroxyl ion are released into solution:

$$Ca_5(PO_4)_3OH \leftrightarrow 5Ca^{2+} + 3PO_4^{3-} + OH^-$$

Thus, the ion activity product with respect to hydroxyapatite IAP_{HA} is determined by multiplying the calcium ion concentration (or rather the chemical activity) raised to the power 5 with the trivalent phosphate concentration raised to the power 3 by the hydroxyl concentration, all in moles per liter:

$$IAP_{HA} = (Ca^{2+})^5 \times (PO_4^{3-})^3 \times (OH^-)$$

In very dilute solution the activity of an ion is similar to its concentration, but as the dissolved salt concentration increases, the activity becomes significantly less than the concentration because of ion interactions. Activity is related to concentration by the activity coefficient, which can be calculated with knowledge of the ionic strength; that is, the saltiness of a solution. The concentration in turn is affected by the extent of formation of complex ions (e.g., $CaH_2PO_4^+$).

When a solution containing hydroxyapatite is saturated and the mineral is in equilibrium with the ions in solution, the IAP_{HA} equals the solubility product of hydroxyapatite KSP_{HA}, a constant that has a value of 7.41×10^{-60} mol^9/l^9 at 37 °C. Thus, at equilibrium:

$$IAP_{HA} = KSP_{HA} = (Ca^{2+})^5 \times (PO_4^{3-})^3 \times (OH^-) \\ = 7.41 \times 10^{-60}\ mol^9/l^9$$

This value could also result, for example, from solution calcium and phosphate concentrations of 0.2925 mmol/L at pH 6 and 37 °C (Table 9.1, case 2).

Many salts (e.g., NaCl) are much more soluble in hot water than in cold, but hydroxyapatite and most other calcium phosphates are slightly more soluble in cold water, for example, $KSP_{HA} = 3.72 \times 10^{-58}$ mol^9/L^9 at 25 °C. Therefore, when a person drinks a hot fluid, their teeth are not liable to dissolve any more than when they drink the same fluid cold.

Why is apatite solubility increased by acid?

Unlike many salts, such as table salt (NaCl), the solubility of hydroxyapatite and other calcium phosphates is greatly affected by the pH of the water in which it is dissolving. This is explained above. As PO_4^{3-} and OH^- accumulate in solution, together with Ca^{2+}, dissolution of hydroxyapatite gradually slows down and stops as the solution becomes saturated. If acid is added, PO_4^{3-} ions and OH^- ions combine with H^+ to form HPO_4^{2-} ions and H_2O respectively, thereby removing a proportion of PO_4^{3-} ions and OH^- ions from solution:

$$\begin{array}{lcc} Ca_5(PO_4)_3OH \leftrightarrow Ca^{2+} + & 3PO_4^{3-} + & OH^- \\ & \downarrow H^+ & \downarrow H^+ \\ & HPO_4^{2-} & H_2O \\ & \downarrow H^+ & \\ & H_2PO_4^- & \end{array}$$

In this case the IAP_{HA} decreases; the solution is then said to be unsaturated and more hydroxyapatite dissolves until saturation is re-established. For example (Table 9.1, case 1), where the pH of the solution containing 0.2925 mmol/L calcium and phosphate is changed to pH 5, the IAP_{HA} is now much less than the KSP_{HA} and the solution is unsaturated. Conversely, when the pH is 7, the IAP_{HA} is greater than the KSP_{HA} and the solution is then said to be supersaturated with respect to hydroxyapatite (Table 9.1, case 3). When the pH of a supersaturated solution is gradually lowered, a point at which the solution becomes just saturated with respect to the mineral in question occurs. In the example in Table 9.1, this pH is 6. Physically, dissolution of a hydroxyapatite crystal is not isotropic but proceeds more rapidly along the c-axis. This may result in a central cavity in partly dissolved crystals, a phenomenon sometimes seen in electron microscope images of carious enamel; see Fig. 9.3 [30].

Table 9.1 Calcium and phosphate concentrations, activities, and activity products with respect to hydroxyapatite for the same solution at pH 5, 6, and 7 and at a temperature of 37 °C.

	Case 1	Case 2	Case
pH	5.0	6.0	7.0
Basic strength (mol/l)	8.887×10^{-4}	8.926×10^{-4}	3.653×10^{-4}
Total calcium concentration (mol/l)	2.925×10^{-4}	2.925×10^{-4}	2.925×10^{-4}
Ca^{2+} activity (mol/l)	2.553×10^{-4}	2.539×10^{-4}	2.452×10^{-4}
Total phosphate concentration (mol/l)	2.925×10^{-4}	2.925×10^{-4}	2.925×10^{-4}
Total PO_4^{3-} concentration (mol/l)	1.652×10^{-13}	1.546×10^{-11}	9.395×10^{-12}
PO_4^{3-} activity (mol/l)	1.215×10^{-13}	1.136×10^{-11}	5.822×10^{-12}
OH^- activity (mol/l)	4.787×10^{-10}	4.787×10^{-9}	4.787×10^{-8}
Total activity product (mol⁹/l⁹) $(Ca^{2+})^5 \times (PO_4^{3-})^3 \times OH$	9.31×10^{-62}	7.41×10^{-60}	1.35×10^{-57}

In each case the total calcium and phosphate concentrations are the same, 0.2925 mmol/l. In case 2, $IAP_{HA} = KSP_{HA}$ (7.41×10^{-60}), thus this solution is saturated with respect to hydroxyapatite.

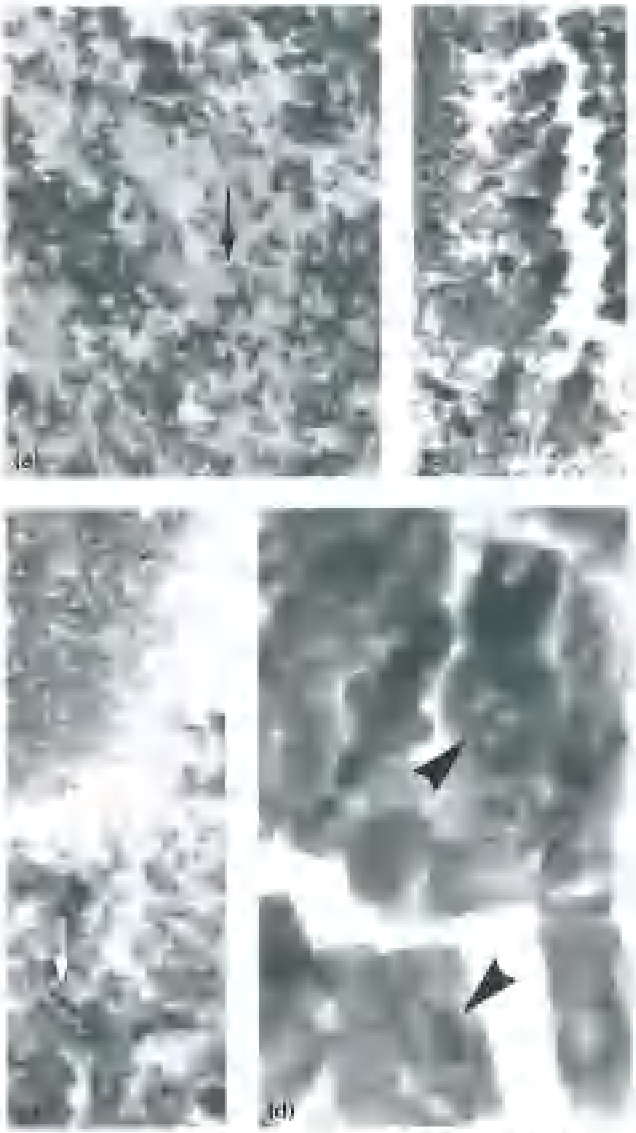


Figure 9.3 Transmission electron micrographs of part of the body of a caries lesion that is severely demineralized (a). The arrows in (a) and (c) indicate crystals with central dissolution. In (b) and (d) so-called caries crystals are shown. Some of these are in fact partly dissolved crystals with redeposition of minerals in the centers of crystals indicated with arrow heads.

It is apparent from the solubility product equation that if there is an excess of one ion in solution, then less of the others is required to attain the KSPHA. This is sometimes called the 'common ion' effect and explains why addition of either calcium or phosphate to a solution in which hydroxyapatite is dissolving reduces the amount that will dissolve. The solubility product principle also explains why removal of calcium from a solution in equilibrium (e.g., with a calcium-binding agent such as ethylenediaminetetraacetic acid) will cause more hydroxyapatite to dissolve.

Since the activity product of hydroxyapatite is a function of the calcium ion concentration raised to the power 5, one might predict that a change in solution calcium concentration would have the most profound effect on $\mathrm{IAP}_{\mathrm{HA}}$. However, change in pH affects both OH^- and the proportion of the total phosphate present as PO_4^{3-}, as well as complex ion formation, and with typical concentrations found in oral fluids, changing pH has a larger effect on the activity product than changing the calcium concentration [21].

In summary, hydroxyapatite crystals dissolve in acid because the surrounding solution becomes unsaturated owing to the removal of PO_4^{3-} *and* OH^- *ions from solution. The driving force for dissolution is the degree of undersaturation.*

Effect of carbonate and fluoride on apatite dissolution and growth

Ion substitutions influence the physical and chemical properties of the mineral and, most importantly with respect to enamel, change its solubility. Carbonate inclusion makes hydroxyapatite more soluble [17], but fluoride inclusion has the opposite effect, decreasing the effective KSP. Fluorapatite, which has a $\mathrm{KSP}_{\mathrm{FA}}$ of 3.2×10^{-61}, is less soluble than hydroxyapatite, but approximately 50% replacement produces the least-soluble mineral: $\mathrm{KSP}_{\mathrm{FHA50}} = 6.6\times10^{-62}$ [16]. Because of the relatively small amount of fluoride in native enamel, carbonate has an overriding effect on enamel solubility, increasing the $\mathrm{KSP}_{\mathrm{enamel}}$ to 5.5×10^{-55} [15], although there is evidence that only prism junction material is quite as soluble [25], the bulk of the enamel mineral having a KSP closer to 10^{-58}. When determining the saturation status of oral fluids with respect to enamel, a KSP of this order should be used rather than $\mathrm{KSP}_{\mathrm{HA}}$. However, because of the changeable nature of enamel mineral the exact $\mathrm{KSP}_{\mathrm{enamel}}$ is difficult to determine.

Traces of fluoride in solution when hydroxyapatite dissolves render the solution highly supersaturated with respect to fluorapatite and especially fluorhydroxyapatite, which then tends to precipitate or overgrow on the existing hydroxyapatite. Small amounts of fluoride are therefore removed from solution during apatite crystal regrowth. However, since carbonate-free or low-carbonate apatite is less soluble, this will tend to form in preference to the original apatite. Thus, when a carbonated fluorhydroxyapatite crystal dissolves and reprecipitates, fluoride tends to be reincorporated, whereas carbonate is discarded [15]. The overall effect of this solution fluoride is to reduce dramatically the amount of calcium that may be liberated from enamel in acid solution. *This is the scientific basis for the current view that low concentrations of fluoride in solution in the environment of the tooth are more beneficial in reducing caries than high concentrations of fluoride incorporated into enamel (Fig. 9.4) as stated by Fejerskov et al. in 1981 [4].*

If powdered enamel is repeatedly exposed to acid its dissolution is incongruous, meaning that the initial products

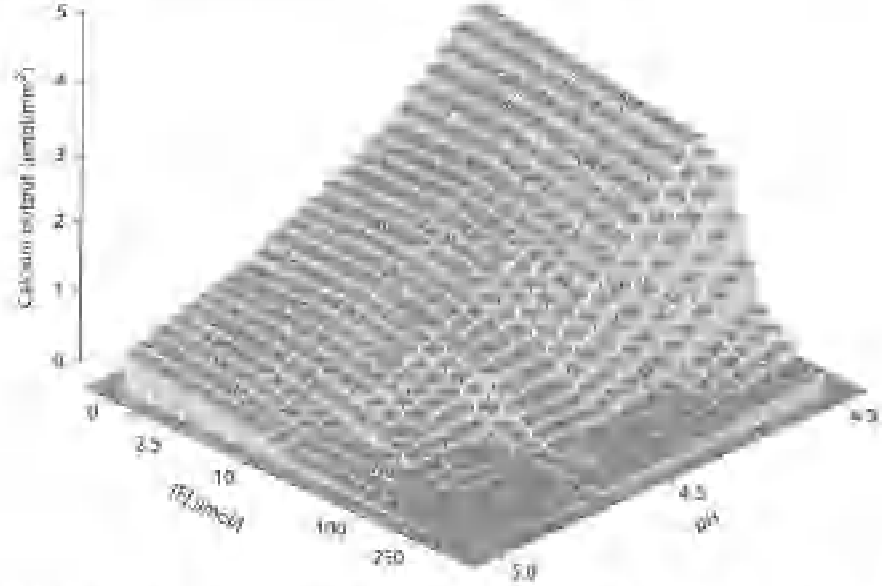


Figure 9.4 Calcium output from enamel during demineralization in solutions initially containing 2.2 mmol/L calcium chloride and 2.2 mmol/L potassium phosphate adjusted to the pH and fluoride (F) levels indicated. For original figure, refer to [27,28].

are not those expected from enamel mineral. Carbonate, sodium, and magnesium are released preferentially during the first exposure [12], and this may reflect either the release of adsorbed ions or the dissolution of enamel mineral and simultaneous reprecipitation of a more perfect fluorhydroxyapatite with a lower solubility. During such a reprecipitation process crystals may become coated with a different calcium phosphate phase (e.g., brushite), which then becomes the 'solubility-controlling' phase [22]. Moreover, separate whitlockite crystals may precipitate [25], which may lead to the formation of 'caries crystals,' the relatively large rhomboidal crystals sometimes seen at the prism periphery in carious enamel (Fig. 9.3).

Enamel is not homogeneous throughout its thickness as, for example, crystals in the 50–100 μm outer surface contain more fluoride and less carbonate than crystals in the bulk enamel at time of eruption (see Chapter 14). This is most likely a result of the pH fluctuations that accompany the frequent cell modulations of the ameloblasts during pre-eruptive maturation [8]. This renders, in principle, the outer micrometers of enamel less soluble than the bulk of the tissue.

Demineralization and remineralization of the dental hard tissues

Under physiological conditions (pH 7.4) saliva and the oral fluids are supersaturated with respect to hydroxyapatite and fluorapatite (Fig. 9.5). That is the necessary precondition for the maintenance of dental apatite in the mouth. If the oral fluids were unsaturated with respect to apatite the dental hard tissues would dissolve. In general, the higher the supersaturation with respect to the actual salt the greater is the tendency for its formation. Thus, the bars in Fig. 9.5 indicate a considerable tendency to form fluorhydroxyapatite and hydroxyapatite in particular when salivary secretion is stimulated. This explains why most supragingival calculus consists of mixed fluorhydroxyapatite and hydroxyapatite. It also shows that there is no rationale in adding extra calcium or phosphate in various dietary compounds – saliva is already supersaturated. The only effect might be enhanced formation of dental calculus! Occasionally, octacalcium phosphate or brushite has been observed as a component of calculus. Figure 9.5 shows that saliva is unsaturated with respect to calcium fluoride, which explains why this salt only exists in the oral cavity for a limited period (e.g., after topical fluoride treatments with high fluoride concentrations such as varnishes and 2% NaF solutions) and invariably will dissolve. When CaF_2 is formed inside a porous enamel surface (e.g., after acid etching followed by topical fluoride treatment) it will of course dissolve at a slower rate (several days) than if it is formed on an outer tooth surface.

When the pH in the surrounding medium (saliva/plaque fluid) decreases, the solubility of the tooth mineral apatite increases dramatically (Fig. 9.6). In general, the solubility of apatite increases by a factor of 10 with a drop of each single pH unit [1]. Therefore, the mineral is vulnerable to an acidic environment. Exposure to acids may lead to two types of lesions: *the caries lesion* (Fig. 9.7) and *erosion* (Fig. 9.8). The initial stages of carious lesion formation are characterized by a partial dissolution of the outermost enamel, almost an erosion, but as the above chemical conditions are prevailing the process instantaneously results in a 20–50 μm thick, rather well mineralized surface layer and a subsurface body of the lesion with a mineral loss (Fig. 9.7). As these processes continue over prolonged periods of time, up to 30–50%

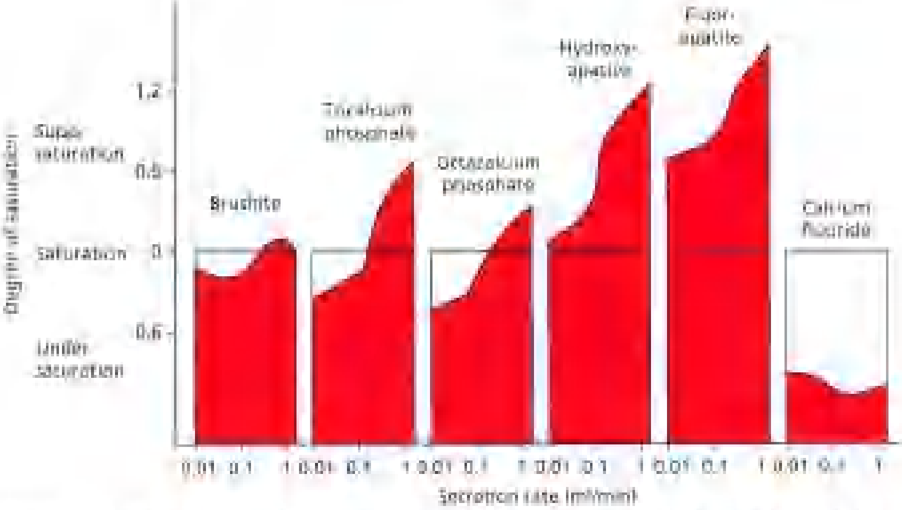


Figure 9.5 Degrees of saturation with respect to various calcium phosphates and to calcium fluoride in parotid saliva [14]. The degrees of saturation are given by log n(ion product in saliva)/(solubility product), in which n is the number of ions in the actual salt. The salts may all at least occasionally occur in the oral cavity as part of teeth or calculus, or as a precipitate after topical fluoride application. Saliva is highly supersaturated with respect to the apatites, which is the basis of the integrity of the teeth in the mouth. The saturation with respect to the other calcium phosphates explains their occurrence in calculus, while the undersaturation with respect to calcium fluoride shows that saliva invariably dissolves that salt. Reproduced with permission of Elsevier.

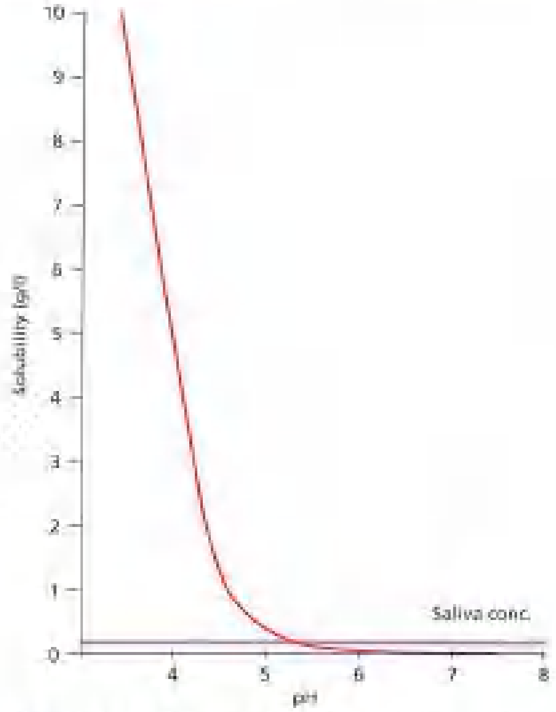


Figure 9.6 Solubility of hydroxyapatite as a function of pH. Salivary concentrations of calcium and phosphate are indicated by the horizontal line. The solubility of apatite increases considerably as pH decreases. It should be noted that caries develops in the pH range around 4.0–5.5, while teeth are eroded in the pH range 2.5–4.0.

Figure 9.7 Microradiogram of a white spot lesion showing the subsurface, demineralized lesion deep to a relatively well mineralized surface layer. Note the preferential loss of mineral along the striae of Retzius whereby these and the prism pattern become clearly visible.

Figure 9.8 Microradiogram of an erosion of a human tooth. No subsurface demineralization is seen as the enamel is dissolved layer by layer.

mineral loss occurs, extending deep into the enamel and dentin (see Figs 5.47 and 5.59), while a 20–80 µm thick, rather well mineralized surface zone partly remains.

In contrast, the erosion lesion shows features of complete demineralization and dissolution layer by layer. Thus, the dental hard tissues remaining after even extensive erosion do not show signs of partial demineralization except surface dissolution, but some of the enamel is removed. The mineral content of the remaining enamel is unchanged. Therefore, alone, there is not a porous surface to redeposit minerals into and, as a logical consequence, fluoride does not help in treating or even preventing erosions from occurring (e.g., the chemical explanation earlier in this chapter).

The histological features are reflected in the clinical appearance: the active caries lesion is chalky white and porous, while the appearance of eroded enamel is usually hard and shiny.

A third type of enamel dissolution by acids is seen when enamel is conditioned for the retention of resin fillings. The etch pattern is similar to that of the erosion, in the sense that it is a surface etching without formation of a surface layer covering a subsurface demineralization. However, the etching acid penetrates considerably deeper into the enamel and exposes the prism pattern to a much larger extent than is seen in eroded enamel. When the water in these surface etchings is removed by drying (see scanning electron micrograph in Fig. 9.9) the etched area appears white and chalky.

Caries is defined as chemical dissolution of the dental hard tissues by acidic bacterial products from degradation of low molecular weight sugars. In contrast, erosion is defined as dissolution of apatite mineral caused by acids of any other origin introduced into the oral environment, except for acids used for conditioning of enamel and dentin for retentive purposes during restorative dentistry.

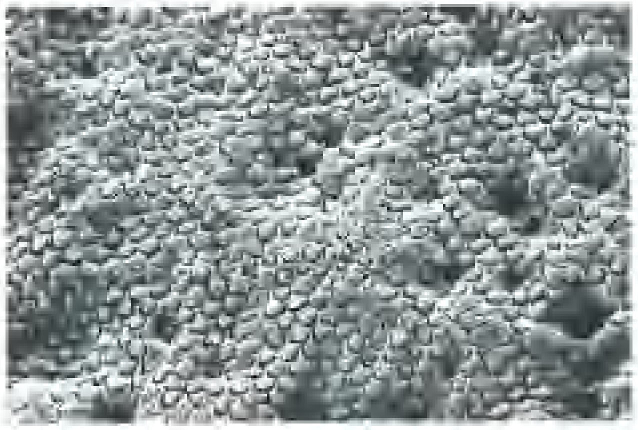


Figure 9.9 Scanning electron micrograph of an enamel surface after a conditioning etching with phosphoric acid. The prism pattern is clearly seen, with accentuated arcade-shaped prism boundaries.

Caries demineralization

As pH is lowered in the oral fluids, saliva, and plaque fluid, the supersaturation with respect to hydroxyapatite is reduced and at 'critical' pH the fluids become just saturated with respect to hydroxyapatite. Because fluorapatite is less soluble than hydroxyapatite is, plaque fluid remains supersaturated with respect to fluorapatite when it is undersaturated with respect to hydroxyapatite (Figs 9.10 and 9.11). Under these conditions a carious lesion forms. Subsurface hydroxyapatite is dissolved, while fluorhydroxyapatite is formed in the surface layers of enamel. In general, the more undersaturated the plaque fluid, with respect to hydroxyapatite (i.e., the lower the pH), the greater the tendency for dissolution of the enamel apatite.

The concurrent supersaturation with respect to fluorapatite is responsible for the maintenance and integrity of the surface layer. Experimentally, the more supersaturated the solution, with respect to fluorapatite, the thicker and less demineralized the surface layer remains. However, it is very important to appreciate that in a cariogenic oral environment with innumerable fluctuations in pH for days, months, and years these surface zones will be constantly dissolving and redepositing mineral, which is reflected in a highly irregular, almost moth-eaten surface appearance, as seen in microradiography (Fig. 9.12). This formation of fluorapatite at the expense of hydroxyapatite in surface enamel leads in time to a high content of fluorhydroxyapatite in the surface layer of the carious lesion (Fig. 9.13).

In Fig. 9.13, it should be noted that the fluoride concentration in the subsurface body of the lesion of the enamel is not increased. As long as the surface layer remains intact and has a reasonable mineral content, fluoride does

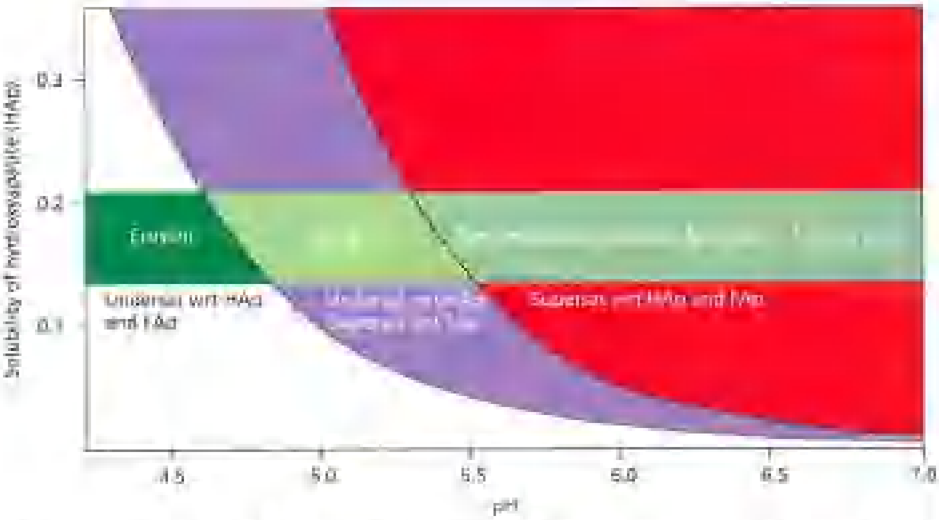


Figure 9.10 Solubility of hydroxyapatite (HAp) and fluorapatite (FAp) as a function of pH in the range 4–7. Above the solubility line for HAp, solutions will be supersaturated with respect to both HAp and FAp. In saliva, formation of calculus and remineralization of caries lesions may occur. Between the two solubility lines solutions will be undersaturated with respect to HAp and saturated with respect to FAp. In saliva, HAp tends to dissolve and FAp may form, that is, a caries lesion may develop. Below the solubility line for FAp, both apatites may dissolve and erosions develop.

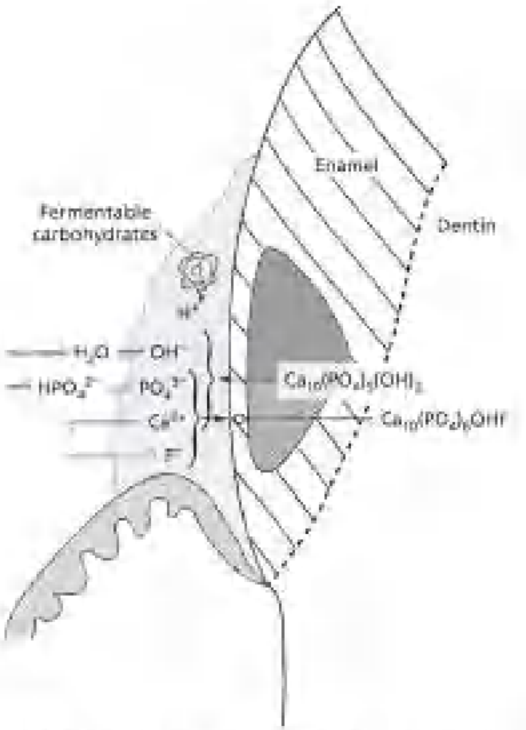


Figure 9.11 A schematic drawing showing the effect of the numerous pH fluctuations in the biofilm on the dental enamel. This diagram reflects the solubility of hydroxyapatite and fluorapatite as a function of pH in the range of 4.5–5.5 as demonstrated in Fig. 9.10. While hydroxyapatite dissolves in the subsurface region, the fluoridated apatite can build up in the surface layer of the tooth.

Figure 9.12 Microradiogram of a caries lesion in enamel with a highly varying loss of mineral in the body of the lesion. Both the Retzius lines and the prism pattern with cross-striation of several prisms are clearly visible. Note how the apparently greater degree of well-mineralized surface layer exhibits obvious surface dissolution along the very surface that gives a moth-eaten appearance. Clinically, this will be apparent as surface roughness when moving the tip of an explorer across the surface – and the lesion will have an opaque appearance.

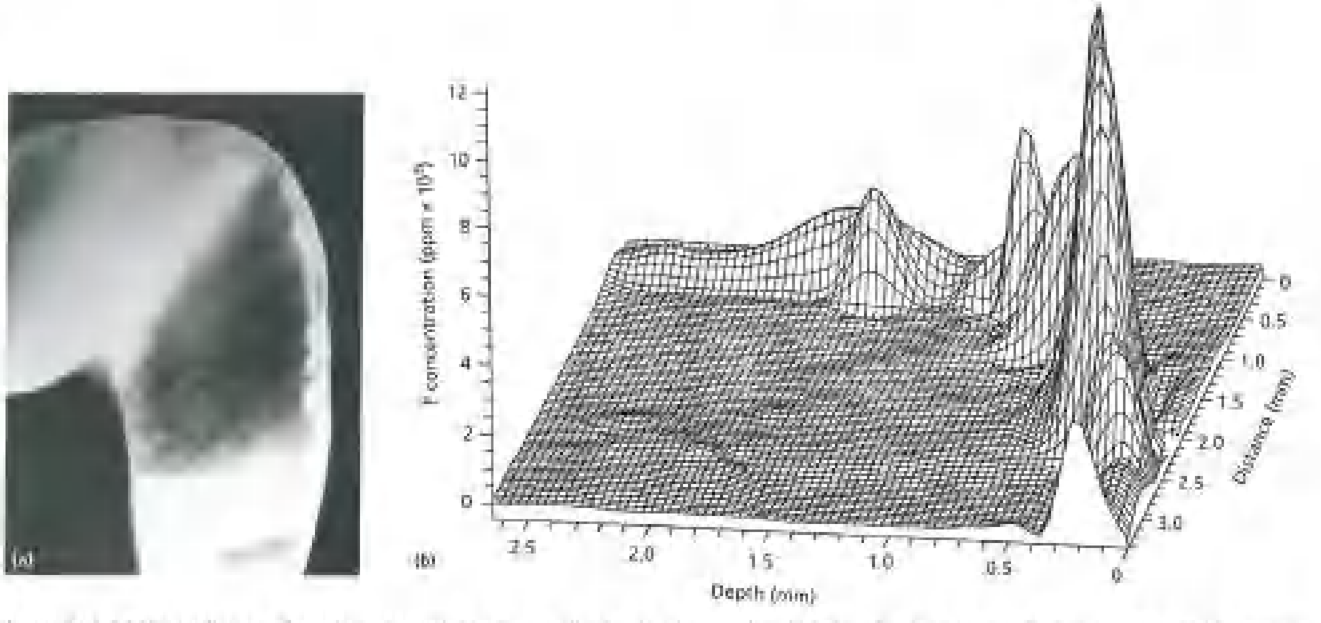


Figure 9.13 (a) Microradiogram of a caries lesion with a well-mineralized surface layer, under which the subsurface demineralization extends to and further into the dentin. (b) The graph demonstrates a high fluoride content in the surface layer and very little fluoride in the subsurface lesion body despite a high exposure to fluoride. A slight increase at the border between the enamel and dentin can be distinguished.

but diffuse into the body of the lesion. Rather, it reacts as it diffuses inwards, causing fluorhydroxyapatite formation in the outer layers, predominantly. In a number of respects the surface layer exerts a protective effect to prevent further dissolution of the lesion body as long as the pH fluctuations are in the range of 4.0–5.6 (see Fig. 9.10).

Remineralization of enamel

As will be understood, remineralization of enamel requires that calcium and phosphate ions are able to diffuse into the porous subsurface enamel usually through the relatively intact surface zone. All pores in enamel – whether in normal enamel or porous carious enamel – are not 'empty,' but filled with proteins. In the surface of the enamel, salivary proteins penetrate, but it should be acknowledged that in vital teeth there is an outflow of ions from dentin through the enamel due to the blood pressure in the pulp. Ions in general only slowly penetrate into a lesion with an intact surface layer even under extreme laboratory conditions. A single pH fluctuation in plaque is unlikely to affect the pH in the interior of a lesion [11]. The effect of a pH drop is larger when the surface layer is broken down. In extreme laboratory experiments [9, 10], attempts were made to consecutively fill up the pores in demineralized enamel lesions with phosphate and calcium ions, whereafter the pH in the environment was elevated to create a stage of supersaturation within the enamel. However, no remineralization within the carious enamel was found. Instead, mineral deposited on the tooth surfaces (Fig. 9.14) rather than remineralizing the subsurface porous caries lesion formed *in vivo* under natural conditions. Remineralization of dental lesions requires the presence of partially demineralized apatite crystals that can grow in size as a result of exposure to solutions supersaturated with respect to apatite. The formation of entirely new crystals in a subsurface lesion is not likely, whereas it is seen in the surface of the enamel lesions where numerous pH fluctuations have occurred (Fig. 9.15). These conditions set limits to what can be expected from remineralization.

As an erosion is characterized as a lesion in which enamel is etched away and the crystals are lost, very little, if any, remineralization of eroded enamel can be expected, despite the lesion being exposed to supersaturated saliva for long periods. The etched surface is covered by the salivary proteins and rapidly the etched outermost crystals are abraded away (see Chapter 5). Even after weeks the surface exhibits a faint picture of acid-etched enamel (Fig. 9.16).

In contrast, the carious lesion contains partially demineralized crystals, and considerable remineralization of surface enamel in lesions free of plaque has been observed (Fig. 9.17). Thus, surface remineralization of carious lesions that developed during orthodontic treatment is not uncommon (see Chapter 5), leaving the body of the lesion as a white scar under a shiny hard surface (Fig. 9.17) and during experimental conditions in situ in Fig. 9.18. The surface changes are a combination of abrasion of the porous enamel and a slow redeposition of mineral in and onto the partly dissolved crystals (Fig. 9.16). Owing to slow diffusion, however, it does not seem possible to maintain the necessary supersaturation in the lesion fluid; therefore, remineralization of the lesion body is not obtained to any significant degree *in vivo*! The surface layer of the lesion protects the underlying lesion body not only from demineralization, but also from remineralization.

When caries lesions are developed in situ experimentally these conditions have been studied systematically (Figs 9.18 and 9.19), and it is apparent that so called 'remineralization' in the clinic is predominantly a result of surface modification (abrasion and mineral uptake) and not reflecting mineral uptake within the body of the lesion. Thus, this fully explains the histological features of arrested natural caries lesions when examined by microradiography (Fig. 9.20).

On rare occasions the lesion body may be remineralized when the surface layer has been lost and biofilm covering the rough exposed surface area is removed. Under such rare conditions there is free access for salivary calcium, phosphate, and fluoride ions (Fig. 9.21). However, it must be noted that the loss of the surface layer also means a free access of cariogenic acids, and thus an increase in the demineralization rate. Therefore, with the possible exception of orthodontic lesions, therapeutic removal of the surface layer to increase remineralization is *not* recommended.

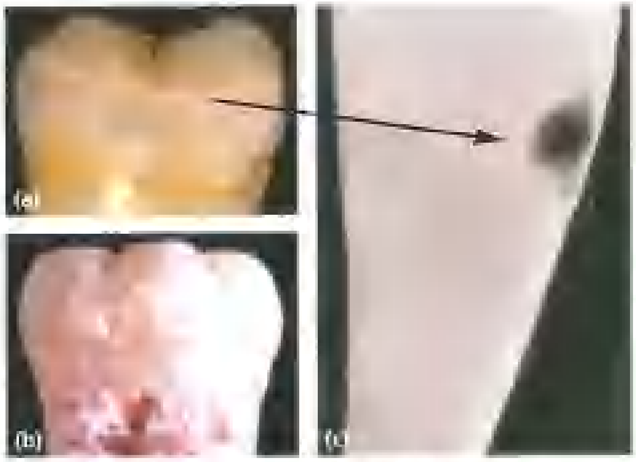


Figure 9.14 Laboratory attempt to take teeth with natural active caries lesions (a) and (c), and expose these consecutively to solutions saturated with respect to phosphate and calcium respectively in order to fill up the pores of the lesions with these ions followed by elevating the pH in the solutions to create a supersaturation within the enamel lesions. The only result was mineral deposition on the tooth surface (b). From [9, 10]. Reproduced with permission of John Wiley & Sons.

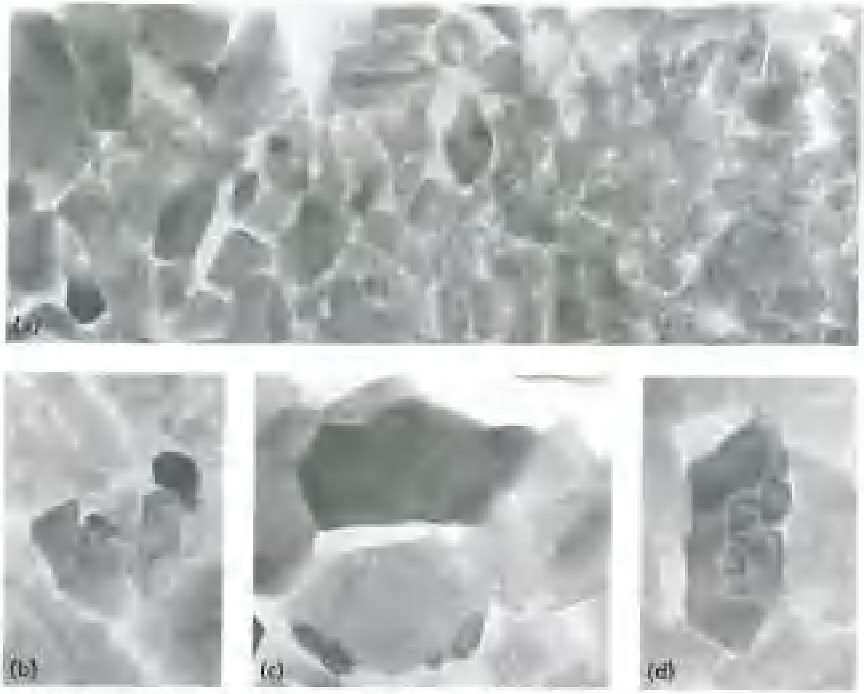


Figure 9.15 Transmission electron micrographs from the very surface of inactive, remineralized caries lesions. In addition to irregular mineral deposits between hexagonal enamel crystals (a), numerous small hexagonal crystals form onto partly demineralized larger crystals (b, c), ending within the dissolved crystals (d).

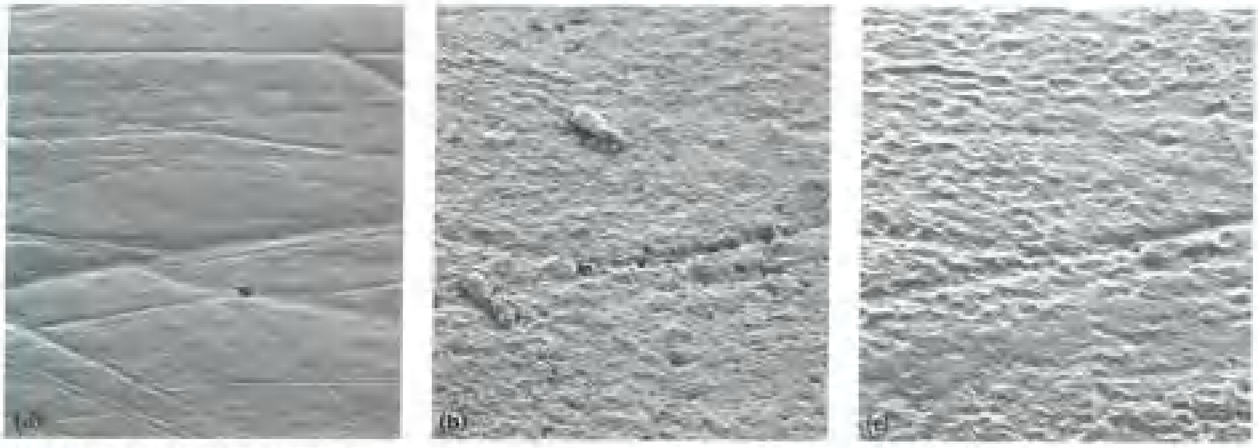


Figure 9.16 Scanning electron micrographs of replicas from an enamel surface before (a) and after acid conditioning (b). After 3 weeks the typical etch pattern of the prisms can be discerned. The enamel scratch (from brushing with an abrasive toothpaste) in (a) can be seen also in (b) and (c), whereas the small scratches has been eliminated.

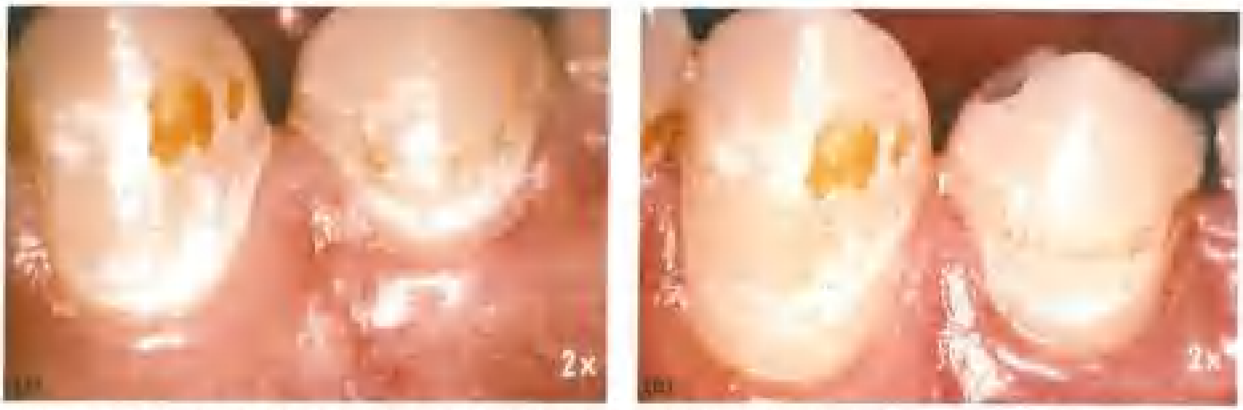


Figure 9.17 Active enamel caries lesions following removal of orthodontic brackets (a) and after 1 month of proper oral hygiene (b). The lesions have diminished a little in degree of opacity (partly mineral uptake, but in particular surface polishing) and are inactive but remain from then on as scars in the enamel.

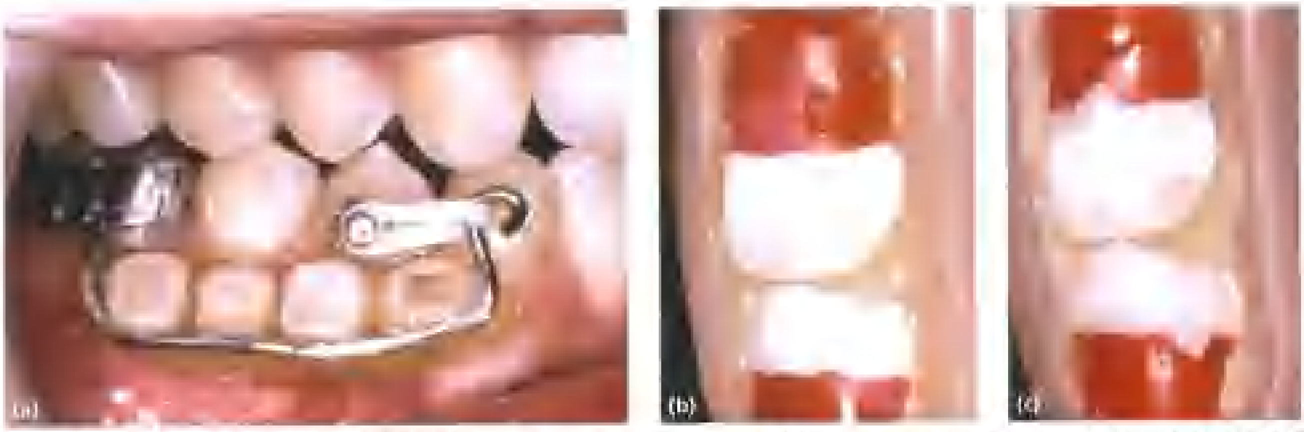


Figure 9.18 In-situ experimental caries lesion development and remineralization. (a) An example of how small enamel samples can be inserted in a device and placed in the mouth of volunteers for month. (b) Caries lesions created in the laboratory are exposed to proper oral hygiene and followed for 3 months (c). Note that even a very standardized subsurface artificial caries lesion cannot be totally eliminated by mineral uptake and extensive tooth polishing with a fluoride-containing toothpaste.

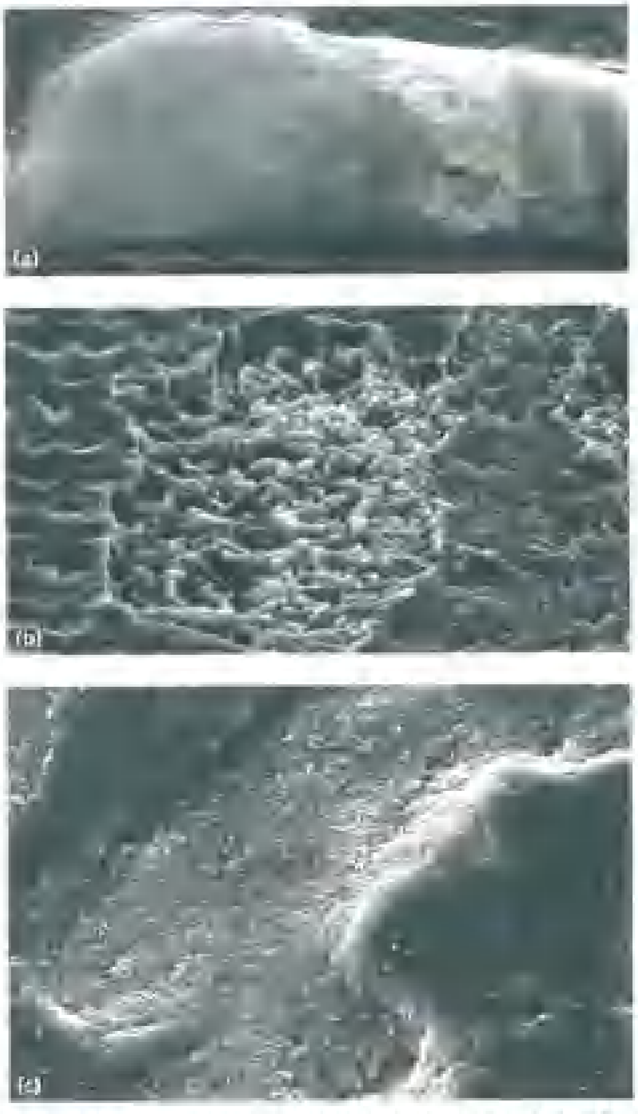


Figure 9.19 Scanning electron micrographs of the lesions shown in Fig. 9.18b and c. Note how the etched surface in (b) is partly polished away after 3 months (c).

Remineralization of dentin

As described in Chapter 5, the natural root-surface carious lesion is characterized by a subsurface loss of mineral very similar to that seen in enamel caries. This is true irrespective of whether it develops while the root surface is still covered by cementum or has exposed dentin. From a chemical point of view, therefore, it is tempting to suggest that the basic physicochemical events leading to an established natural root-surface lesion are very similar to those occurring during enamel caries development. Having said this, it is important to realize that the overall structural composition of cementum and dentin results in substantial differences in the way in which microorganisms interact with dentin and root surfaces during carious lesion development (see Chapter 5). Thus, in addition to the inorganic chemical events, there will be proteolytic activity in order to remove part of the collagenous matrix remaining after demineralization. To understand the chemical events occurring during carious lesion development in dentin and cementum, different in-situ models have been used for experimentation. An in-situ model is a specimen of tooth tissues inserted into the human oral environment to study lesion formation (see Fig. 9.18). However, the outcome of in-situ caries models may differ substantially depending on their design [5], and, therefore, the choice of model may influence the conclusions drawn from these studies. For example, in one design, root specimens were mounted in a sheltered position underneath orthodontic bands in palatal appliances and exposed to the oral environment for 1–4 weeks [19]. The type of root-surface lesion created under these conditions is characterized by a shallow surface etching.

In contrast, this section will consider chemical events occurring when root-surface lesions are developed over 3–6 months under conditions where the surfaces are freely exposed to the oral fluids [18]. In Fig. 9.22 the microbial deposits on the tooth surface were not removed during the first 3 months of the study. During the second 3-month period two topical treatments with a 2% solution of sodium fluoride were given for 2 min, one at the beginning of the treatment period when plaque removal was started and the second after 1.5 months of regular plaque removal. The illustration shows that the treatment resulted in an overall mineral gain in the surface layer and within the body of the lesion. In a separate experiment during the second 3-month period no additional oral hygiene measures were taken, resulting in additional mineral loss (Fig. 9.23). It is not possible on the basis of such experiments to draw conclusions about the relative importance of fluoride toothpaste, topical fluoride treatment, and plaque removal on the outcome of lesion development. It is remarkable that no studies have attempted to distinguish the effect of plaque removal from that of fluoride alone on lesion development. However, topical fluorides inhibit caries, especially when dental cleaning is insufficient [20].

Notice that actively progressing root carious lesions can arrest with an increase in mineral content of the surface layer. Perhaps this increased mineral results from daily fluoride exposure from toothpaste combined with a reduced cariogenic challenge due to regular plaque removal. In many ways the basic chemical events occurring during carious lesion development in enamel, dentin, and cementum appear similar. As stressed earlier in this chapter, it is thus to be expected that fluorapatite will gradually accumulate in the surface of the tissues as a result of ongoing demineralizing and remineralizing processes. Hence, a subsurface enamel carious lesion is covered by a surface layer with a high fluoride

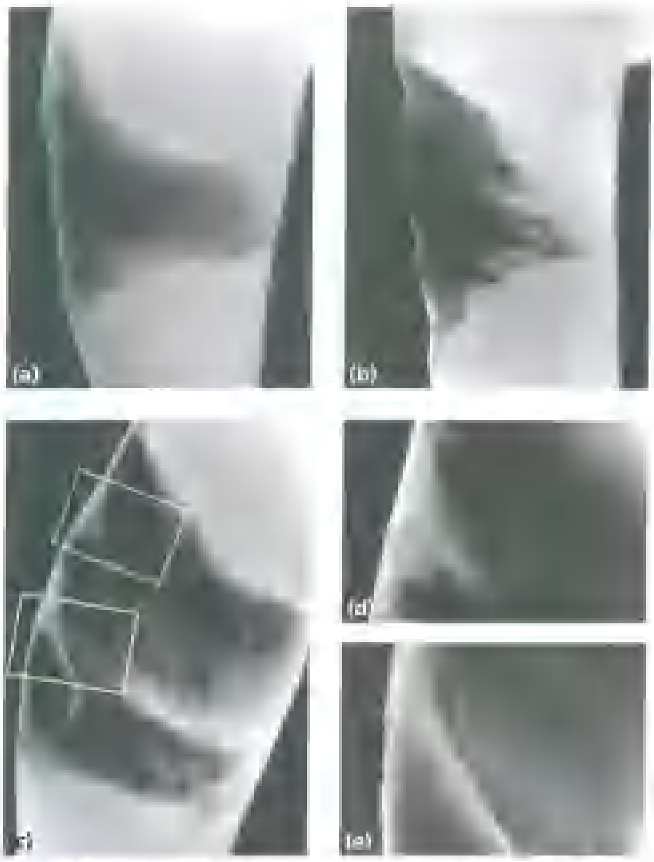


Figure 9.20 Microradiographs of three inactive caries lesions that had been arrested for several years. Note that the demineralization extends throughout the enamel. The surface zone varies extensively in mineral content both between different lesions (a, b) and within lesions (c–e).

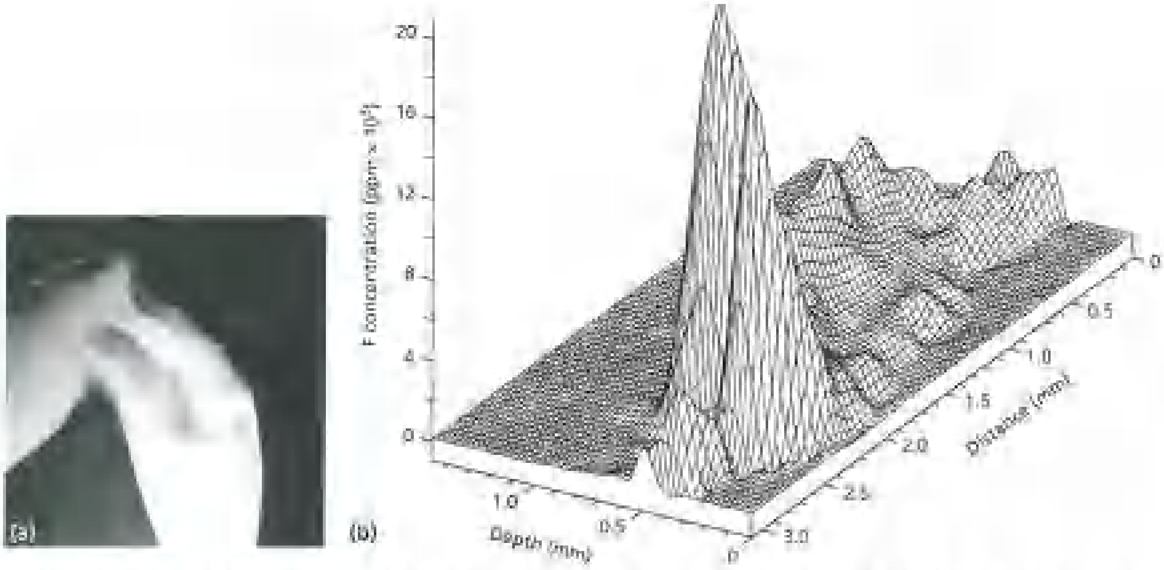


Figure 9.21 Microradiograph of a caries lesion remineralized for years *in vivo* (a). The surface layer of this third molar has been abraded away, giving the saliva access to the lesion body and resulting in a considerable uptake of mineral. The graph of the fluoride scan (b) shows uptake of extraordinary amounts of fluoride in the remineralized zones of the lesion.

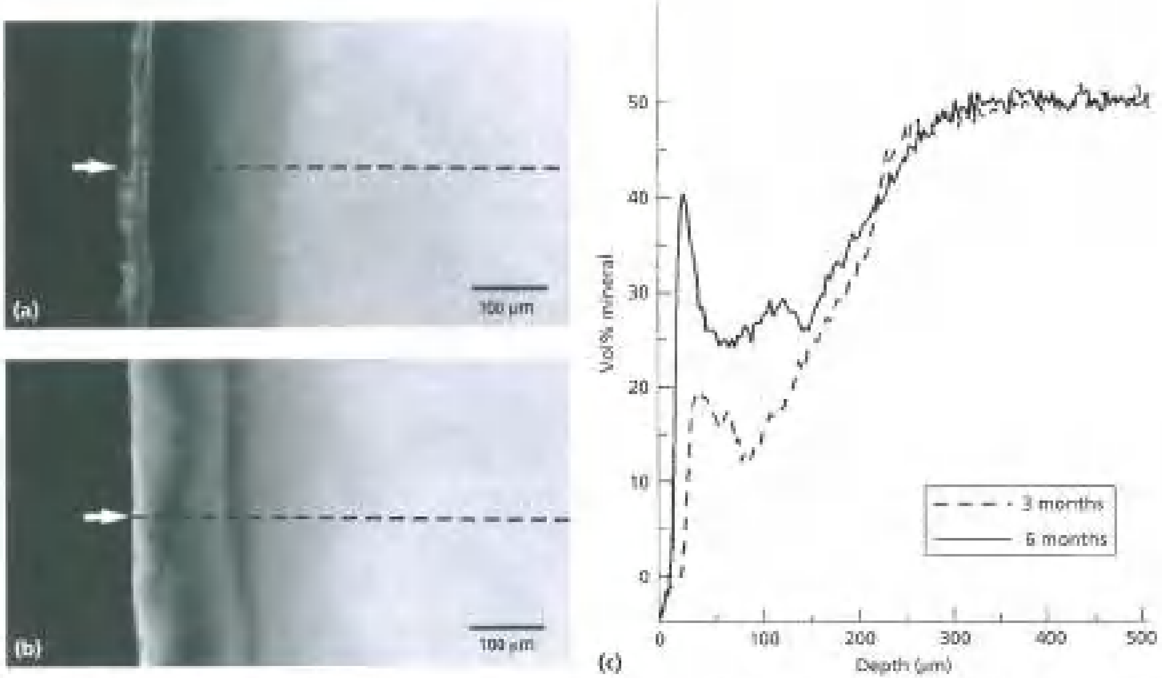


Figure 9.22 Microradiograph of an experimental root caries lesion in situ after (a) 3 months with daily plaque removal, followed by (b) 3 months with daily plaque removal and topical fluoride treatment. (c) The mineral content as a function of depth corresponding to the dotted lines in (a) and (b). The treatment resulted in an overall mineral gain because of an increase of the mineral content in the surface layer and formation of a mineral zone in the body of the lesion 125 µm deep to the surface. Scale bar: 100 µm. For original figure, refer to [18]. Reproduced with permission of Sage Publications.

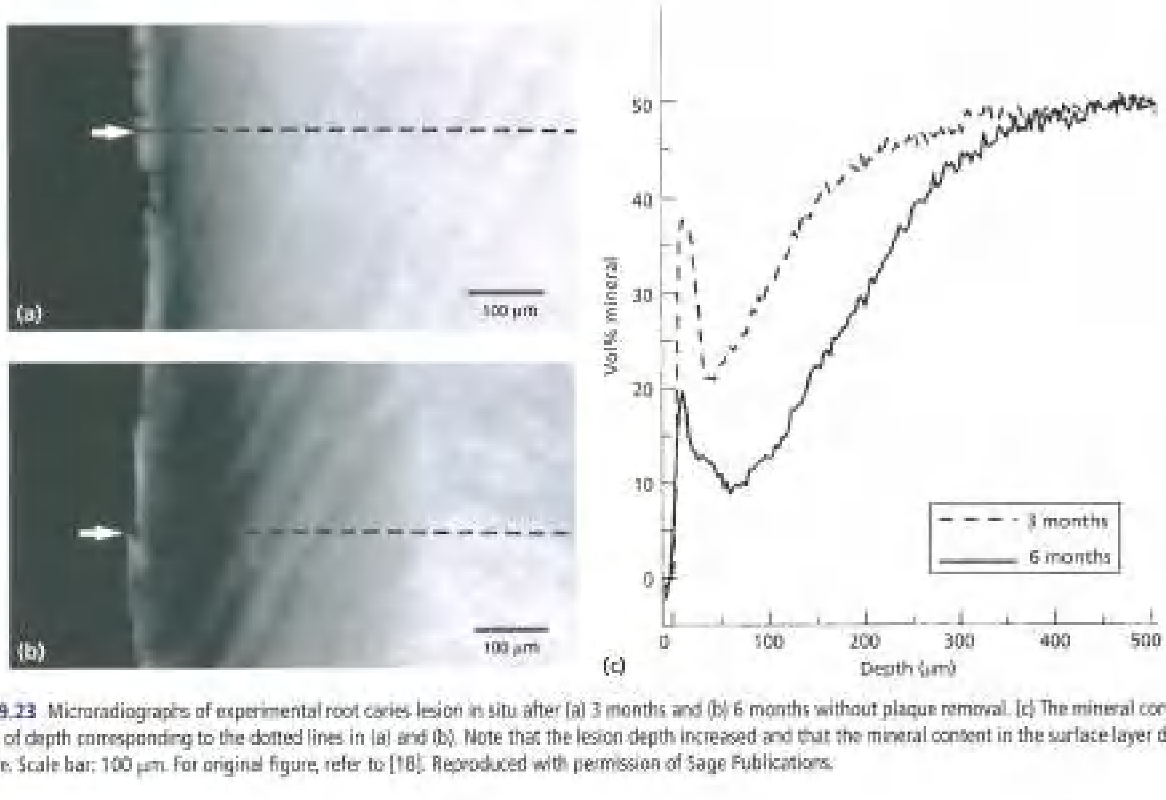


Figure 9.23 Microradiographs of experimental root caries lesion in situ after (a) 3 months and (b) 6 months without plaque removal. (c) The mineral content as a function of depth corresponding to the dotted lines in (a) and (b). Note that the lesion depth increased and that the mineral content in the surface layer decreased over time. Scale bar: 100 µm. For original figure, refer to [18]. Reproduced with permission of Sage Publications.

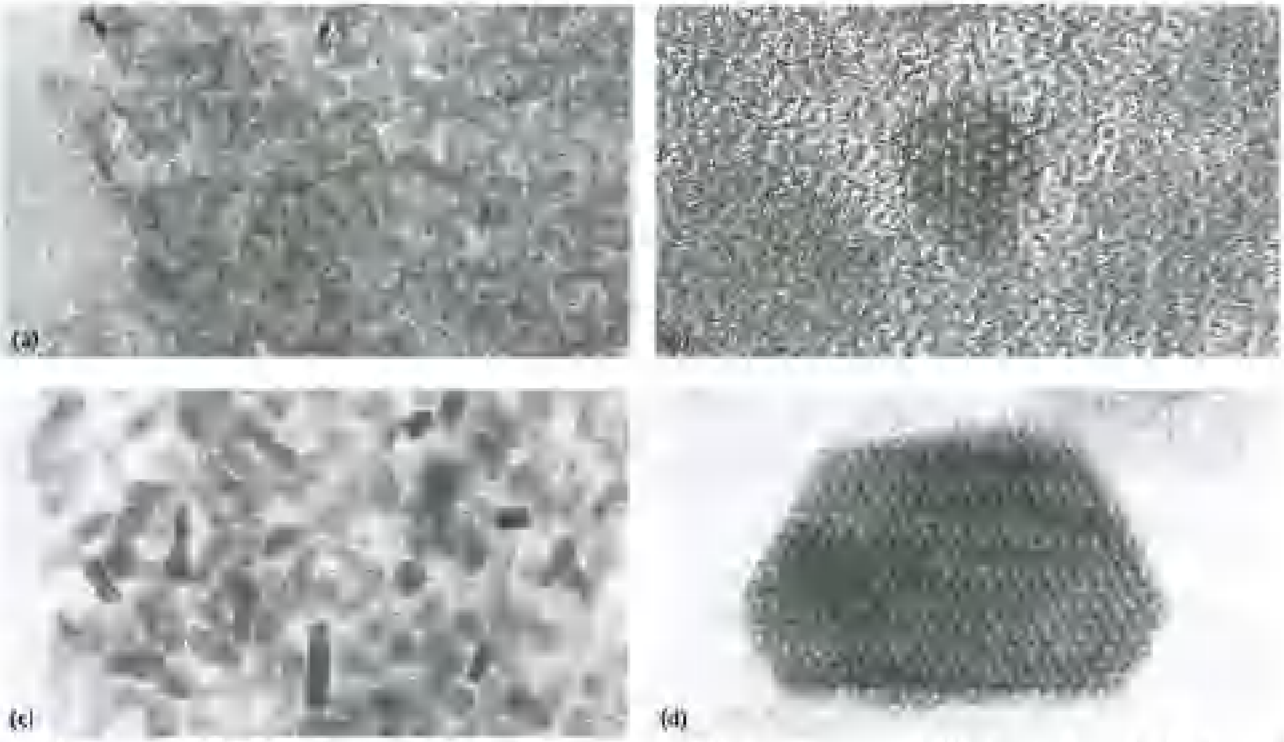


Figure 9.24 Transmission electron microscopic pictures of normal cementum not exposed to the oral environment (a, b) and exposed root surface (c, d). Note the difference in crystal size showing evidence of crystal growth when apatite crystals in cementum had been exposed to the oral cavity. For original figure, refer to [33]. Reproduced with permission of Sage Publications.

content – higher than that of surrounding normal enamel – and likewise the well-mineralized surface layer covering a subsurface dentin or cementum lesion contains a much higher fluoride content than that of normal tissues [31].

Root surfaces (exposed cementum/dentin) appear to be more susceptible to carious attack than enamel surfaces are. A clinical manifestation of this is the occurrence of dentin caries in some patients with dry mouths, where the enamel is caries free. In the above-mentioned in-situ study it was striking that even with daily plaque control, root surfaces, sound but previously unexposed to the oral environment, undergo changes in mineral distribution. This may lead to a subsurface mineral loss, which is only detectable at the microscopic level. Unerupted root surfaces that become exposed to the oral environment as a result of gingival recession or periodontal surgery are very prone to lesion development [7, 23]. The very small apatite crystals in dentin and cementum, compared with those of enamel, have a more reactive surface. Thus, unerupted root surfaces exposed to the oral environment may undergo substantial modification of the mineral as a result of metabolic activity in the biofilms. This may explain the differences in crystal packing and size in the root surfaces of unexposed and exposed carious root surfaces (Fig. 9.24). These processes reflect a substantial uptake and redeposition of minerals into crystals that are partly dissolved. The permeability and reactivity of the root surfaces may change so that they become less susceptible to future cariogenic challenges [29].

The complex events leading to mineral loss and deposition in dental hard tissues exposed to the oral environment are not fully understood. Although the in-situ models may mimic the physicochemical events occurring during lesion formation *in vivo*, it should be remembered, for example, that teeth with a vital pulpo-dentinal organ will respond to most exogenous stimuli through the apposition of minerals along and within the dentinal tubules [6]. This phenomenon, together with the outward flow of dentinal fluid from the pulp, may be expected to reduce the rate of lesion progression *in vivo* significantly in dentin [24]. This may explain why caries seems to progress more rapidly in dentin in nonvital teeth.

Background literature

Elliott JC. *Structure and chemistry of the apatites and other calcium orthophosphates.* Amsterdam: Elsevier, 1994.

Holden A, Morrison P. *Crystals and crystal growing.* Cambridge, MA: MIT Press, 1982.

LeGeros RZ. *Calcium phosphates in oral biology and medicine.* Basel: Karger, 1991.

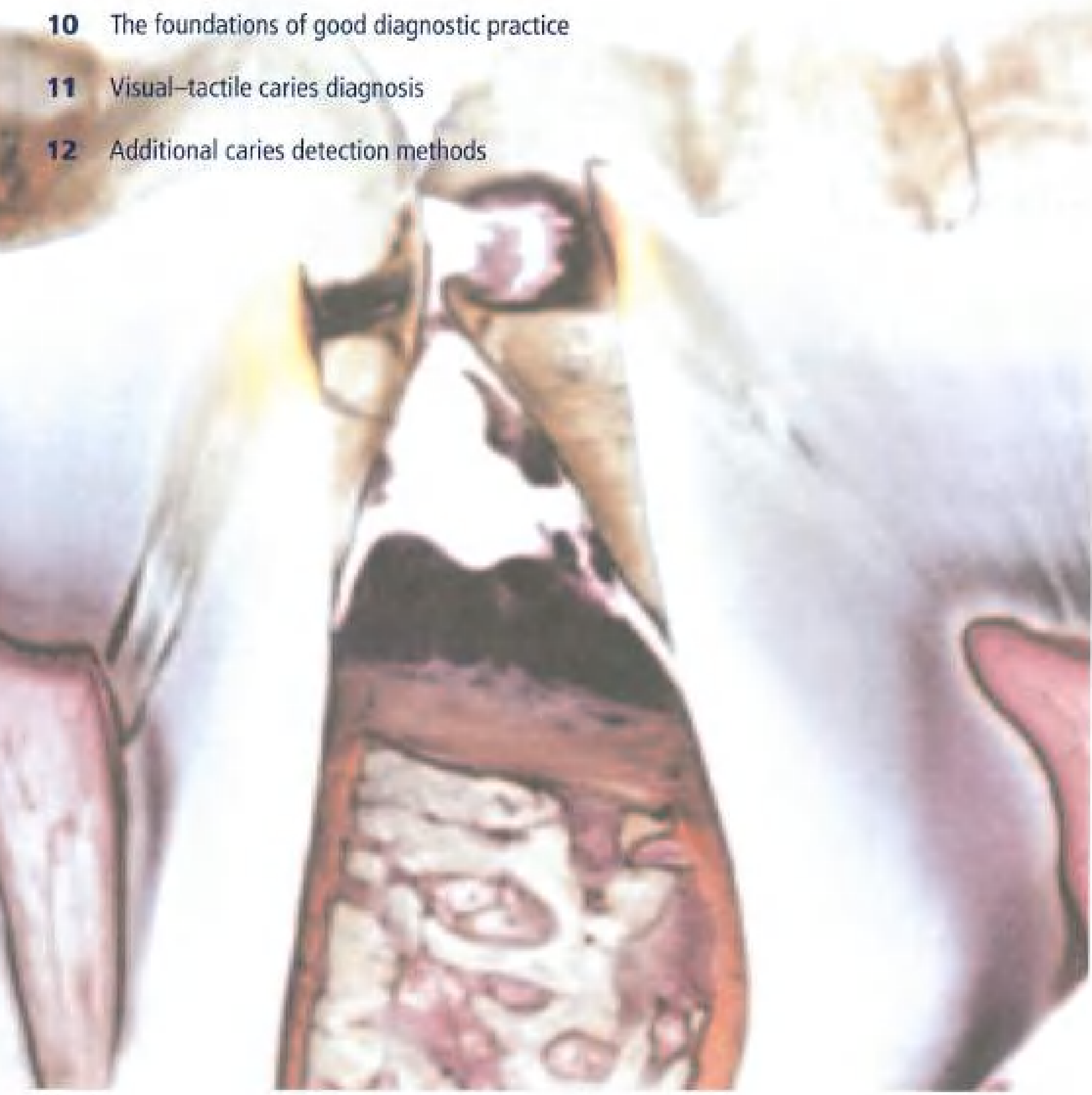
Schroeder HE. *Formation and inhibition of dental calculus.* Berne: Hans Huber, 1969.

References

1. Bernardi G, Kawasaki T. Chromatography of polypeptides and proteins on hydroxyapatite columns. *Biochim Biophys Acta* 1968; **160**: 301–10.
2. Brown WE. Solubilities of phosphates and other sparingly soluble compounds. In: Griffith EJ, Beeton A, Spencer JM, Mitchell DT, eds. *Environmental phosphorus handbook*. New York: John Wiley & Sons, Inc., 1973: 203–239.
3. Curzon MEJ, Cutress TW. *Trace elements and dental disease*. Bristol: John Wright, 1983.
4. Fejerskov O, Thylstrup A, Larsen MJ. Rational use of fluorides in caries prevention. A concept based on possible cariostatic mechanisms. *Acta Odont Scand* 1981; **39**: 241–49.
5. Fejerskov O, Nyvad B, Larsen MJ. Human experimental caries models: intra-oral environmental variability. *Adv Dent Res* 1994; **8**: 134–43.
6. Frank RM, Vogel JC. Ultrastructure of the human odontoblast process and its mineralisation during dental caries. *Caries Res* 1980; **14**: 367–80.
7. Furseth R. A study of experimentally exposed and fluoride treated dental cementum in pigs. *Acta Odontol Scand* 1970; **28**: 833–50.
8. Josephsen K, Takano Y, Frische S, Praetorius J, Nielsen S, Aoba T, Fejerskov O. Ion transporters in secretory and cyclically modulating ameloblasts: a new hypothesis for cellular control of preeruptive enamel maturation. *Am J Physiol Cell Physiol* 2010; **299**: 1299–307.
9. Larsen MJ, Fejerskov O. Remineralization from a clinical point of view. *Dtsch Zahnärztl Z* 1987; **42**: 91–4.
10. Larsen MJ, Fejerskov O. Chemical and structural challenges in remineralization of dental enamel lesions. *Scand J Dent Res* 1989; **97**: 285–96.
11. Larsen MJ, Pearce EIF. Some notes on the diffusion of acidic and alkaline agents into natural human caries lesions in vitro. *Arch Oral Biol* 1992; **37**: 411–16.
12. Larsen MJ, Pearce EIF, Jensen SJ. Notes on the dissolution of human dental enamel in dilute acid solutions at high solid/solution ratio. *Caries Res* 1993; **27**: 87–95.
13. LeGeros RZ. Chemical and crystallographic events in the caries process. *J Dent Res* 1990; **69**: 567–74.
14. McCann HG. The solubility of fluorapatite and its relationship to that of calcium fluoride. *Arch Oral Biol* 1968; **13**: 987–1001.
15. Moreno EC, Zahradnik RT. Chemistry of enamel subsurface demineralisation in vitro. *J Dent Res* 1974; **53**: 226–35.
16. Moreno EC, Kresak M, Zahradnik RT. Fluoridated hydroxyapatite solubility and caries formation. *Nature* 1974; **247**: 64–5.
17. Nelson DGA. The influence of carbonate on the atomic structure and reactivity of hydroxyapatite. *J Dent Res* 1981; **60**: 1621–9.
18. Nyvad B, ten Cate JM, Fejerskov O. Arrest of root surface caries *in situ*. *J Dent Res* 1997; **76**: 1845–53.
19. Ögaard B, Rølla G, Arends J. *In vivo* progress of enamel and root surface lesions under plaque as a function of time. *Caries Res* 1988; **22**: 302–5.
20. Ögaard B, Arends J, Rølla G. Action of fluoride on initiation of early root surface caries *in vitro*. *Caries Res* 1990; **24**: 142–4.
21. Pearce EIF. Relationship between demineralisation events in dental enamel and the pH and mineral content of plaque. *Proc Finn Dent Soc* 1991; **87**: 527–39.
22. Pearce EIF, Larsen MJ, Cutress TW. Studies on the influence of fluoride on the equilibrating calcium phosphate phase at a high enamel/acid ratio. *Caries Res* 1995; **29**: 258–65.
23. Selvig KA, Zander HA. Chemical analysis and microradiography of cementum and dentin from periodontally diseased teeth. *J Periodontol* 1962; **33**: 303–10.
24. Shellis RP. Effects of a supersaturated pulpal fluid on the formation of caries-like lesions on the roots of human teeth. *Caries Res* 1994; **28**: 14–20.
25. Shellis RP, Heywood BR, Wahab FK. Formation of brushite, monetite and whitlockite during equilibration of human enamel with acid solutions at 37 °C. *Caries Res* 1997; **31**: 71–7.
26. Sønju T, Rølla G. Chemical analysis of the acquired pellicle formed in two hours on cleaned human teeth *in vivo*. Rate of formation and amino acid analysis. *Caries Res* 1973; **7**: 30–8.
27. Ten Cate JM, Duijsters PP. Influence of fluoride in solution on tooth demineralization. I. Chemical data. *Caries Res* 1983; **17**: 193–9.
28. Ten Cate JM, Duijsters PP. Influence of fluoride in solution on tooth demineralization. II. Microradiographic data. *Caries Res* 1983; **17**: 513–19.
29. Ten Cate JM, Jongebloed WL, Simons YM, Exterkate RAM. Adaptation of dentin to the oral environment. In: Thylstrup A, Leach SA, Qvist V, eds. *Dentine and dentine reactions in the oral cavity*. Oxford: IRL Press, 1987: 67–76.
30. Tohda H, Takuma S, Tanaka N. Intracrystalline structure of enamel crystals affected by caries. *J Dent Res* 1987; **66**: 1647–53.
31. Tohda H, Fejerskov O, Yanagisawa T. Transmission electron microscopy of cementum crystals correlated with Ca and F distribution in normal and carious human root surfaces. *J Dent Res* 1996; **75**: 949–54.
32. Yanagisawa T, Takuma S, Tohda H, Fejerskov O, Fearnhead RW. High resolution electron microscopy of enamel crystals in cases of human dental fluorosis. *J Electron Microsc* 1989; **38**: 441–8.

Part III

Diagnosis



10

The foundations of good diagnostic practice

V. Baelum, B. Nyvad, H.-G. Gröndahl, and O. Fejerskov

Introduction

It is a common claim that dentistry is an artistic craft, as in the expression 'the art of dentistry,' whose means and methods can only be learned and optimized by accumulating clinical experience. This is not true. There are also concepts and principles, rules and guidelines, and we must evaluate the evidence and acquire scientific knowledge to gain a platform, our knowledge base, whereupon we may build our clinical experience.

In this chapter we review the scientific and conceptual underpinnings of caries diagnosis. Dental students and professionals alike may then gain a deeper understanding

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

of the building blocks necessary for creating a good diagnostic strategy for use in their daily clinical practice. The dental professional, who wants to be able to adapt their core diagnostic skills to different settings, and be able to choose the best treatment alternatives, must have a thorough understanding of the fundament of clinical decision-making. The activities and the decision processes involved in caries diagnosis are not identical for all patients or in different populations with different caries profiles. Nor can we assume that caries diagnosis will remain unchanged for all future to come. It is therefore vital that the dental professionals have a clear understanding of the factors influencing their diagnostic practices.

The foundations for our diagnostic practices are laid during undergraduate training. This chapter, therefore, will begin by exploring how dentistry is commonly taught to the bright, but innocent student. We will then proceed to explore why we concern ourselves with caries diagnosis and we show that two rather different lines of thinking operate in our approach to caries diagnosis. Finally, we emphasize that caries diagnosis, irrespective of the method(s) used, is an error-prone enterprise, and that diagnostic decisions are made under uncertainty. The addition of different caries diagnostic methods, or the repetition of caries diagnostic methods, inevitably results in more diagnostic errors. This fundamental diagnostic uncertainty demands that the dentist exercises a considerable degree of restraint when making caries diagnoses that may have irretrievable negative consequences if the diagnosis is incorrect. In most contemporary populations, there is a continued decline in the caries prevalence, the caries incidence, and caries lesion severity. Thus, the risk of causing adverse health outcomes increasingly stems from overzealous operative intervention rather than from overlooking caries lesions.

The making of a dentist

Clinical dentistry is taught under the auspices of the master clinician [69], the clinical 'expert.' The 'art and craft' of diagnostic and therapeutic decision-making is learned mainly through a chair-side apprenticeship. Unfortunately, the scientific and conceptual underpinnings of the practices taught during these clinical sessions may not receive adequate attention. Certainly, master clinicians and general dentists alike tend to be very reluctant to formalize the clinical decision-making processes they use, and prefer to view these decisions as embedded in the 'art of dentistry' [8]. The 'art of dentistry' concept implies that the clinical decision-making process is informal and intuitive, and can only be optimized through accumulated clinical experience. The dental students learn to reproduce what they have been told and shown by the clinical master, whose opinions, perceptions, biases, and value judgments therefore determine the practices adopted. The lack of a strategy for training the master clinicians may result in inconsistent, and even contradictory, teachers.

The 'art of dentistry' and caries scripts

When inconsistencies or contradictions become obvious, dental students are typically told that they result from 'the natural variation in the best clinical judgment of individual dentists concerning individual patients' [8]; that is, they reflect 'the art of dentistry' to be learned by the student. The students are not supposed to explore the differences, nor are they expected to challenge the argument. Instead, they are encouraged to try to understand and memorize as much as possible the particulars of each single patient ('no two patients are the same!') and each clinical situation in order to incorporate these details into a mental inventory of clinical scripts [70]. These clinical scripts incorporate differential diagnostic considerations, that is, the distinction between caries lesions on the one hand and fluorotic lesions, enamel opacities, and hypoplasias on the other hand. Thus, the caries scripts serve as manuals for the entire clinical decision-making process to use whenever we next encounter a similar clinical presentation.

Thereby, the clinical decision-making in dentistry cannot be compartmentalized into distinct diagnostic and therapeutic entities. Caries diagnosis is not an activity undertaken completely independently of the options for intervention, and clinical decision-making is more characterized by the execution of 'this-clinical-picture-needs-this-intervention'-like scripts [70].

Variation in clinical decisions

In view of the learning process described, it is no wonder that many dentists focus on the minutiae of each single clinical representation, and value expert opinions and clinical experience much higher than scientific evidence and evidence-based practice guidelines. It is likewise not surprising that a huge variation exists in the way dentistry is practiced [8, 71, 72, 74]. This variation is characteristic for both diagnostic and therapeutic decision-making, and implies that some dentists provide better or more efficient dental care than other dentists when faced with similar patients.

Is this variation a problem? Can we not just leave things the way they are and continue to let dentists develop their own particular catalogue of clinical scripts? Our answer is a clear no! While the considerable variation does not seem to be an area of major concern among dental professionals, it will be a tangible problem for the patients if they realize that they receive different standards of care with different practitioners. In times of growing patient expectations and increasing patient-initiated litigations, therefore, it may be a wise move for the dental profession to face the variation in order not to fall prey to accusations of deliberate unethical practice [73], whereby credibility may be irretrievably lost among the populations we serve [32, 111].

Can caries scripts be changed?

Dentists' caries scripts are influenced by a large number of factors [10], including personal dentist characteristics such as age and experience, skill and diligence, and knowledge and tolerance for uncertainty; dentist biases concerning the perceived utility of restorations, treatment preferences, diagnostic techniques used, and experience with outliers (such as the innocuously looking lesion that turns out to cover a soft caries lesion extending all the way to the pulp); and, finally, practice characteristics such as busyness, size, delivery system, equipment, guidelines, and personnel.

If the variation in the clinical decisions made by dentists is to be reduced, some dentists must change their clinical caries scripts. This can be achieved in one of two ways [10]: either by means of the introduction into the caries scripts of a new salient factor or, more likely, by a reinterpretation of existing salient factors. Examples of such reinterpretations are many. It is known that older dentists tend to be less aggressive in their decisions to intervene [7], probably due to accumulated clinical experience allowing them to gradually reinterpret some of the factors determining their caries scripts. Hence, older dentists may have had the experience that caries does not progress at the rate they once thought, or that restorations do not last as long as they were once led to believe. Other examples comprise the observation that Australian dentists practicing in a water-fluoridated area have been found to be more inclined to adopt a wait-and-see attitude when presented with a given radiographic lesion than dentists practicing in Norway [42]. This was ascribed to Australian dentists having different experiences of caries lesion progression. Others have noted that teeth with decay or 'unsatisfactory' fillings are less likely to be restored when located in patients residing in a fluoridated area than when found in patients from a nonfluoridated area [49, 50].

In this context, it is important to realize that the patients seen in our dental schools are typically not representative of the general population. Dental school patients tend to be admitted based on a need for the specific mechanical and technical procedures taught during undergraduate dental training. This means that the oral disease spectrum presented to the dental student may be heavily biased towards more prevalent and severe oral disease than is actually characteristic for the general population. Thereby, the dental student may be left with the impression that good dental practice hinges more on mechanical/technical intervention than is appropriate for the general population.

The above examples all concern the propensity to intervene; that is, whether and how to intervene therapeutically for a given clinical or radiographic presentation. However, numerous steps have been taken before reaching the stage of deciding upon interventions. Decisions have been made regarding the clinical recording methods employed and the addition of bitewing radiography or other sense-enhancing diagnostic methods. These decisions are not made consciously and *de novo* for each single tooth in each single patient but are dictated by the routines and practices of the dentist, as first learned at dental school and subsequently modified through experience. Thereby, these diagnostic decisions also contribute as a source of variation in the clinical decisions made among dentists.

Fortunately, evidence suggests that variation from this source can be reduced. Hence, a study of the diagnostic performance of dentists before and after attending a 1.5 h seminar explaining the key elements in clinical diagnosis showed that diagnostic decisions improved and became more consistent as a result of a short education in probabilistic reasoning [24]. While it may seem quite paradoxical that learning about uncertainty will enhance diagnostic consistency, there are analogous examples from other branches of dentistry illustrating that clinical experience and expertise do not guarantee the most consistent diagnoses [46].

The dental examination: in the best interest of our patients

Patients come to us for one of two different reasons: they either have a concrete and tangible dental problem, such as toothache or tooth mobility, for which they seek our help, or they go for a routine check-up. In many high-income countries, the routine screening examinations predominate among the dentist–patient contacts, whereas in low-income countries symptom-driven contacts are much more frequent, as indeed they were decades ago in high-income countries.

The symptom-driven dental visit

These two scenarios, the symptom-driven dental visit and the routine (screening) check-up visit, have fundamentally different implications for the patients. The symptom-driven dental visit is strictly patient initiated and prompted by actual symptoms; that is, concrete and tangible complaints, which make the patient seek help to obtain symptom relief. The success or failure of the dentist is obvious in such circumstances. If the diagnostic activities undertaken result in the identification of the sources and causes of the problem, and if the ensuing intervention results in symptom relief, gratification is immediate for both the dentist and the patient: the diagnosis was correct, the dentist solved the problem, and the patient got rid of their symptoms.

The routine (screening) check-up visit

The routine check-up visit, on the other hand, involves an asymptomatic patient, and thereby amounts to a screening examination. In many instances, the routine dental visit will have been prompted by some recall scheme devised by the dentist, rather than being strictly patient initiated. During this routine visit, the dentist looks for signs of oral diseases, which includes an examination of all tooth surfaces for the presence of signs of caries. If such signs are found, some form of intervention is carried out to prevent disease progress. Thereby, the gratification of both the dentist and the patient is based on a set of assumptions that can be summarized as follows: if the screening examination had not been carried out and the interventions had therefore not been made, the patient would have fared worse in the future.

The two situations have one thing in common, however: the dental professionals will say that they undertake their activities in the best interest of the patient. In other words, we look for caries to find the causes of tangible symptoms presented by the patient, or to prevent asymptomatic caries lesions from developing into tangible symptoms with all the unfortunate sequels that this may have.

What are we looking for? What is caries?

The shrewd reader of this textbook will undoubtedly already have spotted that the notion of caries varies. Many of the terms aired in preceding and ensuing chapters all pertain to dental caries, but from rather different perspectives, such as chemistry, bio-imaging, microbiology, pathology, and epidemiology. This illustrates a lack of a common understanding of what is meant by the term *caries* [15]. This ambiguity stems, in turn, from a more fundamental lack of clarity about what constitutes a 'disease' [114, 115, 135]. A popular understanding of the disease 'dental caries' holds that the disease caries is a process – a sort of engine usually termed the 'caries process' – that converts the direct causes of caries (the microbial biofilm on the tooth surfaces and the fermentable carbohydrates from the diet) into the signs and symptoms of caries; that is, the caries lesions (Fig. 10.1). This understanding, which is termed *essentialistic* [115, 135], can be shown to be logically erroneous [15]. Nonetheless, this essentialistic thinking has led to the unfortunate belief in the existence of a fixed caries 'truth,' placed somewhere in the limbo between the causes of caries and the signs and symptoms of caries. The meaning of this is perhaps best understood if we apply a timeline. Hence, the causes of caries must – by virtue of the definition of a cause – precede the caries process, which – if the caries process causes signs and symptoms – must precede the signs and symptoms of caries that it generates (Fig. 10.1). This mistaken belief is the basis for statements such as 'diagnosis is the act or art of identifying a disease from its signs and symptoms' [76] and 'diagnosis is defined as the determination of disease, but not as the determination of the signs and symptoms thereof' [120].

However, there is no disease, called caries, which differs from its signs and symptoms. This is illustrated by the notable absence of the term *dental caries* in Fig. 10.2, which

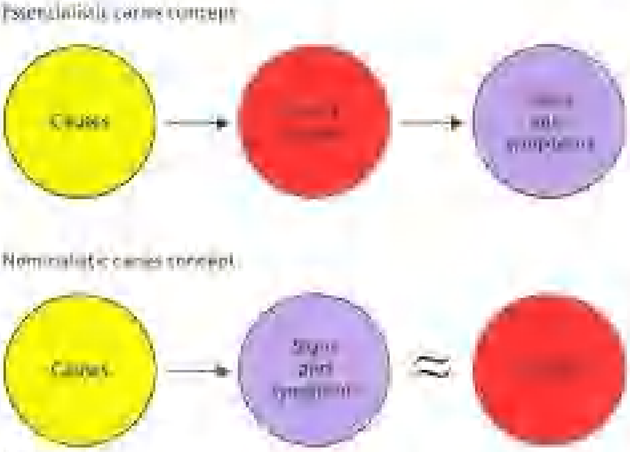


Figure 10.1 Essentialistic versus nominalistic caries concepts. The essentialistic concept holds that a caries truth exists interposed between the causes and the signs and symptoms. The nominalistic concept holds that dental caries is no more than a label attached to tooth surfaces sharing certain defining characteristics; that is, a convenient and succinct way of describing the signs and symptoms.

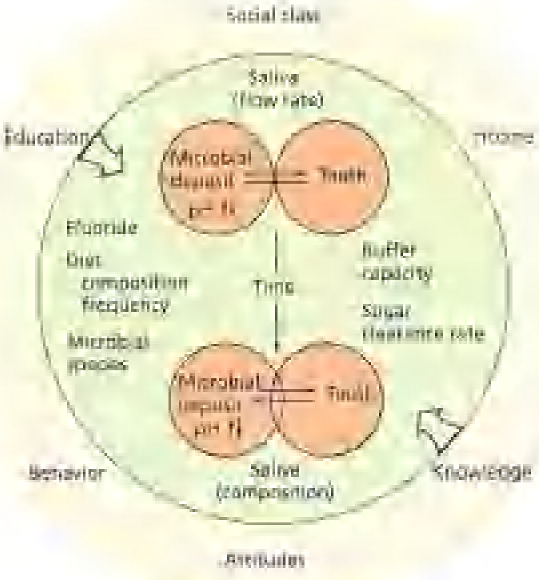


Figure 10.2 The 'caries process' – a schematic illustration of the causes of caries lesions (=signs and symptoms). Those causes that act at the tooth surface level are found in the inner circle, while the more distant determinants are found in the outer circle. Adapted from [43]. Reproduced with permission of the University of North Carolina School of Dentistry.

also shows that the 'caries process' is no more than a convenient descriptor for the entire complex of causal factors that produces the signs and symptoms we label as 'caries lesions.' The result of the causal processes is the formation of caries lesions. Dental caries is therefore no more than a label attached to clinical presentations that share certain defining characteristics. In other words, *dental caries* is a term that describes the signs and symptoms resulting from the completion of the caries causal complex. This caries view is termed *nominalistic* (Fig. 10.1). Nominalism is the underpinning of the old dictum 'there are no diseases, just sick people.' This dictum merely states the fact that the clinical management of sick people is greatly facilitated by the use of disease classifications, because a disease name (e.g., 'dental caries') can (in a very short form) be used to communicate all the knowledge about etiology, pathogenesis, treatment, and prognosis that is relevant to a patient with the particular set of signs and symptoms, labeled 'dental caries.'

Essentialistic versus nominalistic caries concepts

Understanding the distinction between the essentialistic and the nominalistic caries concepts is important for understanding the logical underpinnings of caries diagnosis. The essentialistic view leads to the belief in the existence of a caries truth, a key, which is termed the caries 'gold standard,' against which caries diagnostic methods and criteria can be evaluated. Caries diagnosis thereby becomes a matter of searching for the caries truth, and this view assumes that a universal and fixed distinction exists between 'caries' and 'sound.' However, as will be shown, the truth about caries is hard to pin down, and the distinction between 'caries' and 'sound' is indefinable.

The nominalistic view of caries leads to a more patient-centered approach, because we label dental caries and caries lesions to suit our particular needs; that is, in a way that makes it possible to achieve the best long-term health outcome for the tooth or patient in question. In the nominalistic view, we are not particularly concerned with the caries 'truth' because we know it is indefinable. The focus is on the health benefits of undertaking our diagnostic activities. We seek to optimize the health outcome by selecting diagnostic methods and categories that lead us to the best interventions and thereby to the best long-term health outcome for the patient. The close link between the management options and the relevant caries diagnostic categories is a centerpiece of the nominalistic caries concept.

The elusive truth about caries

The truth is necessarily elusive about a causal process (Fig. 10.2) that we cannot observe [135]. We can observe some of the essential components, such as the biofilm on the tooth surfaces. We know from related scientific fields (see Chapters 5–7 and 9) that something (the caries causal processes) is happening in the interface between the tooth and the biofilm, and this something we might choose to call 'caries' (this is what essentialists will do). However, this would lead us to conclude that caries lesion formation is ubiquitous wherever a biofilm is attached to a tooth surface [43], which we know is not true. Moreover, if we were to follow this logic through, we should simply use the presence of a biofilm to diagnose caries, and we would not really need to inspect the tooth surface for anything else. This has not happened because we know that the processes taking place in the interface between the biofilm and tooth are not one-way processes that only lead to demineralization and caries lesion formation. We know, for example, that these processes may sometimes drift in the opposite direction, towards calculus formation in the plaque, which is not compatible with an essentialistic understanding of caries.

Attempts have been made to define caries as a net mineral loss [58], but problems have immediately arisen. Hence, a logical next question is how much loss of mineral should have happened to deserve the diagnosis of dental caries? Any net mineral loss, no matter how infinitesimally small, is nonetheless a net mineral loss. Thereby, our assessment of the caries truth becomes dependent on the resolution of the measuring instruments and techniques available to us. In principle, it is possible to conceive of measurement devices with infinitely high resolution, and high-resolution transmission electron microscopy can record loss of mineral at the crystal level. It is not possible, therefore, to state a fixed caries truth that is independent of the scale of measurement. Decades ago, Mandelbrot [89] showed that the length of geographical curves, such as coast lines, has no true value and that any given estimate obtained always refers to a particular scale of measurement. The same holds for caries: the diagnosis 'sound' or 'caries free' always refers to a particular scale of measurement, reflected in the diagnostic instrument resolution.

Even if we were indeed able to measure the very first mineral loss from the enamel surface, this would make little sense from a clinical perspective. As shown in Fig. 10.3, the metabolic activities taking place in the biofilm on the tooth surface result in pH fluctuations. These fluctuations may be small and erratic [44, 45, 116] and may even occur in the absence of obvious external stimuli such as sucrose intake [116]. When the effects of such pH fluctuations are accumulated over time, they describe a series of mineral losses ('demineralization') or gains ('remineralization') of the dental hard tissues [90], depending on the chemical composition of the plaque fluid. Most episodes of mineral losses will be balanced by episodes of gains, and the whole series of events will not cause discernible signs and symptoms of caries (i.e., caries lesions), let alone jeopardize the integrity of the tooth structure. As long as the results of the processes stay within these limits no one needs to be concerned with the exact state of affairs (the 'truth') with respect to the net

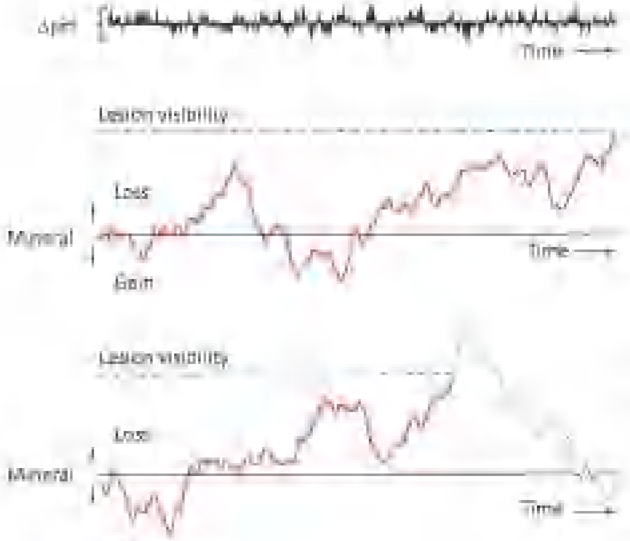


Figure 10.3 Schematic illustration of microevents at a surface over time. The upper fluctuating line indicates pH fluctuations in a biofilm over time (minutes, hours, days). The curves show different examples of fluctuating mineral loss (up) or gain (down) in enamel as a result of innumerable fluctuations in pH. The horizontal dotted lines indicate where loss of mineral may be seen clinically as a white spot.

mineral loss or gain, because the mineral losses and gains are transient and self-limiting in nature. The biological processes described are physiological processes occurring in any biofilm on a tooth surface and should not be confused with caries.

The key messages are two-fold:

- It is meaningless to continue to pester ourselves with attempts to refine the search for the 'truth' about caries. Rather, we need to consider what is sensible and meaningful from a clinical patient-oriented health outcome perspective. The essentialistic gold-standard caries paradigm is unhelpful, because it leads us into a blind alley in search of an elusive caries 'truth'.
- For the future, we should base ourselves in the nominalistic, patient-centered paradigm, according to which we choose those caries diagnostic criteria that correspond to the interventions resulting in the best long-term health outcomes for the tooth and the patient.

The wealth of caries diagnostic methods and criteria

As will also be evident from Chapters 11 and 12, the caries diagnostic options available to the dentist are abundant and wide ranging. Broadly speaking, they fall into one of three groups that may be designated the Classics, the Newcomers, and the Prospects. The Classics comprise the visual–tactile inspection, which may include fiber-optic transillumination (FOTI) and bitewing radiography, including digital radiography (Chapters 11 and 12) [3, 35, 58, 65–68, 70, 100, 133]; the Newcomers encompass laser fluorescence (DIAGNOdent®), quantitative laser fluorescence (QLF), and the electrical caries monitor (ECM) (Chapter 12) [11, 52, 78, 83, 86, 104, 118, 119, 124, 125]; and the Prospects are based on techniques such as multi-photon imaging, thermography, infrared fluorescence, optical coherence tomography, ultrasound, and terahertz imaging [26, 54] not yet developed for clinical use.

Within each diagnostic method, several different sets of criteria exist to be used with the method. The Classics' methods illustrate this, as Ismail [68] identified 29 different sets of visual–tactile caries diagnostic criteria reported in the literature between 1966 and 2000. Within these criteria the actual maneuvers undertaken during the visual–tactile clinical examination may vary a lot; for example, with respect to the use of explorers [55] or in the perceived necessity to clean and dry the teeth prior to the examination [68]. Similarly, bitewing radiography covers a host of options [58, 132, 133], including conventional versus digital radiography, number of exposures, different film and storage phosphor plate types, as well as different criteria used to describe the radiographic observations.

The evolution in caries diagnostic methods

There is little doubt that most of the caries diagnostic activities undertaken in modern clinical practice have evolved from tradition. They are, therefore, deeply rooted in the history of dentistry. Until the beginning of the 20th century the only caries diagnostic option available to the dental professional was the visual–tactile clinical inspection, or 'ocular-instrumental' examination [109] as it was then called. The early 20th century was the prime time for proponents of the focal infection theory [14, 22, 130], and a main concern among dental professionals was not so much caries per se but rather the danger that caries could lead to 'pulpless teeth.' The 'pulpless' tooth was considered a serious risk for grave systemic diseases in other parts of the body, and for decades periapical radiographs had been used to diagnose such teeth. However, in 1925, a different form of radiography was proposed [109] – the 'bitewing radiographic examination' – to be used annually or biannually to detect cavities of decay before they caused pain, as pain is indicative of pulp involvement. Raper [109] noted that dentists overlook many carious cavities when using only 'ocular-instrumental' examination, and demonstrated this by letting a young woman with a 'pretty good set of teeth' undergo a radiographic bitewing examination, which revealed five cavities and two insufficient fillings. The woman subsequently went to each of 10 independent dentists for an 'ordinary ocular instrumental examination' focused on observations 'in between the teeth.' This resulted in 'ten out of ten . . . not find[ing] what the roentgen ray had revealed' [109]. This reasoning marked the birth of the concept of the additional caries diagnostic yield, which we discuss in more detail later.

Diagnostic test assessment in the essentialistic gold-standard paradigm

Despite the obvious flaws of the essentialistic gold-standard paradigm, the dental profession has almost exclusively based approaches to the evaluation of caries diagnostic methods on the mistaken faith in the existence of a caries 'truth,' a caries gold standard. In view of the popularity of the reasoning that follows from this belief, it is important to understand in some detail the methods used and their limitations.

In the gold-standard paradigm, the focus of attention is the degree of correctness of the diagnosis. We estimate this correctness by comparing our actual findings using the diagnostic test method with the 'truth' as expressed by our gold-standard reference method (see discussion below).

The observations made using the caries diagnostic test method belong to one of four measurement scales (Table 10.1): the dichotomous, the nominal, the ordinal, or the numerical scale, the latter being either continuous or discrete. A dichotomous (or binary) measurement scale is one where observations fall in one of two possible categories, such as cavity present/cavity absent. A nominal scale of measurement is one where observations belong to one of several categories, such as sound/enamel caries/dentin caries/filled. For observations belonging to an ordinal scale, it is possible to rank order the categories, such as none/mild/moderate/severe, but the distance between categories – that is, how much worse is 'moderate' than 'mild' – is not known. For measurements belonging to a numerical scale, we can both rank order the observations and tell exactly how far apart they are. In the discrete numerical scale, the observations are restricted to integers, whereas the observations in the continuous numerical scale can take on any value. An example of the latter is the apatite fluorescence induced when dental hard tissues are exposed to coherent light from lasers. Fluorescence belongs to a continuous measurement scale, but may be expressed as an integer, as is done by the DIAGNOdent device for caries detection where the signal is converted to an integer with a theoretical range from 0–99.

Clinical and radiographic caries diagnostic recordings typically belong to the dichotomous, the nominal or the ordinal scale (Table 10.1), whereas the more advanced methods, such as laser fluorescence (DIAGNOdent, QLF) and electrical resistance measurement (ECM), in principle produce recordings on a continuous numerical scale, which, as shown above, may be converted to a discrete numeric scale.

Diagnostic accuracy: sensitivity and specificity

If our caries diagnostic observations originate in a dichotomous scale, it is very easy to compare our findings with the caries 'truth' as expressed by our gold-standard reference method. This is done in a simple 2 × 2 table (Table 10.2). From this table we can calculate the diagnostic test *sensitivity* as TP/(TP + FN) and the test *specificity* as TN/(FP + TN). The test sensitivity expresses the probability that our diagnostic method (the test) indicates 'caries' when caries is truly present; and the test specificity expresses the probability that the test indicates 'no caries' when caries is truly not present. The ideal caries diagnostic test method has sensitivity = specificity = 1, indicating that the test always reflects the true state of affairs.

From a clinical perspective, sensitivity and specificity values are not overly interesting, because they are based on a-priori knowledge of the true state of affairs: caries presence or absence. In the real-life clinical diagnostic situation, the caries 'truth' is unknown, and the probabilities of interest to the dental clinician would instead be the predictive value positive and negative of the caries diagnostic test in question. Referring to Table 10.2, it is more interesting for the clinician to know if a positive diagnostic test result can be trusted as evidence of caries (predictive value positive), and whether a negative test result is indeed indicative of a sound surface (predictive value negative).

Table 10.1 Examples of measurement scales used in caries diagnosis.

	Measurement scale			
	Dichotomous	Nominal	Ordinal	Numerical
Diagnostic method	Visual–tactile	Visual–tactile or radiographic	Radiographic	Laser fluorescence
Possible outcomes	Cavity present Cavity absent	Sound Decayed Filled Filled with decay Missing	Sound Lesion < ½ into enamel Lesion ≥ ½ into enamel, but not in dentin Lesion into dentin, but < ½ way through Lesion > ½ through dentin	Readings in the range from 0 to 99

Table 10.2 The diagnostic test matrix for a dichotomous test result (T) in the diagnosis of caries.

		True caries status = gold standard	
		Caries present	Caries absent
Test result	T+	True positive (TP)	False positive (FP)
	T−	False negative (FN)	True negative (TN)

Predictive values positive and negative

In caries diagnostic research, predictive values have been calculated from the very same data sets that gave rise to the accuracy parameters (i.e., based on the data corresponding to Table 10.2), or by application of Bayes' theorem. Bayes' theorem may be used to convert prior disease probabilities (by means of sensitivity and specificity values) to posterior disease probabilities (expressed in the predictive values positive and negative). The concepts of prior and posterior probabilities are perhaps best understood by considering an example. Suppose a man phones you at your dental clinic, asking whether you think he might have caries. In the absence of any other information, your best estimate of the probability of caries would be 0.50, corresponding to the fifty–fifty chance of being correct when guessing. Thinking that the older the man is, the more probable is caries, you would probably attempt to come up with a more informed estimate, for example, by asking the man about his age. Such is part of taking the patient history, and this can be considered a (very simple) diagnostic test. If, moreover, you happen to know that the prevalence of caries among 50–59-year-old men (the age group to which the man on the phone belongs) in your area is 90%, you can revise your prior caries probability estimate of 0.50 to a posterior probability estimate of 0.90. This is precisely what Bayes' theorem is about: the revision of prior (not so informed) disease probabilities into posterior (more informed) disease probabilities using new evidence (diagnostic test information).

Bayes' theorem dictates that the caries predictive values positive (PV+) and negative (PV−) can be calculated using these formulas:

$$PV+ = \frac{\text{Prev} \times \text{Sens}}{\text{Prev} \times \text{Sens} + (1 - \text{Prev}) \times (1 - \text{Spec})}$$

and

$$PV- = \frac{(1 - \text{Prev}) \times \text{Spec}}{(1 - \text{Prev}) \times \text{Spec} + \text{Prev} \times (1 - \text{Sens})}$$

where Sens and Spec denote the sensitivity and specificity respectively and Prev denotes the prevalence (prior probability) of caries.

A closely related method involves the use of likelihood ratios [47] to convert prior disease odds to posterior disease odds. The likelihood ratio for a positive test result is defined as sensitivity/(1 − specificity), and the likelihood ratio for a negative test result is (1 − sensitivity)/specificity. Odds are mathematically related to disease probabilities by the formula Odds = $P/(1-P)$, and the relevant predictive values are therefore easily calculated.

Receiver operating characteristic curves

When the caries diagnostic observations belong to an ordinal scale, or a numerical scale (Table 10.1), it is possible to calculate pairs of sensitivity and specificity estimates for each possible threshold value that can be used to turn the measurement scales into a dichotomous scale. The pairs of accuracy estimates defined by (1 − specificity, sensitivity) are defining points for a curve, termed the receiver operating characteristic (ROC) curve (Fig. 10.4). The ideal diagnostic test in the gold-standard paradigm has sensitivity = 1, indicating that all caries lesions are found; and 1 − specificity = 0, indicating that no sound surface is erroneously deemed carious. This corresponds to the point defined by the left-hand upper corner in the diagram in Fig. 10.4.

ROC curves are commonly summarized by calculating the area under the curve (AUC), as a fraction ranging between 0 and 1. The numerical value of the AUC for a given caries diagnostic test can be interpreted as the probability that a randomly chosen caries lesion will elicit a higher diagnostic test value than a randomly chosen sound surface [56, 80]. An AUC value of 0.50 corresponds to the area under the diagonal in Fig. 10.4 and indicates a fifty–fifty chance that a carious surface will elicit a higher test value than will a sound surface. In other words, an AUC value of 0.50 indicates a useless caries diagnostic test.

Evaluating caries diagnostic methods

Although the clinical and the bitewing radiographic examinations have remained the centerpieces of caries diagnosis since the early 20th century, a more formal approach to the evaluation of the clinical and radiographic caries diagnostic methods had to await the middle and later half of the 20th century. As World War II approached, focus moved away from focal infection being the main concern in relation to caries. Increasing attention was paid to issues concerning the best ways to treat and prevent the disease. In the late 1930s the beneficial effects of fluoride on caries incidence began to crystallize, and the correctness (validity or accuracy) of clinical and radiographic caries diagnosis gradually became an area of concern [4, 31]. Beginning with formal statistical evaluations of the reproducibility (reliability) of the radiographic diagnostic methods [6], formal statistical evaluations were also instigated of the correctness (validity)

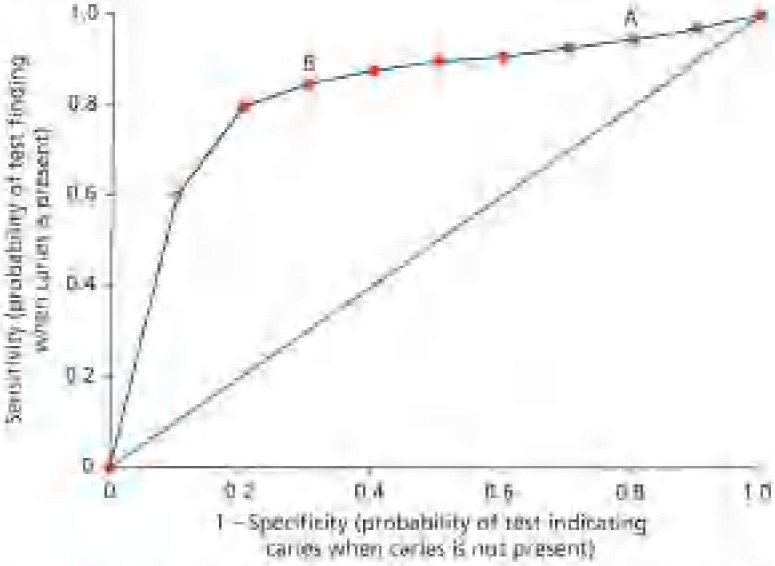


Figure 10.4 The ROC curve connecting points determined by (1 – specificity, sensitivity). The test is a hypothetical caries test with nine threshold values. The end-points (0, 0) and (1, 1) do not count as threshold values because they respectively correspond to never declaring caries present or always declaring caries present. See text for explanation of points A and B (p.183).

of the caries diagnoses made [31], using a gold-standard methodology. The issues of the correctness and reproducibility of caries diagnostic methods were further expanded when caries epidemiology gained interest and called for standardization of diagnostic methods and criteria and calibration of examiners. The diagnostic test evaluation methods then outlined have increasingly been applied to evaluate the host of new diagnostic options developed and offered for use in dental practice over the last few decades.

Leaps in the essentialistic gold-standard reasoning

Which is the caries gold standard?

In the preceding, we have shown that the truth about caries is elusive. It is not surprising, therefore, that a wealth of different methods has been proposed and used for establishing the caries gold standard [58, 64, 134]. The variation is so great in the gold-standard reference methods that the test method investigated in one study may be serving as the reference gold-standard method in other studies [58, 60]. Not only may so many gold standards lead to circular reasoning, there is also a considerable danger that new reference methods are adopted merely on the grounds of showing no statistically significant difference from older ones. Since a new test method can never be observed to perform better than the reference (gold-standard) method used for comparison [134], there is a real danger that the confused use of the gold-standard methodology may make new tests seem worse methods even when they are actually better methods [47].

Spectrum bias and transferability

The gold-standard reference for caries is often established using *in vitro* methods applied to extracted teeth assessed for the presence or depth of demineralization [58, 64] by radiographic, visual, or histological methods. The tooth materials available for such assessment are often limited and selective, and the use of these *in vitro* methods usually results in a distorted disease spectrum compared with the disease spectrum that would be observed *in vivo* in the free-living populations, for which the caries diagnostic methods are intended. Comprehensive reviews by Bader *et al.* [12, 13] have shown that the caries 'prevalence' in the tooth 'populations' used for 'gold-standard' evaluation of caries diagnostic methods is often exceedingly high (50–90%) compared with the situation encountered in free-living natural populations, where estimates of less than 20% are more probable. This means that caries lesions are grossly overrepresented in the tooth 'populations' studied, while sound surfaces are severely underrepresented. It is increasingly recognized that the diagnostic accuracy parameters, sensitivity and specificity, are not diagnostic test constants, but vary according to the disease spectrum [18, 47, 51, 77, 108]. The disease spectrum is, in turn, influenced by a host of socio-demographic factors, including age, gender, place of residence, and access to dental health care. This means that there is a considerable risk that most of the accuracy estimates provided in the literature may have limited relevance and transferability for caries diagnosis in free-living populations. This problem also affects the predictive values, whether calculated by means of Bayes' theorem, the likelihood ratio method, or from the biased tables that gave rise to the sensitivity and specificity parameters. Either way, the predictive values obtained will attain a similarly limited transferability to free living populations and, therefore, are likely to be of modest relevance for clinical caries diagnostic decision-making.

Problems in interpreting sensitivity and specificity

As indicated above, the ideal caries diagnostic test has sensitivity and specificity values of 1, predictive values of 1, and an area under the ROC curve of 1. However, in real life these parameters never reach 1, and some trade-offs must be made. One rule devised for the evaluation of the appropriateness of a diagnostic test from sensitivity and specificity estimates is based on Youden's index [136]. The index value is the maximal value of the sum of the accuracy parameters minus one (i.e., max[sensitivity + specificity − 1]), over all possible cut-points (threshold values; see p. 180) if applicable. Youden's index ranges between 0 (indicating a limited correctness of the test) and 1 (indicating a high degree of correctness of the test) [117]. The Youden index values required for a test being considered useful are typically above 0.6, and no caries diagnostic test has consistently been shown to fulfill this requirement, as evidenced by the extensive reviews of caries diagnostic methods by Bader *et al.* [12, 13].

In Youden's index the same weight is attached to the sensitivity and specificity of the test, meaning that the consequences of making a false-positive diagnosis are considered equivalent to the consequences of a false-negative diagnosis. That, however, is not a valid assumption. There is a world of difference between the long-term consequences of erroneously inserting a restoration and those of overlooking a caries lesion. This difference becomes even greater in regular dental attendees in low caries populations, in whom an overlooked lesion is likely to be found on the next appointment, before having progressed to an extent that would alter the treatment options.

Caries lesion: ruled in or ruled out?

Diagnostic tests are expected to help us achieve the dual aim of ruling in and ruling out disease. However, diagnostic tests are usually good in only one or the other, but rarely in both [126]. When the sensitivity approaches 1 the test is good at detecting disease when it is present, whereas when the specificity approaches 1 the test is good in detecting health. However, great care must be exercised when interpreting the absolute values of sensitivity and specificity, as the example provided in Table 10.3 shows. The data shown originate in an *in vivo* study [64] of three commonly used diagnostic methods for cavity detection in approximal surfaces: the conventional visual–tactile clinical examination, bitewing radiography, and FOTI. Neither FOTI nor bitewing radiography allow for immediate detection of cavities, and the FOTI and bitewing radiographic observations need interpretation. With FOTI a shadow extending into dentin was interpreted as evidence of cavitation, and with bitewing radiography a radiolucency extending into dentin was assumed to indicate cavitation. The true cavitation status of the surfaces was subsequently established by a direct visual inspection of the surfaces following a 3-day tooth separation using orthodontic rubber rings or separation springs.

The visual clinical method was observed to produce the lowest total number of diagnostic errors (5.3% of all diagnoses), closely followed by FOTI (5.9%), whereas bitewing radiography nearly doubled the total number of errors (9.2%).

The direction of the errors differed: whereas the errors made in the visual–tactile clinical examination and with FOTI were biased towards overlooking carious cavities (65% and 97% respectively of the 60 cavities were overlooked), bitewing radiography produced an overweight of false-positive cavity diagnoses (65% of the 108 positive diagnoses were false) (Table 10.3). This occurred despite bitewing radiography having the highest Youden index value (0.556 for bitewing radiography versus 0.327 for the visual–tactile clinical examination and 0.040 for FOTI), the highest sensitivity (0.631 versus 0.342 and 0.041), and an apparently only slightly lower specificity (0.925) compared with the visual–tactile clinical examination (0.985) and FOTI (0.999). However, it is precisely the combination of the slightly lower specificity and the high occurrence of noncavitated surfaces (i.e., the low caries prevalence) that

Table 10.3 Number of errors resulting from the application of three caries diagnostic methods used to detect cavitated lesions

		Caries diagnostic method					
	N	Visual–tactile		FOTI		Radiographic	
'The truth'		C	NC	C	NC	C	NC
Cavitation (C)	60	21	39	2	58	38	22
No cavitation (NC)	940	14	926	1	939	70	870
Total *N*	1000	35	965	3	997	108	892
Predictive values		0.60	0.96	0.67	0.94	0.35	0.98

The methods include visual–tactile clinical examination (sensitivity 0.342, specificity 0.985), FOTI (sensitivity 0.041, specificity 0.999), and bitewing radiography (sensitivity 0.631, specificity 0.925). A true cavity prevalence of 6% is assumed.

results in bitewing radiography producing substantially more false-positive diagnoses than the visual–tactile clinical examination.

The predictive values shown in Table 10.3 indicate that cavitation is best ruled out by bitewing radiography (PV− = 0.98), whereas cavitation is best ruled *in* by the visual–tactile clinical examination (PV+ = 0.60). (FOTI appeared to have a slightly higher predictive value positive than the clinical examination, but a calculation based on only three positive diagnoses is quite unreliable.) In other words, if these results were universally applicable, they would indicate that we should trust the positive visual–tactile clinical findings and trust the negative bitewing findings.

Problems interpreting receiver operating characteristic curves

AUC values have often been used to compare caries diagnostic test methods [46, 53, 62, 95], typically by testing the null hypothesis that the AUC values for two alternative methods do not differ statistically significantly. Rarely do these studies discuss the fundamentally important distinction between clinical and statistical significance, just as the observation of no statistically significant difference between two methods often (mis-)leads researchers to conclude equality of the methods. This is very problematic owing to the lack of agreement about the most appropriate caries gold standard, leading to the aforementioned confusion of diagnostic test methods with gold-standard reference methods.

ROC curves are interpreted as global measures of diagnostic test performance because they produce a single summary, the curve or the AUC, which condenses several alternative options for the diagnostic threshold (cut-point) used to declare caries presence or absence into a single number. This means that the ROC curves and their areas do not have immediate applicability for the clinical diagnostic situation. In the clinical situation, we cannot act on an ROC curve or an AUC value; we need to select our diagnostic threshold level by selecting only one point among the many points that define the ROC curve. This is perhaps best understood considering Fig. 10.4, which shows the ROC curve for a hypothetical caries diagnostic test with nine possible threshold values. Let us assume that these are: lesion < ¼ into enamel, ≥¼ into enamel, ≥½ into enamel, ≥¾ into enamel, into dentin but < ¼, ≥¼ into dentin, ≥½ into dentin, ≥¾ into dentin, or reaching pulp. If we choose the diagnostic threshold level at point A = ≥½ into enamel, we will find more caries lesions than if we choose a more restrictive threshold level for a positive diagnosis, say at point B = ≥½ into dentin. If we choose threshold A, we will diagnose caries with a high sensitivity (0.93), but a low specificity (0.30); and if we select threshold B, we will diagnose caries with a somewhat lower sensitivity (0.85), but a higher specificity (0.70). Thereby, we are back to the situation described above for the interpretation of sensitivity and specificity estimates. For the purpose of selecting our diagnostic threshold we thus have to make a trade-off between sensitivity and specificity. This is a decision whether we are happier with false-positive diagnoses (i.e., overaggressive lesion diagnosis) or with false-negative diagnoses (i.e., overlooking lesions), and this decision cannot be made merely on the basis of the ROC curve or the AUC estimate.

Caries diagnostic correctness: a blind alley

Dentistry is a craft that has grown from its cottage industry roots into attempting to embrace a professional and scientific evidence-based approach to the activities undertaken. Seen in this light, the evaluations carried out of the correctness of our caries diagnostic methods based on the essentialistic gold-standard reasoning must be complimented. However, as shown above, the essentialistic thinking leads to failure when the 'truth'-defining characteristics are found in naturally occurring physiological processes, such as those determined by microbial activity in biofilms located on tooth surfaces. Biological systems and processes tend to involve a multitude of self-regulating mechanisms. This influences diagnosis because a potentially deleterious sequence of events in a biological system is often naturally countered by a subsequent beneficial sequence of events, and therefore requires neither diagnosis nor intervention. Just think of the countless 'errors' that occur during the innumerable daily cell divisions necessary for maintaining human organ function. These are taken care of by naturally occurring clean-up mechanisms. This self-regulation means that diagnostic research will increasingly come to recognise that trying to identify the 'first step' in a potentially deleterious sequence of events may amount to entering a blind alley. Rather, researchers and clinicians alike should be concerned with the identification of clinically relevant 'points of no return'. These may be defined as points that, if they are surpassed, tangibly alter the prognosis for the patient, or substantially alter the treatment options towards the worse.

Diagnostic test evaluation in the nominalistic caries paradigm

So far, we have shown that there is no easy or 'objective' way to decide whether a caries diagnosis is correct or not. The key to appropriate caries diagnosis is not found in a gold-standard reference method, but in the outcomes of our caries diagnostic activities. The best caries diagnostic method is the one that results in the best long-term dental health outcome for the tooth and the patient. It follows that the more relevant approach to caries diagnostic test evaluation uses the randomized, controlled clinical trial (RCCT) study design to determine whether a new caries diagnostic method results in better long-term health outcomes than the traditional method does. The use of the RCCT design allows evaluation of the professionally determined dental health outcome and may also include evaluation of patient preferences and cost aspects. However, no such RCCTs have yet been carried out, and we must therefore make do with a different approach.

The approach taken is a clarification and elucidation of the key salient factors involved in the making of caries scripts [10]. As pointed out earlier in this chapter, a number of factors determine the nature and content of the 'this-clinical-picture-needs-this-intervention'-like caries scripts used by dentists for caries management purposes.

Long-term health outcomes: the management options?

As previously pointed out, the caries management options are crucial in determining what should be diagnosed. Cavitated caries lesions usually need restorations because it is very difficult to keep such lesions under sufficient plaque control to prevent further progress of the lesion. Cavities located in easily accessible buccal surfaces, and occasionally occlusal surfaces, could be exempted from this general rule, as it is possible to keep such cavities fairly plaque free and thus arrest further progression [99]. However, aesthetic considerations may prevent the patient from accepting this management option, as arrested caries lesions tend to be dark and aesthetically displeasing. Noncavitated lesions may be classified as either inactive/arrested lesions or as active/ongoing lesions (Chapter 11). Obviously, an inactive noncavitated caries lesion needs no intervention unless the patient expresses aesthetic concerns. The management options for the active noncavitated caries lesion are nonoperative and include plaque control, use of topical fluorides, and dietary intervention (see Chapter 17).

It follows that the information sought when performing clinical caries diagnostic examinations concerns lesion cavitation and lesion activity, as these features are decisive for the best management options and, therefore, the best long-term health outcome.

Inter- and intra-examiner errors in caries diagnosis

Any caries diagnostic test method is error prone owing to less than perfect intra- and inter-examiner reproducibility [61, 87, 100]. Dentists are neither able to reproduce completely their own caries recordings nor those of a fellow dentist. A real-life example of this is shown in Table 10.4 [100]. A dentist was asked to repeat on different days the clinical caries examinations made on 50 children. During the first examination, the dentist observed 90 cavities in the 5510 tooth surfaces examined. During the second examination, a similar number (87) of cavities were observed, indicating a difference of 'only' three cavities between the two examinations. In the dental diagnostic research literature, it is commonplace to describe the agreement between examinations, or between examiners, using the percentage agreement. Table 10.4 shows that this was high, amounting to 99% of all diagnoses made. However, owing to the fact that some of the agreement may have been obtained by chance, it is also customary to account for this by calculating the chance-corrected agreement in the form of Cohen's κ [25]. In the example provided in Table 10.4, κ was 0.82, indicating an agreement that was 82% of the maximum obtainable chance-corrected one.

Is this good or bad agreement? The dental research literature commonly answers this question by referring the κ value to one of the normative scales published for the interpretation of κ values [23, 79]. Depending on the choice of reference scale, a κ value of 0.82 would justify descriptors such as 'very good,' 'excellent,' or 'almost perfect.' Unfortunately, such descriptors often lead dental researchers to completely ignore the existence of measurement errors, and this is a fundamental flaw in much dental diagnostic reasoning. Table 10.4 shows that a total of 104 teeth received a cavity diagnosis at one or the other examination. Only 73 (70%) of these were from the same teeth, and from a clinician's point one may indeed wonder whether confirmation of only 70% of the cavities is suggestive of the near-perfect reproducibility of the caries diagnostic method. In real life, the dentist would probably restore all 90 cavities observed at the first examination, even though 17 of these would not have been confirmed, had a second examination taken place. The reproducibility data of Table 10.4 suggest, moreover, that examination of the children again (e.g., after a recall period of 6 months), might result in an additional 14 cavities being detected and restored. Undoubtedly, most dentists would perceive the additional cavities observed at the second visit as resulting from caries progression, just as they would never realize the probable overtreatment of the 17 unconfirmed cavities that they restored following the first examination (Table 10.4).

The example highlights that diagnostic decisions are made under uncertainty, and that the repetition of less than perfect diagnostic methods leads to an accumulation of

Table 10.4 Example of data table arising when assessing the intra-examiner reliability of caries diagnoses made at the cavity level.

		Second examination		
		No cavity	Cavity	
First examination	No cavity	5406	14	5420
	Cavity	17	73	90
		5423	87	5510

% agreement = 5479 × 100/5510 = 99.4%.

$\kappa = (P_{obs} - P_{exp})/(1 - P_{exp}) = 0.82$

diagnostic errors. As the error-free diagnostic method does not exist, we should acknowledge this uncertainty and integrate it into our clinical script inventory. Routine dental screening examinations (check-up visits) involve the regular repetition of less-than-perfect diagnostic methods in asymptomatic patients, and this clearly calls for a consideration of the intra-examiner agreement for our diagnostic methods. The inter-examiner agreement in dental diagnosis is typically lower than the intra-examiner agreement [61, 87, 100], and these findings imply that it can indeed be risky to undergo routine dental examinations too often, just as they illustrate the additional risk of diagnostic errors from changing dentist. As many dentists continue to consider restorative treatment *the* treatment of caries [39], these diagnostic errors only add to the risk of entering the patient into the cycle of re-restorations [34–38], termed 'iatrogenesis' [37].

A famous tonsillectomy example published more than 70 years ago [2, 17], and later confirmed for other treatments [5], may be used to illustrate the potential problems involved. The tonsillectomy study was based on a screening of 1000 11-year-old children for the need for tonsillectomy. Children, who were deemed negative on the first physical examination, were reexamined by another physician and this scheme continued for three rounds. The study clearly demonstrated that undergoing more screening examinations will cause more 'disease' to be found, and the absurd end result was that only 65 of 1000 children would still remain untreated after three routine screening examinations. Although this example is extreme, it is nevertheless worth keeping in mind, considering that the dental professions encourage the populations served to adopt dental attendance patterns involving routine screening examinations, typically every 6–12 months [94, 98].

How do we deal with the unavoidable diagnostic uncertainty?

First, it is necessary to realize that it is only human to err. Perfection is simply not compatible with human observation. As a dental profession, we should clearly strive to reduce diagnostic errors as much as possible, and we can undoubtedly achieve much more in this respect. Regular calibration exercises might reduce differences between dental clinicians, and make them see more eye to eye on different clinical presentations. However, no one has ever been able to demonstrate that diagnostic errors can be eradicated by means of intense calibration. The data presented on intra-examiner reproducibility in caries diagnosis testify to this, as no examiner has been reported to consistently be able to avoid diagnostic errors in caries diagnosis. The bottom line is that we should accommodate the fact that we cannot completely eradicate diagnostic errors in caries diagnosis, whereby the diagnostic errors become inevitable facts that we need to take into account when we make clinical decisions.

The key question to answer is this: What will happen if I make a diagnostic mistake? The false-positive diagnosis of a cavity where no cavity exists may needlessly enter the tooth into the vicious cycle of re-restoration [20, 39]. Restorations have a limited survival in relation to the human life span [20, 105, 107, 112, 131], and they tend to grow bigger for each replacement [20, 39]. Each replacement carries with it a risk of adverse effects on the pulp, a considerable risk of iatrogenic damage to neighboring teeth [81, 85, 91, 106], and economic costs to the patient.

The consequences of a false-negative diagnosis of a cavity (i.e., overlooking a carious cavity) depend on a number of factors. If the patient in question is at a high risk of rapid caries progression and only attends the dentist in case of symptoms, there is a real risk that an overlooked carious cavity may progress to pulp involvement and serious dental hard tissue breakdown, causing pain and endangering tooth survival, before a dentist has had a chance to detect it. However, evidence suggests that this risk may often be exaggerated. Studies show that the risk of a primary tooth being extracted [97, 122], developing pain [96], or becoming extracted due to pain [96, 123] is not influenced whether the tooth is restored or not. While these results may in part be explained by difficulties in making adequate restorations in children [112], they also serve to challenge a widely held treatment philosophy.

If, on the other hand, the patient in whom we have overlooked a carious cavity is characterized by slow caries progression, and attends the dentist fairly regularly, it is likely that the overlooked cavity will be detected at a later dental visit before any serious additional tissue destruction has occurred. If such is the case, the health outcome consequences of having overlooked the lesion may be limited.

The false-positive diagnosis of an active noncavitated caries lesion will not result in operative treatment but in nonoperative intervention, including plaque control, topical fluorides, and dietary intervention. While this represents a cost for the patient, it does not result in a deleterious health outcome.

The consequences of overlooking an active noncavitated caries lesion (a false-negative diagnosis) depend on several factors. If the patient is caries active and an irregular dental attendee then there is a risk that the lesion may progress to the cavitation stage before it is detected. Thereby, the consequence could be unnecessary entry into the cycle of re-restoration as detailed above. If, however, the patient shows low risk/slow caries progression and/or is a regular attender it is probable that the caries lesion will be detected at a later visit before having progressed to the cavitation stage.

The major sections of the populations living in high-income countries are characterized by continued declines in the prevalence and severity of caries lesions, indicating a continued lowering of the caries progression rates (Chapter 4). The answers to the key questions discussed above imply that in such circumstances dentists should adopt very stringent caries diagnostic criteria and allow all diagnostic doubts to benefit the tooth by choosing the nonoperative options over the irreversible operative options. In populations living in high-caries countries characterized by increasing caries incidence, dental clinicians should exercise diligence and meticulousness in the detection of signs of noncavitated stages of caries lesion formation, in order to postpone the entry to the vicious cycle of re-restorations for as long as possible. In such high-caries populations, the benefit of the doubt concerning the presence or absence of noncavitated lesions should be biased towards providing nonoperative caries treatment. In other words, the possible cost of unnecessarily carrying out such nonoperative treatments should not preclude their routine use if noncavitated lesions are suspected. Having said so, it is also clear that classical chair-side dentistry stands little chance of exerting influence over the caries situation in populations where caries is increasing, and that population strategies must be implemented to bring about effective control of the caries situation.

The additional diagnostic yield argument

As previously mentioned, bitewing radiography was introduced as an adjunct to the visual–clinical caries examination based on the argument that bitewing radiography leads to detection of lesions that would otherwise remain undetected. This additional diagnostic yield argument is effectively a sensitivity enhancement argument, though this does not imply that we adhere to the gold-standard tradition. The additional yield argument is still frequently invoked in the caries diagnostic literature, although the focus has moved away from the detection of cavities towards the detection of earlier stages of caries lesion formation [57, 58, 73], and so called 'hidden' caries in occlusal surfaces [128, 129].

Indeed, most studies comparing the diagnostic yield of a clinical and a radiographic caries examination conclude that substantially more lesions are detected in approximal surfaces [30, 63, 75, 87, 102] and occlusal surfaces [27, 48, 103, 127] using bitewing radiographs than by clinical examination alone. This explains the common recommendation to use bitewing radiography as an adjunct to the clinical examination. It is implicit in the additional diagnostic yield argument that a positive diagnosis has been reached when at least one of the diagnostic test methods used is positive. However, while this decision rule increases the sensitivity of the combined diagnostic test, it also diminishes the specificity, and this is likely to have the unintentional consequence of actually increasing the total number of diagnostic errors [16]. Using the data in Table 10.3, it can be shown that adding bitewing radiography to the visual–tactile examination, and considering a positive diagnosis reached when at least one of the diagnostic tests is positive, will result in an increase in the total number of errors from 52 (visual–tactile examination alone) to 67 (both methods combined). More cavities are correctly detected, but this occurs at the expense of an increase in the number of false-positive diagnoses from 14 to 63! Therefore, adding diagnostic test methods also means adding diagnostic errors [16].

The potential magnitude and seriousness of this problem has also been highlighted in a study of the variation among dentists in radiographic caries diagnoses [41]. The study indicated that dentists generally produce many false-positive diagnoses of dentin caries when examining approximal or occlusal surfaces that are either sound or with caries confined to the enamel, as are indeed most surfaces. Overall, 21% of the diagnoses made were false-positive diagnoses and more than 70% of the dentists had at least three false-positive diagnoses of 16 possible.

In the land of the blind the one-eyed is king

It is a serious limitation of the additional diagnostic yield argument that the actual yield observed depends on the diagnostic criteria used with the diagnostic methods being added. The additional yield of bitewing radiography is really only apparent when the clinical criteria have been restricted to recording cavitated lesions only [16]. When the clinical caries examination also comprises recording of the noncavitated stages of lesion formation, the added value of bitewing radiography is no longer obvious [16, 87, 88]. In fact, these studies indicate that in such circumstances the clinical caries examination will result in the detection of many more lesions than will the bitewing radiographic examination, indicating that the clinical examination is superior in detecting the early caries lesions [87, 88] that can be controlled by nonoperative means (Chapter 11).

Different diagnostic methods tell different stories

When considering whether to add another caries diagnostic method to the basic clinical visual–tactile examination one must account for the fact that the different diagnostic methods portray rather different aspects of caries lesions. Depending on the specifics of the diagnostic criteria used, the visual–tactile clinical examination focuses primarily on surface characteristics (Chapter 11) and to a lesser extent on lesion size/depth. Conversely, the bitewing radiographic observations primarily reflect the depth of penetration of demineralization into the dental hard tissues, and the more advanced methods reflect yet other physico-chemical aspects of caries lesions (Chapter 12).

Adding observations, therefore, is no simple matter and involves a number of assumptions about the criteria to use that best portray the same underlying dimension or the feature sought. Returning to the example given in Table 10.3, the bitewing radiographic diagnostic criterion used to indicate cavitation was a radiolucency extending at least into

Figure 10.5 Undemineralized section of lower first molar and second premolar both showing caries lesions with complications in the pulpo-dentinal complex. Only the first molar shows a cavity and the premolar might be recorded as sound. Hasegawa Collection, Chiba University, Japan. Courtesy of Professor T. Yanagisawa.

the outer third of the dentin [61]. Thereby, the assumption has been made that all radiolucencies extending into the outer third of the dentin represent cavitated caries lesions. But is this a tenable assumption? The cover illustration of this book (Fig. 10.5) shows that it is not. The scientific literature also leans towards a negative answer, as only two small studies [93, 113] have been able to demonstrate clinical cavitation in all (100%) of the approximal radiographic lesions extending into dentin. Most other studies indicate a high frequency of cavitation (75–90%) [1, 28, 29, 92] or a substantially lower cavitation frequency (28–65%) [19, 84, 101, 110, 121] of radiographic dentin lesions (see also Table 12.1). Therefore, if we uncritically use the observation of a radiographic dentin lesion to overrule the clinical observation, the risk may be substantial that an unnecessary restoration is inserted. There are many adverse effects associated with the insertion of a restoration, including iatrogenic damage to neighboring teeth [81, 85, 91, 106] and limited restoration longevity [20, 105, 107, 112, 131] (Chapter 21). While we have to accept these adverse effects when the restoration is necessary, they are intolerable wherever they could have been avoided.

Concluding remarks

In this chapter we have shown that two different lines of thinking exist in caries diagnostic reasoning. The essentialistic view pursues a search for the caries 'truth,' while the nominalistic view is more concerned with making diagnoses that reflect the best caries management options. Until now, the former has dominated caries diagnostic research and caries diagnostic test evaluation, although the changing caries concepts have rendered this gold-standard paradigm increasingly inadequate. According to the nominalistic view, the crux of caries diagnosis is to categorize caries lesions to reflect the best management options, which in turn necessitates a profound understanding of the caries causal processes and how they may be interfered with.

We have shown that the central role of the clinical inspection and the bitewing radiographic examination for caries diagnosis does not originate in formal diagnostic test evaluations, but is deeply rooted in the history of dentistry. Bitewing radiography was introduced as an adjunct to the clinical caries examination more than 80 years ago using the additional diagnostic yield argument. However, an additional diagnostic yield of bitewing radiography is discernible only when the clinical examination is limited to cavity diagnosis. The additional benefit of bitewing radiography may indeed be questioned when the clinical examination encompasses the noncavitated stages of caries lesion formation. We have pointed out that the visual–tactile clinical examination and the bitewing radiographic examination capture different features of caries lesions, and that the features most relevant for the selection of the best management options are those reflected in the visual–tactile caries examination.

Based on these considerations we suggest that good caries diagnostic practice involves the following elements:

- Selection of a visual–tactile diagnostic method that links directly to the management options for caries: cavitated versus noncavitated and active versus arrested are the features that determine the management options, and hence should be recorded.
- Full exhaustion of the visual–tactile diagnostic method – that is, recording of noncavitated lesions is a must.
- Careful consideration of the pros and cons of adding other diagnostic test methods, such as bitewing radiography, to the visual–tactile method.
- Continued attention to the possibility of diagnostic errors, such that *doubt always should bias toward less invasive decisions*.

References

1. Akpata ES, Farid MR, Al-Saif K, Roberts EAU. Cavitation at radiolucent areas on proximal surfaces of posterior teeth. *Caries Res* 1996; **30**: 313–6.
2. American Child Health Association. *Physical defects: the pathway to correction*. New York: American Child Health Association, 1934: 80–96.
3. Analoui M, Stookey GK. Direct digital radiography for caries detection and analysis. *Monogr Oral Sci* 2000; 17: 1–19.
4. Arnold FA, Dean HT, Singleton DE. The effect on caries incidence of a single topical application of a fluoride solution to the teeth of young adult males of a military population. *J Dent Res* 1944; 23: 155–62.
5. Ayanian JZ, Berwick DM. Do physicians have a bias toward action? A classic study revisited. *Med Decis Making* 1991; 11: 154–8.
6. Backer Dirks O, van Amerongen J, Winkler KC. A reproducible method for caries evaluation. *J Dent Res* 1951; 30: 346–59.
7. Bader JD, Shugars DA. Understanding dentists' restorative treatment decisions. *J Publ Health Dent* 1992; 52: 102–10.
8. Bader JD, Shugars DA. Variation in dentists' clinical decisions. *J Publ Health Dent* 1995; 55: 181–8.
9. Bader JD, Shugars DA. Variation, treatment outcomes, and practice guidelines in dental practice. *J Dent Educ* 1995; 59: 61–95.
10. Bader JD, Shugars DA. What do we know about how dentists make caries-related treatment decisions? *Community Dent Oral Epidemiol* 1997; 25: 97–103.
11. Bader JD, Shugars DA. A systematic review of the performance of a laser fluorescence device for detecting caries. *J Am Dent Assoc* 2004; 135: 1413–26.
12. Bader JD, Shugars DA, Bonito AJ. Systematic reviews of selected dental caries diagnostic and management methods. *J Dent Educ* 2001; 65: 960–8.
13. Bader JD, Shugars DA, Bonito AJ. A systematic review of the performance of methods for identifying carious lesions. *J Publ Health Dent* 2002; 62: 201–13.
14. Baelum V. The epidemiology of destructive periodontal disease. Causes, paradigms, problems, methods and empirical evidence. Dissertation. Aarhus: University of Aarhus, 1998.
15. Baelum V, Heidmann J, Nyvad B. Dental caries paradigms in diagnosis and diagnostic research. *Eur J Oral Sci* 2006; 114: 263–77.
16. Baelum V, Hintze H, Wenzel A, Danielsen B, Nyvad B. Implications of caries diagnostic strategies for clinical management decisions. *Community Dent Oral Epidemiol* 2012; 40: 257–66.
17. Bakwin H. Pseudodoxia pediatrica. *N Engl J Med* 1945; 232: 691–7.
18. Begg CB, Greenes RA. Assessment of diagnostic tests when disease verification is subject to selection bias. *Biometrics* 1983; 39: 207–15.
19. Bille J, Thylstrup A. Radiographic diagnosis and clinical tissue changes in relation to treatment of approximal carious lesions. *Caries Res* 1982; **16**: 1–6.
20. Brantley CF, Bader JD, Shugars DA, Nesbit SP. Does the cycle of rerestoration lead to larger restorations? *J Am Dent Assoc* 1995; **126**: 1407–13.
21. Burket LW. The accuracy of clinical and roentgenologic diagnosis of dental caries as determined by microscopic studies. *J Dent Res* 1941; 20: 70–6.
22. Burt BA. Influences for change in the dental health status of populations: an historical perspective. *J Publ Health Dent* 1978; 38: 272–88.
23. Byrt T. How good is that agreement? *Epidemiology* 1996; 7: 561.
24. Chen BCK, Jelovic A, Kay EJ, Main PA, Leake JL. Reducing variability in treatment decision making: effectiveness of educating clinicians about uncertainty. *Med Educ* 1998; 32: 105–11.
25. Cohen J. A coefficient of agreement for nominal scales. *Educ Psychol Meas* 1960; 20: 37–46.
26. Colston Jr BW, Everett MJ, Sathyam US, DaSilva LB, Otis LL. Imaging of the oral cavity using optical coherence tomography. *Monogr Oral Sci* 2000; 17: 32–55.
27. Creanor SL, Russell JI, Strang DM, Stephen KW, Burchell CK. The prevalence of clinically undetected occlusal dentine caries in Scottish adolescents. *Br Dent J* 1990; 169: 126–9.
28. De Araujo FB, Rosito DB, Toigo E, dos Santos CK. Diagnosis of approximal caries: radiographic versus clinical examination using tooth separation. *Am J Dent* 1992; 5: 245–8.
29. De Araujo FB, de Araujo DR, dos Santos CK, de Souza MA. Diagnosis of approximal caries in primary teeth: radiographic versus clinical examination using tooth separation. *Am J Dent* 1996; 9: 54–6.
30. De Vries HCB, Ruiken HMHM, König KG, Van't Hof MA. Radiographic versus clinical diagnosis of approximal carious lesions. *Caries Res* 1990; 24: 364–70.
31. Downer MC. Concurrent validity of an epidemiological diagnostic system for caries with the histological appearance of extracted teeth as validating criterion. *Caries Res* 1975; 9: 231–46.
32. Ecenbarger W. How honest are dentists? *Reader's Digest* 1997 (February): 50–6.
33. Ekstrand KR. Improving clinical visual detection – potential for caries clinical trials. *J Dent Res* 2004; 83 (Spec Iss C): C67–C71.
34. Elderton RJ. Implications of recent dental health services research on the future of operative dentistry. *J Publ Health Dent* 1985; 45: 101–5.
35. Elderton RJ. Scope for change in clinical practice. *J R Soc Med* 1985; 78 (Suppl 7): 27–32.
36. Elderton RJ. Clinical studies concerning re-restoration of teeth. *Adv Dent Res* 1990; 4: 4–9.
37. Elderton RJ. Iatrogenesis in the treatment of dental caries. *Proc Finn Dent Soc* 1992; 88: 25–32.
38. Elderton RJ. Overtreatment with restorative dentistry: when to intervene? *Int Dent J* 1993; 43: 17–24.
39. Elderton RJ. Preventive (evidence-based) approach to quality general dental care. *Med Princ Pract* 2003; 12 (Suppl 1): 12–21.
40. Ellwood RP, Cortes DF. In vitro assessment of methods of applying the electrical caries monitor for the detection of occlusal caries. *Caries Res* 2004; 38: 45–53.
41. Espelid I, Tveit AB. A comparison of radiographic occlusal and approximal caries diagnoses made by 240 dentists. *Acta Odontol Scand* 2001; 59: 285–9.
42. Espelid I, Tveit AB, Riordan PJ. Radiographic caries diagnosis by clinicians in Norway and Western Australia. *Community Dent Oral Epidemiol* 1994; 22: 214–9.
43. Fejerskov O, Manji F. Reactor paper: Risk assessment in dental caries. In: Bader JD, ed. *Risk assessment in dentistry*. Chapel Hill, NC: University of North Carolina Dental Ecology, 1990: 215–17.
44. Fejerskov O, Scheie AA, Birkhed D, Manji F. Effect of sugarcane chewing on plaque pH in rural Kenyan children. *Caries Res* 1992; 26: 286–9.
45. Fejerskov O, Scheie AA, Manji F. The effect of sucrose on plaque pH in the primary and permanent dentition of caries-inactive and -active Kenyan children. *J Dent Res* 1992; 71: 25–31.
46. Fleiss JL, Mann J, Paik M, Goultchin J, Chilton NW. A study of inter- and intra-examiner reliability of pocket depth and attachment level. *J Periodont Res* 1991; 26: 122–8.
47. Fletcher RH, Fletcher SW, Wagner EH. *Clinical epidemiology. The essentials*. 3rd ed. Baltimore, MD: Lippincott Williams & Wilkins, 1996.
48. Fracaro MS, Seow WK, McAllan LH, Purdie DM. The sensitivity and specificity of clinical assessment compared with bitewing radiography for detection of occlusal dentin caries. *Pediatr Dent* 2001; 23: 204–10.
49. Grembowski D, Milgrom P. The influence of dentist supply on the relationship between fluoridation and restorative care among children. *Med Care* 1988; 26: 907–17.
50. Grembowski D, Fiset L, Milgrom P, Conrad D, Spadafora A. Does fluoridation reduce the use of dental services among adults? *Med Care* 1997; 35: 454–71.
51. Guggenmoos-Holzmann I, van Houwelingen HC. The (in)validity of sensitivity and specificity. *Stat Med* 2000; 19: 1783–92.
52. Haak R, Wicht MJ. Caries detection and quantification with DIAGNOdent: prospects for occlusal and root caries? *Int J Comput Dent* 2004; 7: 347–58.
53. Haak R, Wicht MJ. Grey-scale reversed radiographic display in the detection of approximal caries. *J Dent* 2005; 33: 65–71.
54. Hall A, Girkin JM. A review of potential new diagnostic modalities for caries lesions. *J Dent Res* 2004; 83 (Spec Iss C): C89–C94.
55. Hamilton JC, Stookey G. Should a dental explorer be used to probe suspected carious lesions? *J Am Dent Assoc* 2005; 136: 1526–32.
56. Hanley JA, McNeil BJ. The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology* 1982; 143: 29–36.
57. Hintze H. Screening with conventional and digital bite-wing radiography compared to clinical examination alone for caries detection in low-risk children. *Caries Res* 1993; 27: 499–504.

58. Hintze H. Radiography for the detection of dental caries lesions. *Dissertation*. Aarhus: University of Aarhus; 2001.
59. Hintze H, Wenzel A. Clinically undetected dental caries assessed by bitewing screening in children with little caries experience. *Dentomaxillofac Radiol* 1994; 23: 19–23.
60. Hintze H, Wenzel A. Diagnostic outcome of methods frequently used for caries validation. *Caries Res* 2003; 37: 115–24.
61. Hintze H, Wenzel A, Danielsen B, Nyvad B. Reliability of visual examination, fibre-optic transillumination, and bite-wing radiography, and reproducibility of direct visual examination following tooth separation for the identification of cavitated carious lesions in contacting approximal surfaces. *Caries Res* 1998; 32: 204–9.
62. Hintze H, Wenzel A, Frydenberg M. Accuracy of caries detection with four storage phosphor systems and E-speed radiographs. *Dentomaxillofac Radiol* 2002; 31: 170–5.
63. Hopcraft MS, Morgan MV. Comparison of radiographic and clinical diagnosis of approximal and occlusal dental caries in a young adult population. *Community Dent Oral Epidemiol* 2005; 33: 212–8.
64. Huysmans M-CDNJM, Longbottom C. The challenges of validating diagnostic methods and selecting appropriate gold standards. *J Dent Res* 2004; **83** (Spec Iss C): C48–C52.
65. International Caries Detection and Assessment System (ICDAS) Coordinating Committee. Criteria manual (draft). International Caries Detection and Assessment System (ICDAS II). Indianapolis Indiana Conference, 2005: 1–7.
66. International Caries Detection and Assessment System (ICDAS) Coordinating Committee. Rationale and evidence for the International Caries Detection and Assessment System (ICDAS II) (draft). Indianapolis Indiana Conference, 2005: 1–43.
67. Ismail AI. Clinical diagnosis of precavitated carious lesions. *Community Dent Oral Epidemiol* 1997; 25: 13–23.
68. Ismail AI. Visual and visuo-tactile detection of dental caries. *J Dent Res* 2004; **83** (Spec Iss C): C56–C66.
69. Ismail AI, Bader JD. Evidence-based dentistry in clinical practice. *J Am Dent Assoc* 2004; 135: 78–83.
70. Ismail AI, Sohn W. A systematic review of clinical diagnostic criteria of early childhood caries. *J Public Health Dent* 1999; **59**: 171–91.
71. Kay EJ, Nuttall NM. Relationship between dentists' treatment attitudes and restorative decisions made on the basis of simulated bitewing radiographs. *Community Dent Oral Epidemiol* 1994; 22: 71–4.
72. Kay E, Nuttall N. Clinical decision making – an art or a science? Part I: an introduction. *Br Dent J* 1995; **178**: 76–8.
73. Kay E, Nuttall N. Clinical decision making – an art or a science? Part II: making sense of treatment decisions. *Br Dent J* 1995; **178**: 113–6.
74. Kay EJ, Nuttall NM, Knill-Jones R. Restorative treatment thresholds and agreement in treatment decision-making. *Community Dent Oral Epidemiol* 1992; **20**: 265–8.
75. Kidd EAM, Pitts NB. A reappraisal of the value of the bitewing radiograph in the diagnosis of posterior approximal caries. *Br Dent J* 1990; **169**: 195–200.
76. Kidd EAM, Mejàre I, Nyvad B. Clinical and radiographic diagnosis. In: Fejerskov O, Kidd E, eds. *Dental caries: the disease and its clinical management*. Oxford: Blackwell Munksgaard; 2003: 111–28.
77. Knottnerus JA, Leffers P. The influence of referral patterns on the characteristics of diagnostic tests. *J Clin Epidemiol* 1992; 45: 1143–54.
78. Kühnisch J, Heinrich-Weltzien R. Quantitative light-induced fluorescence (QLF) – a literature review. *Int J Comput Dent* 2004; 7: 325–38.
79. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977; 33: 159–74.
80. Lee WC. Probabilistic analysis of global performances of diagnostic tests: interpreting the Lorenz curve-based summary measures. *Stat Med* 1999; 18: 455–71.
81. Lenters M, van Amerongen WE, Mandari GJ. Iatrogenic damage to the adjacent surfaces of primary molars, in three different ways of cavity preparation. *Eur Arch Paediatr Dent* 2006; 7: 6–10.
82. Llena-Puy C, Forner L. A clinical and radiographic comparison of caries diagnosed in approximal surfaces of posterior teeth in a low-risk population of 14-year-old children. *Oral Health Prev Dent* 2005; 3: 47–52.
83. Longbottom C, Huysmans M-CDNJM. Electrical measurements for use in caries clinical trials. *J Dent Res* 2004; **83** (Spec Iss C): C76–9.
84. Lunder N, von der Fehr FR. Approximal cavitation related to bite-wing image and caries activity in adolescents. *Caries Res* 1996; **30**: 143–7.
85. Lussi A, Gygax M. Iatrogenic damage to adjacent teeth during classical approximal box preparation. *J Dent* 1998; **26**: 435–41.
86. Lussi A, Hibst R, Paulus R. DIAGNOdent: an optical method for caries detection. *J Dent Res* 2004; **83** (Spec Iss C): C80–3.
87. Machiulskiene V, Nyvad B, Baelum V. A comparison of clinical and radiographic caries diagnoses in posterior teeth of 12-year-old Lithuanian children. *Caries Res* 1999; 33: 340–8.
88. Machiulskiene V, Nyvad B, Baelum V. Comparison of diagnostic yields of clinical and radiographic caries examinations in children of different age. *Eur J Paediatr Dent* 2004; 5: 157–62.
89. Mandelbrot B. How long is the coast of Britain? Statistical self-similarity and fractional dimension. *Science* 1967; **156**: 636–8.
90. Manji F, Fejerskov O, Nagelkerke NJD, Baelum V. A random effects model for some epidemiological features of dental caries. *Community Dent Oral Epidemiol* 1991; 19: 324–8.
91. Medeiros VAF, Seddon RP. Iatrogenic damage to approximal surfaces in contact with Class II restorations. *J Dent* 2000; **28**: 103–10.
92. Mejàre I, Malmgren B. Clinical and radiographic appearance of proximal carious lesions at the time of operative treatment in young permanent teeth. *Scand J Dent Res* 1986; 94: 19–26.
93. Mejàre I, Gröndahl HG, Carlstedt K, Grever AC, Ottosson E. Accuracy at radiography and probing for the diagnosis of proximal caries. *Scand J Dent Res* 1985; 93: 178–84.
94. Mettes TG, Bruers JJM, van der Sanden WJM, Verdonschot EH, Mulder J, Grol RP, Plasschaert AJ. Routine oral examinations: differences in characteristics of Dutch general dental practitioners related to type of recall interval. *Community Dent Oral Epidemiol* 2005; 33: 219–26.
95. Mileman PA, van den Hout WB. Comparing the accuracy of Dutch dentists and dental students in the radiographic diagnosis of dentinal caries. *Dentomaxillofac Radiol* 2002; 31: 7–14.
96. Milsom KM, Tickle M, Blinkhorn AS. Dental pain and dental treatment of young children attending the general dental service. *Br Dent J* 2002; **192**: 280–4.
97. Milsom KM, Tickle M, King D, Kearney-Mitchell P, Blinkhorn AS. Outcomes associated with restored and unrestored deciduous molar teeth. *Prim Dent Care* 2002; 9: 16–19.
98. NHS National Institute for Clinical Excellence. *Dental recall. Recall interval between routine dental examinations*. London: National Institute for Clinical Excellence; 2004: 1–38.
99. Nyvad B, Fejerskov O. Active root surface caries converted into inactive caries as a response to oral hygiene. *Scand J Dent Res* 1986; **94**: 281–4.
100. Nyvad B, Machiulskiene V, Baelum V. Reliability of a new caries diagnostic system differentiating between active and inactive caries lesions. *Caries Res* 1999; **33**: 252–60.
101. Pitts NB, Rimmer PA. An in vivo comparison of radiographic and directly assessed clinical caries status of posterior approximal surfaces in primary and permanent teeth. *Caries Res* 1992; **26**: 146–52.
102. Poorterman JHG, Aartman IH, Kalsbeek H. Underestimation of the prevalence of approximal caries and inadequate restorations in a clinical epidemiological study. *Community Dent Oral Epidemiol* 1999; **27**: 331–7.
103. Poorterman JHG, Weerheijm KL, Groen HJ, Kalsbeek H. Clinical and radiographic judgement of occlusal caries in adolescents. *Eur J Oral Sci* 2000; **108**: 93–8.
104. Pretty IA, Maupomé G. A closer look at diagnosis in clinical dental practice: Part 5. Emerging technologies for caries detection and diagnosis. *J Can Dent Assoc* 2004; 70: 540a–i.
105. Qvist V. Longevity of restorations in primary teeth. In: Hugoson A, Falk M, Johansson S, eds. *Consensus conference on caries in the primary dentition and its clinical management*. Jönköping: The Institute for Postgraduate Dental Education; 2002: 69–80.
106. Qvist V, Johannessen L, Bruun M. Progression of approximal caries in relation to iatrogenic preparation damage. *J Dent Res* 1992; **71**: 1370–3.
107. Qvist V, Laurberg L, Poulsen A, Teglers PT. Longevity and cariostatic effects of everyday conventional glass-ionomer and amalgam restorations in primary teeth: three-year results. *J Dent Res* 1997; **76**: 1387–96.

108. Ransohoff DF, Feinstein AR. Problems of spectrum and bias in evaluating the efficacy of diagnostic tests. *N Engl J Med* 1978; **299**: 926–30.
109. Raper HR. Practical clinical preventive dentistry based upon periodic roentgen-ray examinations. *J Am Dent Assoc* 1925; **12**: 1084–100.
110. Ratledge DK, Kidd EAM, Beighton D. A clinical and microbiological study of approximal carious lesions. Part 1: the relationship between cavitation, radiographic lesion depth, the site-specific gingival index and the level of infection of the dentine. *Caries Res* 2001; **35**: 3–7.
111. Renshaw J. After the first 125 years of the BDJ where might clinical dentistry be heading? *Br Dent J* 2005; **199**: 331–7.
112. Roeleveld AC, van Amerongen WE, Mandari GJ. Influence of residual caries and cervical gaps on the survival rate of class II glass ionomer restorations. *Eur Arch Paediatr Dent* 2006; **7**: 85–90.
113. Rugg-Gunn AJ. Approximal carious lesions. A comparison of the radiological and clinical appearances. *Br Dent J* 1972; **133**: 481–4.
114. Scadding JG. Diagnosis: the clinician and the computer. *Lancet* 1967; **2**: 877–82.
115. Scadding JG. Essentialism and nominalism in medicine: logic of diagnosis in disease terminology. *Lancet* 1996; **348**: 594–6.
116. Scheie AA, Fejerskov O, Lingström P, Birkhed D, Manji F. Use of palladium touch microelectrodes under field conditions for *in vivo* assessment of dental plaque pH in children. *Caries Res* 1992; **26**: 44–51.
117. Schisterman EF, Perkins NJ, Liu A, Bondell H. Optimal cut-point and its corresponding Youden index to discriminate individuals using pooled blood samples. *Epidemiology* 2005; **16**: 73–81.
118. Stookey GK. Optical methods – quantitative light fluorescence. *J Dent Res* 2004; **83** (Spec Iss C): C84–8.
119. Stookey GK. Quantitative light fluorescence: a technology for early monitoring of the caries process. *Dent Clin North Am* 2005; **49**: 753–70.
120. Ten Bosch JJ, Angmar-Månsson B. Characterization and validation of diagnostic methods. *Monogr Oral Sci* 2000; **17**: 174–89.
121. Thylstrup A, Bille J, Qvist V. Radiographic and observed tissue changes in approximal carious lesions at the time of operative treatment. *Caries Res* 1986; **20**: 75–84.
122. Tickle M, Milsom K, Kennedy A. Is it better to leave or restore carious deciduous molar teeth? A preliminary study. *Prim Dent Care* 1999; **6**: 127–31.
123. Tickle M, Milsom K, King D, Kearney-Mitchell P, Blinkhorn A. The fate of the carious primary teeth of children who regularly attend the general dental service. *Br Dent J* 2002; **192**: 219–23.
124. Tranæus S, Shi X-Q, Angmar-Månsson B. Caries risk assessment: methods available to clinicians for caries detection. *Community Dent Oral Epidemiol* 2005; **33**: 265–73.
125. Van der Veen MH, de Josselin de Jong E. Application of quantitative light-induced fluorescence for assessing early caries lesions. *Monogr Oral Sci* 2000; **17**: 144–62.
126. Verdonschot EH, Bronkhorst EM, Burgersdijk RCW, König KG, Schaeken MJM, Truin GJ. Performance of some diagnostic systems in examinations for small occlusal carious lesions. *Caries Res* 1992; **26**: 59–64.
127. Weerheijm KL, Groen HJ, Bast AJJ, Kieft JA, Eijkman MAJ, van Amerongen WE. Clinically undetected occlusal dentine caries: a radiographic comparison. *Caries Res* 1992; **26**: 305–9.
128. Weerheijm KL, Gruythuysen RJM, van Amerongen WE. Prevalence of hidden caries. *J Dent Child* 1992; **59**: 408–12.
129. Weerheijm KL, Kidd EAM, Groen HJ. The effect of fluoridation on the occurrence of hidden caries in clinically sound occlusal surfaces. *Caries Res* 1997; **31**: 30–4.
130. Weintraub JA, Burt BA. Oral health status in the United States: tooth loss and edentulism. *J Dent Educ* 1985; **49**: 368–78.
131. Wendt LK, Koch G, Birkhed D. Replacements of restorations in the primary and young permanent dentition. *Swed Dent J* 1998; **22**: 149–55.
132. Wenzel A. Current trends in radiographic caries imaging. *Oral Surg Oral Med Oral Pathol* 1995; **80**: 527–39.
133. Wenzel A. Bitewing and digital bitewing radiography for detection of caries lesions. *J Dent Res* 2004; **83** (Spec Iss C): C72–5.
134. Wenzel A, Hintze H. The choice of gold standard for evaluating tests for caries diagnosis. *Dentomaxillofac Radiol* 1999; **28**: 132–6.
135. Wulff HR. What is understood by a disease entity? *J R Coll Physicians Lond* 1979; **13**: 219–20.
136. Youden WJ. An index for rating diagnostic tests. *Cancer* 1950; **3**: 32–5.

11

Visual–tactile caries diagnosis

B. Nyvad, V. Machiulskiene, V.M. Soviero, and V. Baelum

Introduction

This chapter on visual–tactile caries diagnosis discusses the very basics of clinical cariology. Dentists diagnose caries every day of their practicing lives. Or do they? Consider for a moment the description of caries in Chapter 2: 'Caries is a result of metabolic activities in the microbial deposits covering the tooth surface at any given site.' Clearly, clinical inspection of the teeth at the chair-side does not allow the dentist to observe the caries process itself. What dentists can do is to examine the consequences of microbial metabolic activity when looking for signs of lesions that have formed as a result of it. This is what caries diagnosis is about: *detection of signs and symptoms of caries.*

The history of visual–tactile caries examination goes back to antiquity. However, the caries diagnostic criteria used and the means and methods employed have changed over time. Until about 90 years ago, when bitewing radiography was introduced [60], clinical caries diagnosis relied completely on a combined visual and tactile examination of the teeth using a probe to search for caries lesions. This practice still prevails, especially in countries where dentists do not have easy access to dental radiography or other 'advanced' diagnostic methods. However, concurrent with the spread of bitewing radiography, generations of dentists seem to have lost reliance on the classical visual–tactile caries examination. Many explanations may be offered for the undermining of the visual-tactile examination by bitewing

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

radiography, including the general fascination with technology and the strive for documentation. However, the risk of underdiagnosis [60] (Chapter 10) is probably the main reason why most cariology courses continue to stress the importance of repeated bitewing examinations. This concept is still haunting the profession, in spite of a considerably lower rate of lesion progression in many populations today. As a consequence, in some parts of the world it is now considered inappropriate to screen a patient for caries without at the same time performing a radiographic examination [14]. There are several reasons why this belief and the resulting clinical practice is very unfortunate, and this chapter will demonstrate that the large majority of initial caries lesions are much better diagnosed by visual-tactile methods only, even in difficult-to-reach areas such as approximal surfaces. However, to do this, dentists must acquire the necessary knowledge and skills.

The aim of this chapter is to discuss the theoretical foundation and the practical implementation of the visual-tactile caries examination, and to show that it is the only clinical method that provides the information necessary for the choice of appropriate treatment.

The diagnostic process

In dentistry, we have often turned to medicine when searching for clarification of concepts and methods, and caries diagnosis is no exception. In medicine, diagnosis is defined as 'the art or act of identifying a disease from its signs and symptoms' [49].

The medical perspective on diagnosis

Medical diagnostic reasoning is thought to be a complex process that involves elements of simple pattern recognition (pathognomonic signs and symptoms), considerations about the probability of various differential diagnostic alternatives, and the generation of hypotheses about the underlying disease, followed by diagnostic tests, the results of which may be used to disprove the hypothesis in favor of an alternative diagnosis (hypothetico-deductive thinking) [48]. Basically, a patient presents with a complaint (symptom), for example abdominal pain. The clinician makes a mental list of the diseases most likely to cause the symptom (a list of tentative diagnoses). Using the most probable tentative diagnosis as a starting point, a deductive process is begun that involves taking a patient history, performing a physical examination, and prescribing diagnostic tests to obtain information that will allow the clinician either to confirm or refute this tentative diagnosis. This process of pattern recognition and testing of alternative hypotheses concerning the diagnosis is continued until a final diagnosis is reached, which is consistent with the results of the various tests carried out. When the diagnosis has been established, the treatment selection process begins. This is usually rather straightforward once the diagnosis is clear. If, for unforeseen reasons, the patient does not respond to the treatment, the physician may ultimately have to reconsider and revise the diagnosis.

The dental perspective

The medical and the dental diagnostic universes differ in important aspects [6]. Most of the patients seen in general dental practice in high-income countries are asymptomatic and come for routine check-ups in the belief that by doing so they achieve better oral health outcomes. This implies a screening examination for caries, periodontal diseases, and other forms of oral pathology. The dentist should not overlook oral disease/pathology in need of treatment, and, at the same time, should avoid unjustified diagnoses leading to overtreatment. Therefore, the main task for the dentist is not to find out what disease the patient has, but whether the patient has caries, periodontal disease, or other forms of oral pathology, and, not least, whether the patient would benefit from treatment. The logic behind this strategy is that the course of these diseases may be changed for the better if they are detected and treated before they reach a stage at which they elicit symptoms or require more invasive intervention. Therefore, in dental practice, diagnosis is closely linked with the management options.

Caries scripts

When screening for oral pathology, the dentist does not use the differential diagnostic approach described for the medical situation. Dentists know that they are examining for a relatively limited number of oral diseases (caries, periodontitis, mucosal lesions). Moreover, the major oral diseases affect different anatomical locations (e.g., the oral mucosa, the periodontium, or the dental hard tissues), and these are examined separately. Even though the number of dental pathologies of differential diagnostic relevance is limited, differential diagnostic reasoning is too difficult to repeat for each tooth surface present in each patient. A caries examination of a patient with a full dentition of 32 teeth would thus involve going through 148 differential diagnostic processes (20 molars and premolars with five surfaces plus 12 incisors and canines with four surfaces). Clearly, this does not happen. When dentists diagnose caries they use preconceived 'caries scripts' to identify particular clinical manifestations of interest. All the differential diagnostic considerations that are relevant for examination of the dental hard tissues, as well as all the management considerations, are incorporated in these caries scripts. Caries diagnostic reasoning predominantly consists of a 'this-clinical-manifestation-needs-this-kind-of-treatment' classification of the tooth surfaces [4]. However, as we shall see in this chapter, the clinical manifestations looked for, and the caries scripts used, have varied over time, as a function of changing knowledge about the caries processes and the management options available.

Why do we diagnose caries?

The medical literature on diagnosis cites at least five reasons why diagnosis is important [37]. These include:

- detecting and excluding disease;
- assessing prognosis;
- contributing to the decision-making process with regard to further diagnostic and therapeutic management;
- informing the patient;
- monitoring the clinical course of the disease.

As discussed before, this list applies well to the medical situation owing to the medical focus on differential diagnosis. However, the situation is different in dentistry, and tends to be the opposite. In caries diagnosis, we know what disease we are looking for, namely the signs and symptoms that we attribute to dental caries. We do not perform classical differential diagnosis in the medical sense, but we seek to differentiate between 'caries-free' and 'caries-affected' tooth surfaces, just as we try to classify lesions into categories. When selecting a lesion classification we should always acknowledge that caries examinations are carried out in order to influence the patient's oral health outcome for the better. A lesion classification must, therefore, reflect the best caries management options available. When caries management options change as a function of new evidence, lesion classifications should change accordingly in order to ensure that we achieve the best possible health benefits for our patients.

Diagnosis from a dental caries perspective

On the basis of this discussion we can now revise the list of reasons for diagnosis provided by Knottnerus and van Weel [37] to suit caries diagnosis. We diagnose, or perhaps more correctly classify, caries lesions in order to be able to:

- achieve the best health outcome for the patient by selecting the best management option for each lesion type;
- inform the patient;
- monitor the clinical course of the disease.

Achieving the best health outcome for the patient by classifying caries lesions corresponding to the best management options for each lesion type

It should now be clear that we cannot discuss the best diagnostic classification of caries lesions without due reference to the management options available. As explained in detail in Chapters 7 and 9, a caries lesion may occur when the metabolic activity of bacteria in the biofilm shifts the physiological equilibrium at the biofilm tooth interface towards a net mineral loss. If not interfered with, this mineral loss may continue until the entire crown of the tooth has been destroyed, leaving only a relic root (the word 'caries' originates in Latin and means 'rot'). Hence, our classification of caries should reflect the best management options for the different stages of lesions.

Cavitated caries lesions

A distinctive stage in the caries process is the stage of cavity formation. When a carious cavity has formed it is much more difficult to control the biofilm by oral hygiene procedures. Therefore, the treatment of choice for such cavitated lesions usually involves operative intervention in the form of restorations (see Chapter 19). This intervention will not manage the causes of caries, but restoring the tooth makes it easier to perform proper oral hygiene. An exception to this rule is the cavitated lesion with a hard floor (inactive lesion) for which the patient has already learned to master proper biofilm control (Chapter 13). Such lesions may only need to be restored for functional or cosmetic reasons.

Noncavitated and microcavitated caries lesions

Noncavitated and microcavitated lesions can be managed by nonoperative means (Chapters 13–18). Like clinically sound surfaces, all noncavitated lesions should as a minimum be subjected to basic prevention, such as daily tooth brushing with fluoride toothpaste. This regimen is a simple but highly effective method of nonoperative caries control when performed properly (Chapters 13 and 14). However, depending on the activity state of the lesions and the risk factors of the patient, some noncavitated lesions may need professional nonoperative treatments (Chapter 17).

Active lesions

Active noncavitated lesions always require professional nonoperative management because such lesions are otherwise likely to progress [54] (Fig. 11.1). By means of professionally applied treatment, progressive (active) noncavitated caries lesions with or without microcavity formation may be turned into arrested (inactive) noncavitated caries lesions. Lesion-specific instruction in improved oral hygiene procedures is a must, since the most effective management for an active noncavitated caries lesion involves daily removal of the biofilm in conjunction with the use of fluoride toothpaste. Occasionally, the dentist may need to help the patient in achieving this goal by performing regular professional cleaning of the teeth. Topical fluoride application is another professional management option that may be applied in patients with several active noncavitated lesions. Moreover, in some patients, caries control cannot be obtained without instructions in proper diet. This highlights the important fact that the general treatment philosophy for active lesions advocated in the decision tree in Fig. 11.1 ('active caries lesion needs professional management') should be tailored to the particular needs of the patient (see Chapter 17).

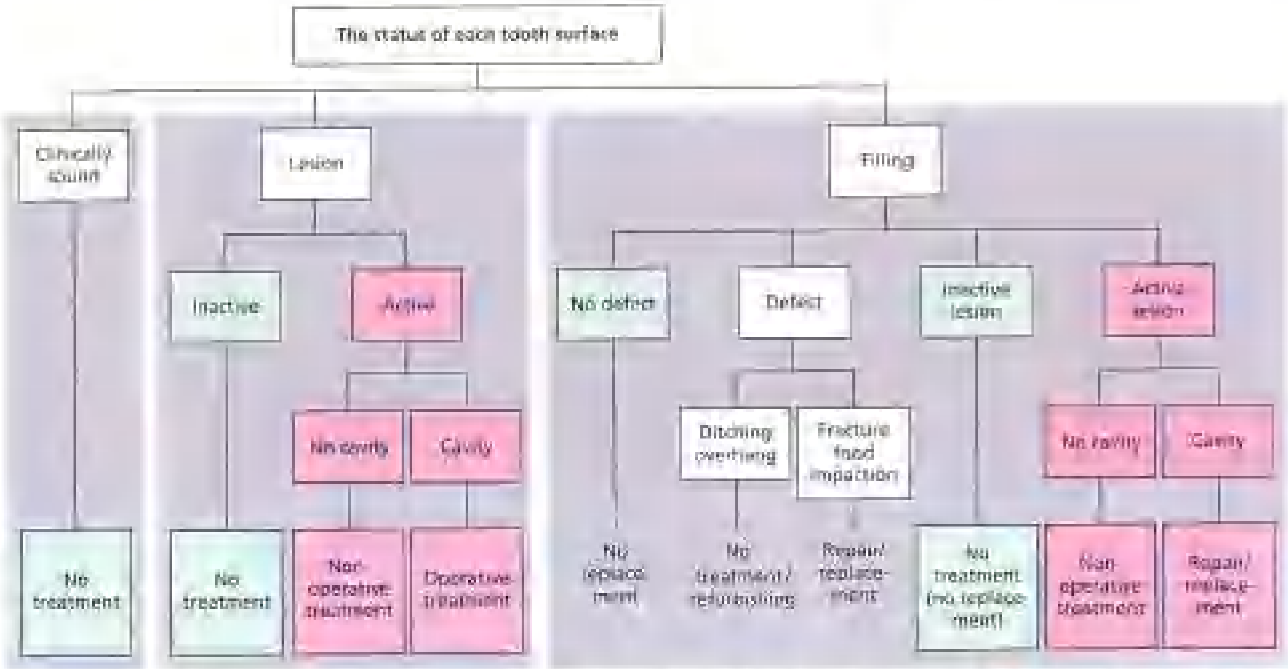


Figure 11.1 Decision-making tree for dental caries, including activity assessment as a key factor in the decision process. The flow diagram promotes the concept that active lesions – cavitated and noncavitated as well as recurrent lesions – need professional management, whereas inactive lesions do not need treatment besides self-performed toothbrushing with fluoride toothpaste. The flow diagram does not consider individual factors that may influence the modality or intensity of the professional treatment. See text for further explanation. Modified after [52]. Reproduced with permission of John Wiley & Sons.

Inactive lesions

By contrast, inactive/arrested lesions do not require professional intervention (see Fig. 11.1). Indeed, such professional intervention would be a waste of time and money. It is important to note that inactive noncavitated caries lesions may also be seen in patients who have never received professional nonoperative interventions, as lesion arrest could happen in response to tooth eruption and salient changes in oral health behavior.

As will be shown later in this chapter, active and inactive noncavitated caries lesions have clinically distinct features. The ideal caries diagnostic method, therefore, is one that allows a distinction between cavitated and noncavitated caries lesions, as well as between active and inactive noncavitated caries lesions. The visual–tactile clinical examination is the only method so far available that can fulfill this purpose.

Informing the patient

The patient is central to the management of the carious process. It is the patient who will control the process, not the dental professional. The dentists' role is to inform the patient of the diagnosis and treatment options, and whether any action is required.

Many patients still expect the dentist to 'take care of their mouths' and think that caries control can be obtained by merely visiting a dentist at regular intervals. If the dentist does not share the diagnosis with the patients and inform them of their crucial role for the control and management of their caries lesions, this may lead to disappointment at best or legal action at worst.

Longitudinal assessment of the caries process

Once it has been decided to intervene with an active caries lesion the dentist should monitor the fate of the lesion over time and record any changes in surface integrity and activity status (see Chapter 17). An active lesion that converts into an inactive lesion or regresses to a sound surface is considered a positive outcome. Active lesions that remain active most often reflect a lack of compliance. In such cases, it should be considered whether the chosen intervention is suitable.

Longitudinal monitoring of caries is also relevant at the population level. Health service planners organize epidemiological studies for surveillance of the caries status in selected populations. Such reports are used to identify possible trends in the caries profile in given populations over time in an attempt to allocate limited economic resources in the most appropriate way.

How early should caries lesions be detected?

The signs and symptoms of caries form a whole continuum of changes, ranging from barely discernible at the ultrastructural level to overt cavities. This raises the question which (lower) threshold to use to distinguish between caries and no caries. So far, this lower threshold has predominantly been determined by the limits of detection of the traditional diagnostic methods, that is, what we are able to detect based on the visual–tactile examination or in bitewing radiographs. The low prevalence of dental caries observed in many countries today has prompted researchers to look for more refined diagnostic tools that can detect carious lesions even earlier (Chapter 12). This development has essentially been driven by the belief that the earlier a lesion is detected, the better the possibility for successful nonoperative intervention. However, there are several reasons why this philosophy of earlier detection may be questioned. First of all, lowering of the diagnostic threshold does not merely result in the detection of more small lesions, but also in more false-positive diagnoses, because caries diagnosis, like any other measurement process, is prone to error (Chapter 10). One consequence of lowering the detection threshold, therefore, could be more unnecessary nonoperative treatment. Second, many subclinical lesions will arrest or regress without active professional intervention as a result of natural physiological processes in the biofilm [28]. Thus, lowering the diagnostic threshold may not be cost-effective. Finally, there is currently no advanced caries diagnostic alternative to the visual–tactile clinical examination that allows a distinction between active and inactive noncavitated lesions. Use of advanced high-resolution diagnostic methods will therefore add to the aforementioned problem of unnecessary nonoperative treatment, primarily because such methods cannot distinguish between active lesions in need of treatment and inactive lesions for which treatment has no effect.

Numerous studies have shown that clinically detectable carious lesions can be arrested by nonoperative interventions at any stage of lesion development when plaque control is adequate (see [52] for a review), particularly when lesions are easily accessible to cleaning [2, 3, 51]. It thus remains to be demonstrated that lowering the diagnostic threshold by means of more refined caries diagnostic methods will bring about a health benefit to the patients that outweighs the additional costs incurred due to unnecessary treatments. Until such evidence has been presented, we cannot recommend lowering of the diagnostic threshold below that which can be obtained by the visual–tactile examination for practical clinical purposes. However, this does not preclude the use of more advanced methods for research purposes (see Chapter 12).

What are the best visual–tactile caries diagnostic criteria?

As shown in Chapter 3, carious lesions come in many sizes and shapes, surface features, and colors. This may explain why the literature has described a large variety of visual or visual–tactile classifications of carious lesions [38]. Each of these classifications has been developed to serve specific purposes by individual researchers, and it may therefore be difficult for the clinician to critically appraise their usefulness. Some classifications focus specifically on the presence of cavitated lesions, while others seek to include both cavitated and noncavitated lesions. Some are mainly concerned about estimation of lesion depth, while others classify lesions according to the dental tissues involved.

In recent years a new dimension has been added to the classical visual–tactile caries examination: the concept of lesion activity assessment [53]. It has thus been shown that, in addition to determining the surface integrity of a lesion (cavitated or noncavitated), it is sensible to classify lesions according to their activity state on the basis of surface characteristics (active or inactive) [54]. These observations hold great promise for clinical cariology as such simple recordings have prognostic value and may assist in treatment planning as well as monitoring individual lesions over time.

It is important to stress that there is no universal set of diagnostic criteria or diagnostic threshold that can be recommended for all purposes. It is up to the clinician/researcher to choose the classification that is best suited for the purpose. For some epidemiological surveys, where reliability and comparability with previous surveys may be key issues, a classification that records cavities only may occasionally be advised. However, in clinical settings and research it is now mandatory that both cavitated and noncavitated lesions are recorded [29, 37]. When a clinician/researcher wants to monitor changes in the activity state of lesions over time it is essential to apply a diagnostic method that has proved its effectiveness for such purposes.

Caries diagnostic methods are frequently introduced without much prior scientific evaluation. This is highly unfortunate, as it may later turn out that a diagnostic technique cannot deliver what it promises. It is often stated that the fundamental requirement for a good diagnostic method is that it is valid and reliable. However, no predetermined bounds have been agreed for the validity and reliability of caries diagnostic tests. It is important, therefore, to have some understanding of these concepts.

The concept of validity

A valid method results in measurements that measure what they purport to measure [38]. For example, whenever we clinically record a carious cavity in an approximal surface, we want our clinical recordings to represent the true state of the surface. In the case of approximal carious cavities we could (theoretically!) establish the truth by extracting the teeth and verifying the presence of cavities by means of meticulous inspection in the laboratory. This is referred to as the so-called 'gold-standard truth.' If we did this experiment, we might generate a 2×2 table as shown in

Table 11.1. Obviously, for the perfectly valid test, the test results show a perfect match with the gold-standard truth. However, only rarely have tests been described that are perfectly valid, and we are usually faced with a situation where we have to consider the consequences of the errors made. In the hypothetical example in Table 11.1 we made 15 true-positive (TP) cavity diagnoses; that is, we found a cavity in 15 cases where a cavity was indeed present. We made 10 false-negative (FN) cavity diagnoses; that is, we overlooked 10 cavities. Thereby, we can calculate the ability of our test to find cavities as test sensitivity = TP/(TP + FN) = 15/(15 + 10) = 0.60 (Table 11.1). We also made five false-positive diagnoses (FP) and 170 true-negative (TN) diagnoses. These numbers can be used to express the ability of the test to exclude cavities where there are no cavities: test specificity = TN/(TN + FP) = 170/(170 + 5) = 0.97. Apparently, in this case our clinical diagnostic test was better suited to rule out cavities (specificity) than to rule them in (sensitivity), but the trade-off also involves balancing the health consequences of 10 overlooked cavities against five diagnoses of nonexistent cavities (see Chapter 10).

The validity concept just described is a form of *criterion validity* that is termed *concurrent validity*. This necessitates a gold-standard reference of truth. However, as discussed in much greater detail in Chapter 10, it is usually not possible to identify a real reference of truth. An example that illustrates this is the diagnosis of active caries, as no gold standard exists for caries activity assessment. In such circumstances, we must resort to a different form of criterion validity, namely *predictive validity*. Predictive validity makes use of the fact that a truly active lesion – if not interfered with – will progress, whereas this will not happen if the lesion is truly inactive. In other words, we predict a higher probability of lesion progression for a caries lesion judged to be active than for one judged to be inactive. This approach was used by Nyvad *et al.* [54] to determine whether certain diagnostic categories were better than others in predicting particular outcomes (e.g., cavity formation). This method of validity assessment is particularly meaningful because it has direct clinical implications for prognosis and treatment decisions [54] (see later this chapter).

From the patient perspective, however, information about *criterion validity* is relatively uninteresting. What matters to the patient is not a precise judgment of the true or predicted state of affairs but rather the prognosis of their condition under different treatment alternatives [67]. Patients will only benefit from a diagnostic test if the information generated by the test can be used to alter the subsequent treatment decision in the direction of a better health outcome [40]. The clinical relevance of a caries diagnostic method is therefore closely linked with its ability to alter the treatment towards interventions that achieve better long-term health outcomes (Chapter 10).

Table 11.1 The 2×2 table that might arise if we attempted to verify our approximal cavity diagnoses in 200 consecutively examined first molars by means of subsequent extraction and inspection of the teeth.

		Gold standard (the truth)		
		Cavity	No cavity	
Result of clinical examination (our test)	Cavity	15 = TP	5 = FP	20
	No cavity	10 = FN	170 = TN	180
		25	175	200

TP, true-positive diagnoses: 15; FP, false-positive diagnoses: 5; FN, false-negative diagnoses: 10; TN, true-negative diagnoses: 170.
Sensitivity is the ability of test to detect cavity when cavity is truly present: TP/(TP + FN) = 15/25 = 0.60.
Specificity is the ability of test to exclude cavity where there is truly no cavity: TN/(TN + FP) = 170/175 = 0.97.

The concept of *reliability*

A reliable diagnostic method is a method that can be used by the same or by different examiners so that they obtain identical results. The reliability of a diagnostic method can easily be evaluated, for example, by repeat (but independent) examinations of a number of patients carried out within a time interval sufficiently short to ensure that no real change in the disease situation has occurred. Examinations may be repeated by a single examiner, in which case we talk about *intra-examiner reliability*, or by different examiners (*inter-examiner reliability*). In the simplest scenario, where the diagnostic method distinguishes between presence and absence of disease (e.g., cavity or not), the results of such repeat examinations can be presented in a 2×2 table (Table 11.2). If we calculate the reliability as the observed proportion of agreement, we see that it is high, amounting to 0.99. However, the observed proportion of agreement may be misinterpreted if it is not taken into account that when most surfaces are cavity free there is a substantial risk that some of the agreement reflects chance. The analogy is that if a person who is completely ignorant of a subject takes a multiple-choice test they will by chance check some correct answers. For this reason, it has become customary in dental diagnostic research to express the reliability in the form of κ, which is a chance-corrected measure of agreement. The κ value for the data shown in Table 11.2 is 0.74, showing that the agreement between the two examiners was 74% of the maximum obtainable beyond chance agreement. As discussed in Chapter 10, this κ value is usually interpreted in the caries diagnostic literature as indicative of a high reliability. Unfortunately, neither the observed nor the chance-corrected agreement κ can be used to judge whether the diagnostic test is good for clinical practice. The two dentists, AA and BB (Table 11.2), have diagnosed a similar number of cavities, 162 and 158 respectively. While this may seem fine, it is indeed problematic from a clinical perspective that the two dentists only agreed

Table 11.2 The hypothetical 2 × 2 table that might arise if we evaluate the inter-examiner reliability of cavity diagnoses in 6000 surfaces in 50 consecutively examined patients.

		Examiner BB		
		Cavity	No cavity	
Examiner AA	Cavity	120	38	158
	No cavity	42	5800	5842
		162	5838	6000

Observed proportion of agreement: (120 + 5800)/6000 = 0.99.
Chance-corrected proportion of agreement $\kappa = 0.74$

on 120 (60%) of the total of 200 cavities diagnosed by one or the other dentist. The practical consequence of such observations of less than perfect reliability should be obvious if we assume that our patients first visited dentist AA, where the 'necessary' 158 restorations were made, and then visited dentist BB only to have an additional 42 cavities filled! With this level of reliability one might advise patients not to change dentist, and in any case not to go too often, as the intra-examiner reliability of caries diagnostic methods is typically only marginally better than the inter-examiner reliability. In Chapter 10 we expand the discussion on how to act clinically in such circumstances.

Commonly used visual–tactile criteria

The following diagnostic classifications represent selected examples of commonly applied strategies for visual–tactile caries diagnosis. Note that the methods differ by their clinical approach. Furthermore, the examples illustrate how differences in the diagnostic criteria may influence the clinical outcome in terms of the number of lesions detected as well as the distribution of individual features of the lesions, such as surface integrity (cavitated/noncavitated) and activity state (active/inactive) (Fig. 11.2).

Recording of cavities only

The World Health Organization (WHO) recommends that carious lesions be diagnosed at the level of cavitation [66]. A community periodontal index (CPI) probe should be used to verify the diagnosis when a lesion has 'an unmistakable cavity, undermined enamel, or a detectably softened floor or wall.' This approach is still advocated owing to the belief that it is not possible to obtain a reliable diagnosis of the noncavitated stages of caries [66]. Even so, several studies have shown that this assumption does not hold when examiners are thoroughly trained and calibrated; for example, [30, 46, 53, 58]. By focusing on frank cavities only, the WHO approach to caries diagnosis ignores the opportunity for nonoperative interventions and, therefore, cannot be recommended in modern caries management.

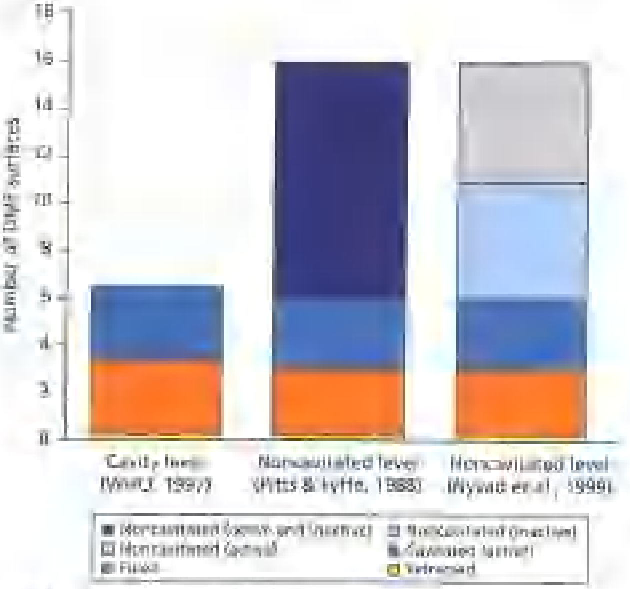


Figure 11.2 The caries profile of 12-year-old Lithuanian children exemplified by three different visual–tactile caries lesion classifications. Note differences in the clinical outcome with regard to total number of lesions, cavitated and noncavitated lesions, and active and inactive lesions. Data from [43].

Recording of cavitated and noncavitated lesions

As discussed before, up-to-date caries recording in surveys and in clinical studies requires that lesions be assessed at the noncavitated level of diagnosis. Pitts and Fyffe [58] presented a classification in which noncavitated lesions were included along with cavitated stages of caries. A plane mouth mirror and a sickle probe were used by the examiners, and the following diagnostic levels were applied:

- D_1 (enamel lesions, no cavity);
- D_2 (enamel lesions, cavity);
- D_3 (dentin lesions, cavity);
- D_4 (dentin lesions, cavity to the pulp).

A major advantage of including noncavitated lesions in the classification is that it gives a more realistic picture of the total caries experience in individuals or populations. Caries recording including noncavitated diagnoses typically increases the diagnostic yield by more than 100% compared with counting cavities only [1, 43, 46, 47, 58] (Fig. 11.2). Trained examiners can reliably perform diagnosis of noncavitated level lesions, and the diagnostic approach is compatible with the philosophy of nonoperative caries control. However, the method does not inform about the activity status of lesions.

Lesion depth assessment

Ekstrand *et al.* [16] presented a visual ranked scoring system for assessment of the depth of lesion penetration, including noncavitated stages of caries. The authors performed visual examination (without the use of a probe!) of cleaned occlusal surfaces on extracted teeth and demonstrated that distinct macroscopic changes on the occlusal surface were related to the histological depth of the lesion [17]. The authors used the following codes:

- no or slight change in enamel translucency after prolonged air drying (5 s);
- opacity or discoloration hardly visible on the wet surfaces, but distinctly visible after air drying;
- opacity or discoloration distinctly visible without air drying;
- localized enamel breakdown in opaque or discolored enamel and/or grayish discoloration from the underlying dentine;
- cavitation in opaque or discolored enamel exposing dentine.

This diagnostic method is based on the well-known phenomenon that noncavitated lesions may change their optical properties depending on whether the lesion is examined in the wet or dry stage [63]. When a wet enamel lesion is dried it becomes more opaque because of increased light scattering in the porous tissue. This phenomenon also explains why a lesion that is distinctly visible in the wet stage penetrates deeper into the tissue than a lesion that can only be seen when it is examined dry. A noncavitated lesion that is only visible after thorough drying may have penetrated halfway into the enamel. However, when a noncavitated lesion is visible on a wet tooth the demineralization may extend into the outer dentin [17].

The International Caries Detection and Assessment System (ICDAS) criteria is an example of a caries detection method that is based on lesion depth assessment (http://www.icdas.org/what-is-icdas). Such criteria have been found to be reliable [31] and valid for assessing lesion depth using the gold standard approach on extracted teeth [32]. However, in spite of the widespread propagation of ICDAS, it has not yet been evaluated whether this particular method of visual caries diagnosis is able to indicate the prognosis of lesions. Moreover, the two-digit mode of recording is time consuming and difficult to apply in clinical practice [12].

Lesion activity assessment: Nyvad criteria

Lesion activity assessment was introduced as a refined visual-tactile method of caries detection to allow dentists to monitor dynamic changes in lesion progression over time [55]. The patho-biological rationale of the method is based on the observation that the surface characteristics of the enamel and dentin change in response to changes in the metabolic activity of the biofilm covering the tooth surface (see for review, see [64]) (Chapter 5). Thus, rather than concentrating on a precise estimation of lesion depth, lesion activity assessment focuses on the surface characteristics of lesions. Two discrete features are addressed: *activity*, as reflected by the surface texture of the lesion, and *integrity*, as expressed by the absence of a cavity or microcavity in the surface.

According to the Nyvad criteria, all lesions – including fillings – should be assigned to one of the following nine diagnostic categories:

- active, noncavitated (score 1);
- active, noncavitated with microcavity (score 2);
- active, cavitated (score 3);
- inactive, noncavitated (score 4);
- inactive, noncavitated with microcavity (score 5);
- inactive, cavity (score 6);
- filling (score 7);
- filling with active caries (score 8);
- filling with inactive caries (score 9).

The typical active noncavitated enamel caries lesion is a whitish/yellowish opacity with loss of luster, exhibiting a 'chalky' or 'milky' appearance. The surface feels rough when the tip of a sharp probe is moved gently across the surface (Fig. 11.3a and b). By contrast, inactive noncavitated enamel caries lesions are generally shiny and feel smooth on gentle probing (Fig. 11.3c and d). The color of an inactive lesion may vary from whitish to brownish or black, but color is not a reliable differential diagnostic characteristic distinguishing active and inactive noncavitated lesions.

Some active lesions exhibit localized shallow surface defects in an otherwise noncavitated enamel surface. Such microcavities may arise as a result of wear and tear in the oral cavity [2, 9] (Fig. 11.3e). Microcavities at the active stage have sharp borders. When the local environment changes (e.g., as a result of tooth eruption), the borders of such shallow defects may become smooth. Hence, enamel lesions with an overall smooth topography should be recorded as inactive, in spite of the presence of a microcavity (Fig. 11.3f).

For cavitated lesions (total collapse of the enamel), the diagnostic criteria mimic those applied for dentin/root caries (see later), typically active lesions being yellowish, soft, or leathery (Fig. 11.3g), while inactive lesions are shiny and feel hard on easy probing (Fig. 11.3h). Inactive lesions often take on a brownish or black color, but again color is not a conclusive criterion for activity.

Lesion activity assessment can also be applied in the primary dentition [61]. Typical examples of Nyvad scores in the primary dentition are shown in Fig. 11.4a–f.

The chalky opacity of an active enamel caries lesion relates to two discrete phenomena. The opaque appearance is explained by an increased internal porosity of the lesion due to subsurface demineralization. The chalky look is caused by dissolution of the intercrystalline enamel spaces in the very surface zone of the lesion that occurs following a period of net mineral loss (surface erosion). When the surface is eroded, the enamel loses its shiny appearance due to diffuse back scattering of light [64] (Fig. 11.5a). This is the reason why an active enamel caries lesion may appear whiter and more opaque than an inactive enamel lesion.

Figure 11.3 Typical clinical manifestations of active and inactive caries lesions according to [53]. Active noncavitated lesion on smooth surface (a) and occlusal surface (b). (c, d) Inactive noncavitated lesion on smooth surface (c) and occlusal surface (d). (e) Active noncavitated lesion with microcavity on approximal surface. (f) Inactive noncavitated lesion with microcavity on smooth surface. Active (g) and inactive (h) cavitated lesions. See text for further explanation. (a), (b), and (d) from [53]. Reproduced with permission of Karger Publishers.

If the surface of an active lesion is exposed to regular mechanical disturbances by, for instance, toothbrushing, then the lesion gradually assumes a smooth surface; however, depending on the depth of demineralization, the internal porosity often persists (Fig. 11.5b). Therefore, in most cases the inactive lesion is seen as a 'scar' in the enamel (see Chapter 5).

Such a refined scoring system necessitates clean and dry teeth. Tacky bacterial deposits that are physically interrelated with the eroded enamel surface [22] often cover the active noncavitated lesions, and removal of this biofilm (using the side of the probe or a brush) is an integral part of the diagnostic process. The probe should never be used to poke vigorously into the tissues but rather serve as a highly refined tactile tool. Rough and careless probing can force the probe through the surface zone of the lesion and create a cavity. In fact, poking with the probe requires a firm grip, which precludes the tactile approach used with the Nyvad criteria.

For some lesions it may be difficult to decide whether the lesion should be scored as active or inactive, since lesions often contain elements of both active and inactive sites. However, from a treatment perspective, it is important not to overlook an active lesion. Therefore, a lesion is scored as active in all cases when any part of the lesion reveals the classical signs of activity (dullness and roughness). When adopting such decision rules, the Nyvad criteria have been shown to be reliable when used under epidemiological conditions by trained examiners in both the primary and permanent dentitions [53, 61].

As discussed previously, lesion activity assessments cannot be validated by the classical gold-standard approach because there is no gold standard for caries activity. However, it has been shown that activity assessments have predictive validity for lesion activity when used in a clinical trial of the effect of daily supervised brushing with fluoride toothpaste [54]. It was thus demonstrated that active noncavitated lesions have a higher risk of progressing to a cavity than inactive noncavitated lesions do, which, in turn, have a higher risk of progressing to a cavity than sound surfaces do. The important implications of these predictions are that activity assessments have prognostic value and, therefore, may help to guide the subsequent course of treatment (see decision tree in Fig. 11.1).

For documentation and monitoring of clinical changes in caries lesion activity, specific symbols have been devised for the different lesion categories (Fig. 11.6). Active lesions are indicated in the caries diagram by filled circles (noncavitated without/with microcavity) and filled boxes (cavities), while inactive lesions are marked by empty circles and boxes respectively. Such symbols have been used successfully at the Dental School in Aarhus for the past 20 years and were recently implemented in a computerized patient record. Alternatively, for epidemiological purposes, for example, each activity score may be recorded by a single digit, as outlined on p. 198.

Figure 11.4 Typical clinical manifestations of active and inactive caries lesions in the primary dentition. (a) Active noncavitated lesion on buccal surface. (b) Active noncavitated lesion with microcavity in occlusal surface. (c) Active cavitated lesion on approximal surface. (d) Inactive noncavitated lesion on occluso-lingual surface. (e) Inactive noncavitated lesion with microcavity on occlusal surface. (f) Inactive cavity on lingual surface.

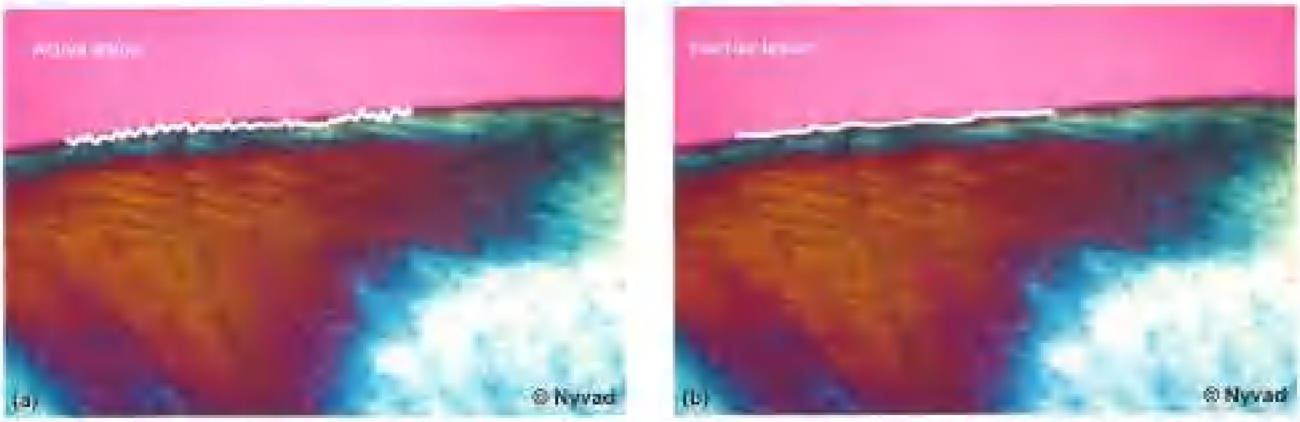


Figure 11.5 Polarized light microscopic images of noncavitated enamel caries lesion showing subsurface loss of mineral responsible for the opaque appearance of the lesion in the clinic. The white contour at the surface layer of the lesion indicates the principal difference between a rough/dull active lesion (a) and a smooth/shiny inactive lesion (b).

● Active caries noncavitated

■ Active caries cavitated

○ Inactive caries noncavitated

☐ Inactive caries cavitated

Figure 11.6 Symbols for indicating lesion activity in the dental diagram. Active lesions are marked by filled circles (noncavitated) and filled boxes (cavities), whereas inactive lesions are marked by empty circles and boxes respectively.

Root-surface caries

Fejerskov and coworkers introduced a classification for diagnosing root-surface lesions that integrates activity assessment and assessment of surface integrity [21]. The criteria were developed on the basis of empirical observations of experimental nonoperative treatments of root-surface caries [51] (see Chapter 13, Fig. 13.4a–d). Active lesions were described as soft or leathery (Fig. 11.7a) and were usually found at plaque retention sites next to the

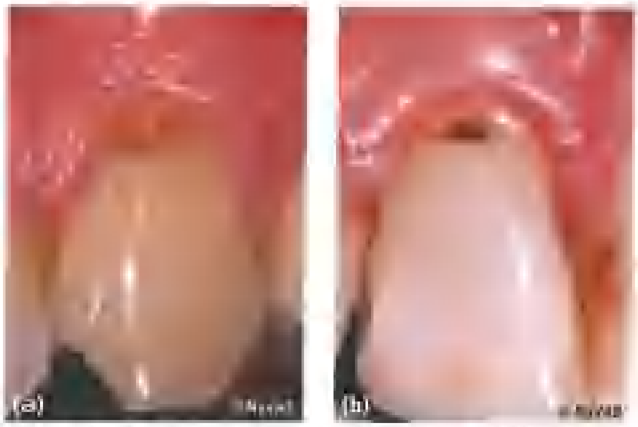


Figure 11.7 (a) Active root surface caries lesion in upper canine presenting a softened surface. (b) Inactive root surface caries lesion in upper incisor showing a smooth discolored surface.

gingival margin or along the cemento-enamel junction. Inactive lesions, on the other hand, were typically located at some distance from the gingival margin, felt hard on gentle probing, and often presented with a shiny appearance (Fig. 11.7b). The color of the lesion was not helpful in distinguishing between active and inactive stages. The following diagnostic categories were proposed:

- inactive lesion without surface destruction;
- inactive lesion with cavity formation;
- active lesion without definitive surface destruction;
- active lesion with surface destruction (cavitation), but cavity is estimated not to exceed 1 mm in depth (visually);
- active lesion with a cavity depth exceeding 1 mm, but not involving the pulp;
- lesion expected to penetrate into the pulp;
- filling confined to the root surface or extending from a coronal surface onto the root surface;
- filling with an active (secondary) lesion along the margin;
- filling with an inactive lesion (secondary) confined to the margin.

Recurrent (secondary) caries

The term recurrent (secondary) caries refers to caries at the margin of restorations [50]. Hence, recurrent caries reflects the result of unsuccessful plaque control. Recurrent carious lesions are most often located on the gingival margins of restorations, both approximally and sometimes on free smooth surfaces, because this is where the biofilm may stagnate. Recurrent caries is less often diagnosed at the margin of occlusal restorations as these are easier to clean.

Diagnosis of recurrent caries may be accomplished according to the Nyvad criteria by differentiating between cavitated and noncavitated as well as active and inactive stages of caries (see p. 198). This approach automatically guides the subsequent treatment (Fig. 11.1). Hence, noncavitated active recurrent lesions that are amenable to plaque removal should principally be managed by nonoperative procedures (Fig. 11.8), while noncavitated inactive recurrent lesions need no further treatment apart from daily toothbrushing (Fig. 11.9). By contrast, active lesions with cavity formation (soft on probing!) that cannot be cleaned properly should be repaired or replaced (Figs 11.10 and 11.11). Diagnosis of caries at the margins of a restoration is sometimes difficult, but it is imperative to distinguish recurrent lesions from ditching (Fig. 11.12) and minor defects. Ditching and minor defects, including overhangs (Figs 11.13, 11.14, and 11.15) may be managed adequately by refurbishing [50]. Repair and refurbishing saves dental tissue and are reliable alternatives to complete replacement of restorations [24]. Occasionally, dark shadows reflecting an underlying amalgam filling (Fig. 11.8) or staining of composite fillings due to residual amalgam (Fig. 11.16) may confuse the diagnosis. Some dentists routinely replace fillings that have staining and minor defects (Figs 11.13, 11.14, 11.15, and 11.16) in the belief that such clinical signs are indicative of microleakage that leads to caries. However, recurrent caries does not develop as a result of microleakage along the tooth–restoration interface [50]. Bacteria may invade the dentin through larger gaps between a filling and a tooth (width >0.4 mm) [34, 36], but narrow ditches are usually not prone to bacterial invasion and should not be confused with recurrent caries, which develops as a surface lesion similar to primary caries lesions (Chapter 5).

Differential diagnosis

When performing a caries diagnosis it should be appreciated that not all opaque lesions on the tooth surface represent dental caries. All opacities reflect a decreased mineral content in the enamel, but these may be caused by different mechanisms, either during enamel formation or post-eruptively. Differential diagnostic considerations of white opaque lesions are particularly relevant in populations showing evidence of dental fluorosis. Because of its developmental origin, dental fluorosis has a symmetric distribution on homologous teeth [13, 62]. For this reason, the dental examination should always start by a quick screening of the entire dentition in order to identify possible enamel changes symmetrically distributed on both sides of the dental arch. In mild cases (TF1), fluorosis appears as fine white horizontal striae reflecting the perichymatal pattern of enamel. When such white lines merge (TF2) in the gingival part of a tooth they might be suggestive of inactive noncavitated caries lesions (smooth on probing) (Fig. 11.17). However, the typical noncavitated enamel caries lesion contrasts with the fluorotic lesion by being arcade-, banana-, or kidney-shaped, reflecting the retention of plaque along the

Figures 11.8–11.16 Figure 11.8: Active recurrent root surface caries lesions on lower canine and premolar next to composite fillings with overhangs (arrows). These lesions should be treated by nonoperative intervention (site-specific improved hygiene and application of topical fluorides) in conjunction with refurbishing of the lesions to facilitate biofilm removal. Note also dark shadow on the buccal surface of the premolar reflecting underlying amalgam filling. Figure 11.9: Inactive recurrent root surface lesion next to amalgam filling on lower incisor. No treatment is needed. Figure 11.10: Active recurrent caries lesion next to composite filling on the occlusal surface. The lesion needs operative treatment because the cavity cannot be cleaned properly. The cavity is soft on probing. Figure 11.11: This filling has fractured across the isthmus and part of the restoration is loose. Biofilm forms beneath the loose amalgam resulting in an active recurrent caries lesion that needs operative treatment. The cavity is soft on probing. Figure 11.12: Ditching along margins of amalgam restoration which most likely developed because of overfilling. No caries is detected. No treatment is needed. Figure 11.13: Gingival amalgam fillings with stained margins and inactive recurrent caries. Refurbishing of the fillings may facilitate oral hygiene. Figure 11.14: Buccal amalgam with overhang and inactive recurrent caries. The filling should be refurbished to make cleaning easier. Figure 11.15: Old amalgam fillings in patient with erosion. Note that the normal anatomy of the teeth has gone and that the fillings are elevated above the eroded enamel/dentin surface. In spite of defective margins, no caries is present. No treatment is advocated. The filling in the neighboring premolar was lost due to progression of erosion. Figure 11.16: Stained margins of composite filling in upper premolar. The stain may be due to incomplete removal of previous amalgam filling. No need for replacement if the margins of the filling are clinically intact.

curvature of the present (or former) location of the gingival margin (Figs 11.3a and c, 11.4, 11.5, and 11.17). Thus, the main discriminatory features for an inactive caries lesion and mild dental fluorosis are the shape of the lesion and the pattern of distribution in the dentition. Of course, noncavitated caries lesions may accidentally be present in both sides of the dentition. However, in most cases of dental fluorosis, white opaque lesions occur on several groups of homologous teeth indicative of their systemic origin (see [55] for a review).

Opacities of non-fluoride origin rarely represent a differential diagnostic problem as they are mostly round or oval and clearly defined from the adjacent enamel.

Figure 11.17 (a) Dental fluorosis (TF1) in the gingival part of upper canine and premolar. Note the fine white horizontal lines which reflect the perichymatal pattern of enamel. This clinical manifestation is distinctly different from the arcade-shaped inactive noncavitated caries lesions shown in (b) reflecting the retention of plaque along the former gingival margin. From [55]. Reproduced with permission of John Wiley & Sons.

Figure 11.18 Well-demarcated opacities of non-fluoride origin in incisal part of lower incisors [55] Reproduced with permission of John Wiley & Sons.

They appear on single teeth, especially incisors (Fig. 11.18), and predominantly in the incisal two-thirds of the crown.

Occasionally, patches of whitish, yellowish, or brownish enamel opacities occur on several molars and incisors in the same individual (molar–incisor hypomineralization, MIH). MIH is defined as hypomineralization of systemic origin of one to four permanent first molars, frequently associated with affected incisors [65]. Permanent first molars are the teeth most commonly affected, but primary second molars are also often compromised [18]. Depending on the severity of the hypomineralization, such developmental defects may exhibit a softened surface with or without post-eruptive loss of enamel (Fig. 11.19). The brownish opacities characterized by a high protein content [19] are particularly at risk of enamel breakdown soon after eruption, and this condition may lead to rapid caries progression because of impaired plaque control of the exposed sensitive dentin (Fig. 11.19d). MIH-associated opacities/hypoplasia are usually easy to differentiate from caries when they occur in areas of the tooth that are normally not affected by caries (e.g., cuspal tips; Fig. 11.19a–c). Higher decayed, missing, and filled teeth (DMFT) values have been reported for children with MIH compared with children without MIH [11, 39]. However, it remains an open question as to whether this is due to children with MIH having a higher overall caries activity or whether the DMFT index is inflated by increased restorative treatment of teeth affected by severe hypoplasia [10, 25].

In recent years dentists have noted an apparent increase in the occurrence of subgingival lesions in otherwise caries-inactive patients (Fig. 11.20a). Some researchers claim that such cavitated lesions may represent root caries lesions [33], but in most cases their subgingival location makes it is more plausible that they are external cervical root resorptions. First, the biofilm in this eco-niche is deprived of dietary carbohydrates that could shift the ecological balance (Chapter 7); and second, the alkaline pH of the gingival fluid precludes the preservation of an acid environment for longer periods of time [7]. Therefore, external cervical root resorption should always be considered a possible differential diagnosis when root defects are observed subgingivally [23]. Root-surface caries lesions may occasionally appear in a subgingival location due to secondary swelling of the gingival tissues. However, root caries lesions are relatively easy to distinguish from cervical root resorptions as the latter are hard on probing and present with sharp undermined borders (Fig. 11.20b). Furthermore, root resorptions may be associated with granulation tissue, which is redder in color than the surrounding gingiva and bleeds freely on probing. Finally, most cervical root resorptions are asymptomatic until a very advanced stage of development [23].

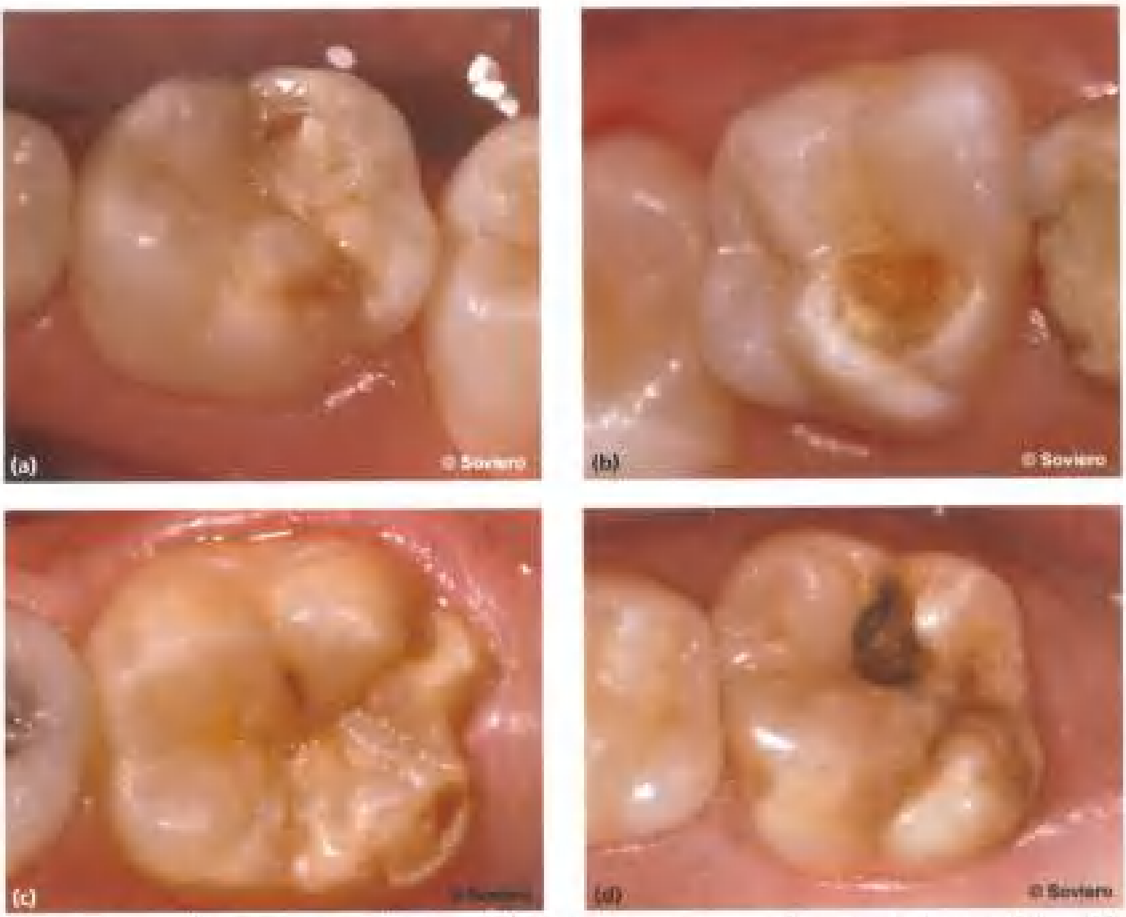


Figure 11.19 MIH in the primary (a, b) and permanent dentition (c, d). Note that MIH-associated hypoplastic enamel defects are easy to differentiate from caries when they appear in areas of the tooth that are commonly not affected by caries, such as cusps. (d) Active cavitated caries lesion with undermined enamel has developed in central occlusal fossa. At this advanced stage of lesion development it is not possible to say whether caries was accelerated because of the presence of a hypoplastic defect in the fissure. Note also areas of opaque enamel in all the MIH-affected teeth.

Figure 11.20 (a) Clinical manifestation of invasive cervical root resorption on lower canine. Note the sharp occlusal border of the lesion and the presence of reddish granulation tissue. (b) It is obvious from the radiograph that the lesion is subgingival. There is a small opening to the periodontal membrane. From [69]. Reproduced with permission of John Wiley & Sons.

Visual–tactile caries examination: a systematic clinical approach

The clinical caries examination should be carried out in a systematic manner after each quadrant of the mouth has been isolated with cotton rolls and a suction device to prevent saliva from wetting the teeth once they have been dried (Fig. 11.21). For practical purposes, begin with the upper right molars and move tooth by tooth to the upper left molars; then jump to the lower left molars and finish up with the lower right molars. It is recommended to examine every tooth surface in the same order, starting from the occlusal surface, then continuing with the mesial, buccal, distal, and oral surfaces. A consistent examination pattern ensures that no teeth or surfaces are missed. In cases of large, extended lesions, there are certain decision rules concerning which surfaces should be recorded. Usually, the detected caries lesion is located on the surface from where it originates, even if it extends slightly into a neighboring surface. However, when the lesion extends from its perceived surface of origin and more than one-third into an adjacent surface, it can be considered as involving two surfaces.

Good lighting and clean, dry teeth

Visual–tactile caries examination requires good lighting and clean, dry teeth. Proper illumination is an essential part of the diagnosis of caries lesion activity. The typical surface characteristics of noncavitated caries lesions, such as loss of luster, roughness, and discoloration, can be observed under direct light only. Thorough drying is performed with a gentle blast of air from a three-in-one syringe. A noncavitated enamel lesion is more easily disclosed when the tooth is dry, since the difference in the refractive index between carious and sound enamel is greater when water is removed from the porous tissue. It is not feasible to give a standardized drying time, as the humidity and salivary flow in the oral cavity may vary considerably from site to site and from patient to patient.

Figure 11.21 Making ready for a visual–tactile caries examination after isolation of the teeth with cotton rolls and a suction device.

The teeth are examined by the aid of a dental mouth mirror and a sharp probe (see later). The mouth mirror is used to displace the cheeks and lips and to facilitate vision in difficult-to-reach areas on the teeth. Reflected light from the mouth mirror can be applied to inspect the surfaces that cannot be observed directly, as well as to search for dark shadows, which may be suggestive of dentinal lesions (Fig. 11.22). Transmitted light from the operating lamp is particularly helpful for examining the approximal surfaces of anterior teeth (Fig. 11.23). Many dentists do not look for noncavitated lesions on approximal surfaces. However, even if direct access to an approximal surface is limited, careful inspection may reveal a noncavitated lesion that extends onto the buccal or lingual surfaces (Fig. 11.24).

Sensible use of the probe

If the teeth are heavily covered by plaque, it is necessary to clean the dentition before a proper caries diagnosis can be performed (Fig. 11.25a and b). However, it should be appreciated that the presence of plaque covering a lesion may be of diagnostic value when assessing lesion activity (see p. 199). Sticky plaque adhering to a chalky/opaque enamel lesion is strongly indicative of activity. Therefore, in most situations it is more sensible to remove the plaque concurrent with performing a caries examination rather than just removing it before looking. In any case, for plaque removal purposes, as well as for assessment of surface roughness, we recommend the use of a sharp metal probe. The probe serves two purposes. First, to remove the biofilm (using the side of the probe!) to check for signs of demineralization and surface break; and second, to 'feel' the surface texture of a lesion, as sensed through minute vibrations of the instrument by the supporting fingers when moving the tip of the probe at an angle of 20–40° across the surface (Fig. 11.26). It may take some training to learn this tactile skill, but once this skill has been acquired it is an important adjunct to the visual assessment. One should definitely abstain from 'poking' vigorously into the tissue, thereby running the risk of causing irreversible damage to the surface layer of a noncavitated lesion [15] (Fig. 11.27), which might potentially accelerate localized lesion progression. Histological evaluation has shown that gentle probing does not disrupt the surface integrity of noncavitated lesions [42]. A clinical caries examination performed according these principles takes about 5–10 min depending on the caries status of the patient [53, 61].

Some researchers are concerned that probing of suspected carious lesions may serve to spread infective plaque (e.g., mutans streptococci) to other teeth in the same mouth [41], thereby facilitating caries lesion development. However, this concern has not been confirmed by longitudinal studies of repeated probing of fissures in

Figures 11.22–11.24 Figure 11.22: Reflected light from the mouth mirror reveals a dark shadow on the mesial approximal surface of upper first molar (arrow). Note also the presence of a noncavitated lesion on the mesio-oral part of the same surface (arrow). Figure 11.23: Transmitted light from the operating lamp allows detection of approximal lesions in upper anterior teeth. Figure 11.24: Inactive noncavitated lesion on the mesial surface of lower molar detected after careful inspection using a mouth mirror (arrow).

Figure 11.25 Lower canine and incisor (a) before and (b) after plaque removal. Note the presence of typical active noncavitated lesions after plaque has been removed with the side of a probe.

second molars at regular intervals [27]. Furthermore, such a hypothesis is incompatible with the ecological concept of caries. Transferred microorganisms would not survive unless their new eco-niche favored their existence (see Chapter 7).

Caries predilection sites

In every dentition there are sites that are at increased risk of lesion development. These sites reflect the stagnation areas for dental plaque, mainly the areas along the gingival margin, occlusal fissures, and gingival margins of restorations.


Figures 11.26 and 11.27 Figure 11.26: Examination of noncavitated caries lesion using the tip of a sharp probe that is moved gently across the surface of the lesion at an angle of 20–40° to assess lesion texture. Figure 11.27. Forceful poking with the probe perpendicular to the lesion should be avoided in order not to cause irreversible damage to the surface of the lesion!

Furthermore, caries predilection sites vary distinctly according to the age of the patient. In preschool children the distal surface of the first primary molar is the most caries prone, followed by the mesial surface of the second primary molar. Children with erupting first and second permanent molars require special attention. Because of a relatively long eruption period, permanent molars run an increased risk of lesion development, particularly on occlusal surfaces [8]. In teenagers, the distal surfaces of the second premolars and the mesial surfaces of the second molars are particularly prone to lesion development [48]. In elderly patients with gingival recession, root caries may become a problem. Root caries lesions are confined to stagnation sites, such as the area along the gingival margin, the cemento-enamel junction, and other difficult-to-clean irregularities on the root surface.

Additional aids in visual–tactile caries diagnosis

Fiber-optic transillumination

Fiber-optic transillumination (FOTI) is a diagnostic method by which visible light is transmitted through the tooth from an intense light source; for example, from a fine probe with an exit diameter of 0.3–0.5 mm. If the transmitted light reveals a shadow when the tooth is observed from the occlusal surface, this may be associated with the presence of a carious lesion. The narrow beam of light is of crucial importance when the technique is used in the premolar and molar region. For optimal performance the probe should be brought in from the buccal or lingual aspect at an angle of about 45° to the approximal surfaces pointing apically, while looking for dark shadows in the enamel or dentin (Fig. 11.28). Shadows are best noticed when the office light is switched off.

Although transillumination is a simple, fast, and cheap supplementary method well known to most practitioners for diagnosing approximal caries in the anterior teeth (Fig. 11.23),

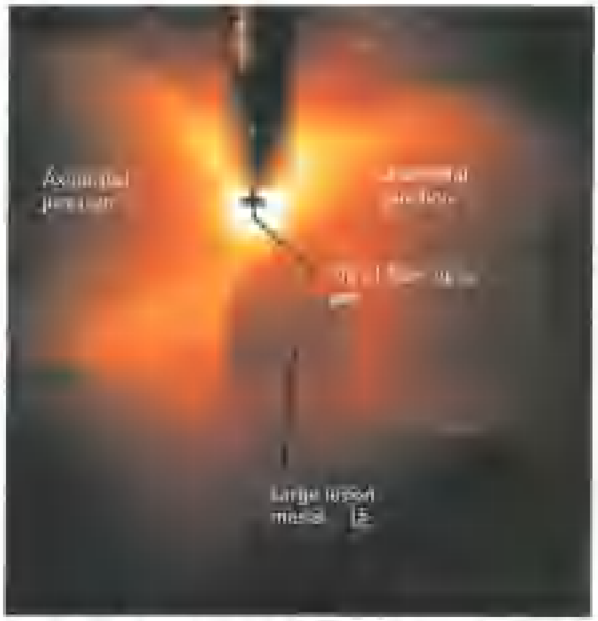


Figure 11.28 Caries lesion detected by FOTI on the mesial aspect of upper second premolar (arrow). The lesion is seen as a dark shadow. Reproduced with courtesy of Dr C. Pine.

the fiber-optic method has never become broadly accepted for detection of lesions in approximal surfaces in the premolar and molar regions. One of the reasons for this may be that the sensitivity of the method is low [5]. Even if the specificity has been reported to be relatively high, 88–100%, depending on type of surface and type of lesion [5], it remains to be documented that FOTI adds substantially to the clinical caries examination for detecting caries lesions.

Tooth separation

It is anticipated that the presence of a cavity, if not interfered with, will increase the rate of progression of a caries lesion. Neither radiographs nor FOTI can help to identify the presence of a cavity on contacting approximal surfaces.

Figure 11.29 (a) An orthodontic elastic separator has been placed between upper premolar and molar. To insert the separator the elastic is stretched between two surgical forceps and one half of the elastic is worked down through the contact point. (b) After 2–3 days the separator is removed. It is now possible to see and 'feel' the surface texture of the lesion with the tip of a probe.

Therefore, other methods, such as tooth separation, have been introduced. With this technique, orthodontic elastic separators are applied for 2–3 days around the contact areas of surfaces to be diagnosed, after which access for inspection and probing is improved (Fig. 11.29a and b).

Most studies that have applied tooth separation have detected more noncavitated enamel lesions than visual–tactile examination without separation or bitewing examination [26, 59]. However, accessibility for inspection after tooth separation is not always improved as much as needed, and use of the technique may create some discomfort, especially in patients with established dentitions. Furthermore, it requires an extra visit. Therefore, at present we do not recommend the technique for routine use in general practice. In the past, however, the technique has generated important knowledge about the relationship between radiographic lesion depth and the presence/absence of cavity formation on contacting approximal surfaces [26, 59]. Such information is highly useful when deciding whether to treat a radiographically observed dentin lesion operatively or nonoperatively (see Chapter 19).

Magnification

Some contemporary textbooks advocate the use of magnification in caries diagnosis. Surely, most dentists above the age of 40 should be concerned with potential eyesight difficulties and wear glasses. However, it should be pointed out that there is no scientific evidence that magnification per se improves caries detection in clinical settings.

Benefits and limitations of visual–tactile caries diagnosis

In this chapter we have reviewed the clinical application of visual–tactile caries examination. We conclude that a visual–tactile caries examination incorporating activity assessment according to the criteria suggested by Nyvad *et al.* [53] is presently the best choice for performing a caries diagnosis. These criteria are the only criteria that reflect the current evidence-based management options for different stages of caries lesion formation. Importantly, we have shown that the criteria have predictive value for lesion activity, which means that they are highly relevant for clinical decision-making. The criteria can be applied for all entities of caries, including root-surface caries, recurrent caries, and caries in primary teeth. Last but not least, a visual–tactile caries examination is quick and easy to perform, it does not require expensive equipment, and unwarranted radiation is prevented.

It should be appreciated that the effectiveness of a visual–tactile caries examination depends strongly on the caries diagnostic level used [43, 45]. When noncavitated diagnoses are included in the classification, the diagnostic yield of the visual–tactile caries examination is greater than that of radiographic examination (Fig. 11.30). This observation may seem surprising as it is often postulated that radiography is superior to clinical caries examination in lesion detection, particularly on approximal surfaces [35, 56]. However, minor mineral losses cannot be detected on radiographs, and the additional diagnostic yield of bitewing radiography is confined to lesions diagnosed at the cavity/dentin level (Fig. 11.30). Furthermore, the radiographic examination is unable to determine lesion activity and cavity formation, and suffers from a high number of false-positive diagnoses (see Chapter 10). Not every dentinal lesion that appears on a radiograph needs a filling, and too much reliance in radiographic diagnosis inevitably leads to overtreatment (see Chapter 12). Visual–tactile caries examination and activity assessment circumvent this problem by identifying most of the lesions that are indicated for professional treatment. Certainly, clinical signs such as dark

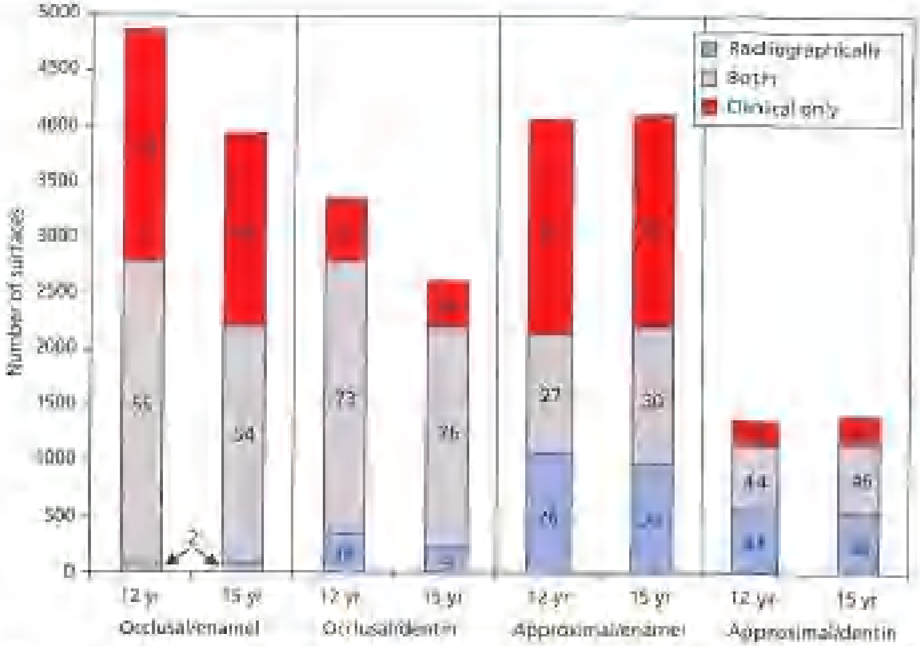


Figure 11.30 Relative diagnostic yields of clinical and radiographic examinations of approximal and occlusal surfaces at the cavitated and noncavitated levels respectively. The data were obtained from children examined at 12 and 15 years of age. Note that at the noncavitated/enamel level of diagnosis, the clinical examination (only) revealed a higher number of lesions than did the radiographic method (only). Only for approximal lesions at the cavity/dentin level of diagnosis did the radiographic method (only) perform better than the clinical examination (only). Age of the individuals did not influence the results [44, 45]. Adapted from Machiulskiene V *et al.* 2004 [45].

occlusal or approximal shadows call for supplementary analyses. However, only after having exploited the full potential of the visual–tactile examination is it time to consider whether additional caries diagnostic tools should be employed.

References

1. Amarante E, Raadal M, Espelid I. Impact of diagnostic criteria on the prevalence of dental caries in Norwegian children aged 5, 12 and 18 years. *Community Dent Oral Epidemiol* 1998; **26**: 87–94.
2. Årtun J, Thylstrup A. Clinical and scanning electron microscopic study of surface changes of incipient caries lesions after debonding. *Scand J Dent Res* 1986; **94**: 193–201.
3. Backer Dirks O. Posteruptive changes in dental enamel. *J Dent Res* 1966; **104**: 480–5.
4. Bader JD, Shugars DA. What do we know about how dentists make caries-related treatment decisions? *Community Dent Oral Epidemiol* 1997; **25**: 97–103.
5. Bader JD, Shugars DA, Bonito AJ. Systematic reviews of selected dental caries diagnostic and management methods. *J Dent Educ* 2001; **65**: 960–8.
6. Baelum V, Heidmann J, Nyvad B. Dental caries paradigms in diagnosis and diagnostic research. *Eur J Oral Sci* 2006; **114**: 263–77.
7. Bickel M, Cimasoni G. The pH of human crevicular fluid measured by a new microanalytical technique. *J Periodontal Res* 1985; **20**: 35–40.
8. Carvalho JC, Ekstrand KR, Thylstrup A. Dental plaque and caries on occlusal surfaces of first permanent molars in relation to stage of eruption. *J Dent Res* 1989; **68**: 773–9.
9. Carvalho JC, van Nieuwenhuysen J-P, Maltz M. Traitement non opératoire de la carie dentaire. *Réal Clin* 2004; **15**: 235–48.
10. Carvalho JC, Silva EF, Gomes RR, Fonseca JAC, Mestrinho HD. Impact of enamel defects on early caries development in preschool children. *Caries Res* 2011; **45**: 353–60.
11. Da Costa-Silva CM, Jeremias F, Souza JF, Cordeiro RCL, Santos-Pinto L, Zuanon ACC. Molar–incisor hypomineralization: prevalence, severity and clinical consequences in Brazilian children. *Int J Paediatr Dent* 2010; **20**: 426–34.
12. De Amorim RG, Figueiredo MJ, Leal SC, Mulder J, Frencken JE. Caries experience in a child population in a deprived area of Brazil, using ICDAS II. *Clin Oral Invest* 2012; **16**: 513–20.
13. Dean HT, Arnold FA, Elvove E. Domestic water and dental caries. *Public Health Rep* 1942; **57**: 1155–79.
14. Deery C, Hosey MT, Waterhouse P. *Paediatric cariology*. London: Quintessence Publishing Ltd, 2004: 9–30.
15. Ekstrand KR, Qvist V, Thylstrup A. Light microscope study of the effect of probing in occlusal fissures. *Caries Res* 1987; **21**: 368–74.
16. Ekstrand KR, Kuzmina I, Bjørndal L, Thylstrup A. Relationship between external and histological features of progressive stages of caries in the occlusal fossa. *Caries Res* 1995; **29**: 243–50.
17. Ekstrand KR, Ricketts DNJ, Kidd EAM. Reproducibility and accuracy of three methods for assessment of demineralization depth on the occlusal surface. *Caries Res* 1997; **31**: 224–31.
18. Elfrink MEC, ten Cate JM, Jaddoe VWV, Hofman A, Moll HA, Veerkamp JSJ. Deciduous molar hypomineralization and molar incisor hypomineralization. *J Dent Res* 2012; **91**: 551–5.
19. Farah R, Monk BC, Swain MV, Drummond BK. Protein content of molar–incisor hypomineralisation enamel. *J Dent* 2010; **38**: 591–6.
20. Fejerskov O. Concepts of dental caries and their consequences for understanding the disease. *Community Dent Oral Epidemiol* 1997; **25**: 5–12.
21. Fejerskov O, Luan W-M, Nyvad B, Budtz-Jørgensen E, Holm-Pedersen P. Active and inactive root surface caries lesions in a selected group of 60- to 80-year-old Danes. *Caries Res* 1991; **25**: 385–91.
22. Frank RM, Brendel A. Ultrastructure of the approximal dental plaque and the underlying normal and carious enamel. *Arch Oral Biol* 1966; **11**: 883–912.
23. Gold SI, Hasselgren G. Peripheral inflammatory root resorption. A review of the literature with case reports. *J Clin Periodontol* 1992; **19**: 523–34.

24. Gordan VV, Riley JL, Geraldeli S, Rindal DB, Qvist V, Fellows JL, Kellum HP, Gilbert GH. Repair or replacement of defective restorations by dentists in The Dental Practice-Based Research Network. *JADA* 2012; **143**: 593–601.
25. Heitmüller D, Thiering E, Hoffmann U, Heinrich J, Manton D, Kühnisch J, Neumann C, Bauer CP, Heinrich-Weltzien R, Hickel R. Is there a positive relationship between molar incisor hypomineralisations and the presence of dental caries? *Int J Paediatr Dent* 2013; **23**: 116–24.
26. Hintze H, Wenzel A, Danielsen B, Nyvad B. Reliability of visual examination, fibre-optic transillumination, and bite-wing radiography, and reproducibility of direct visual examination following tooth separation for the identification of cavitated carious lesions in contacting approximal surfaces. *Caries Res* 1998; **32**: 204–9.
27. Hujoel PP, Mäkinen KK, Bennett CB, Isokangas PJ, Isotupa KP, Pape Jr HR, Lamont RJ, DeRouen TA, Davis S. Do caries explorers transmit infections within persons? An evaluation of second molar caries onsets. *Caries Res* 1995; **29**: 461–6.
28. Ismail AI. Visual and visuo-tactile detection of dental caries. *J Dent Res* 2004; **83** (Spec Iss C): C56–66.
29. Ismail AI. Diagnostic levels in dental public health planning. *Caries Res* 2004; **38**: 199–203.
30. Ismail AI, Brodeur J-M, Gagnon P, Payette M, Picard D, Hamalian T, Olivier M, Eastwood BJ. Prevalence of non-cavitated and cavitated carious lesions in a random sample of 7–9-year-old schoolchildren in Montreal, Quebec. *Community Dent Oral Epidemiol* 1992; **20**: 250–5.
31. Ismail AI, Sohn W, Tellez M, Amaya A, Sen A, Hasson H, Pitts NB. Reliability of the International Caries Detection and Assessment System (ICDAS): an integrated system for measuring dental caries. *Community Dent Oral Epidemiol* 2007; **35**: 170–8.
32. Jablonski-Momeni A, Stachniss V, Ricketts DN, Heinzel-Gutenbrunner M, Pieper K. Reproducibility and accuracy of the ICDAS-II for detection of occlusal caries in vitro. *Caries Res* 2008; **42**: 79–87.
33. Katz RV. The clinical diagnosis of root caries: issues for the clinician and the researcher. *Am J Dent* 1995; **8**: 335–41.
34. Kidd EAM, Beighton D. Prediction of secondary caries around tooth-colored restorations. *J Dent Res* 1996; **75**: 1942–6.
35. Kidd EA, Pitts NB. A reappraisal of the value of the bitewing radiograph in the diagnosis of posterior approximal caries. *Br Dent J* 1990; **169**: 195–200.
36. Kidd EAM, Joyston-Bechal S, Beighton D. Marginal ditching and staining as a predictor of secondary caries around amalgam restorations: a clinical and microbiological study. *J Dent Res* 1995; **74**: 1206–11.
37. Knottnerus JA, van Weel C. General introduction: evaluation of diagnostic procedures. In: Knottnerus AJ, ed. *The evidence base of clinical diagnosis. Theory and methods of diagnostic research*. London: BMJ Books, 2002: 1–17.
38. Last JM. *A dictionary of epidemiology*. 4th ed. Oxford: Oxford University Press, 2001.
39. Leppäniemi A, Lukinmaa PL, Alaluusua S. Nonfluoride hypomineralizations in the permanent first molars and their impact on the treatment need. *Caries Res* 2001; **35**: 36–40.
40. Lijmer JG, Bossuyt PM. Diagnostic testing and prognosis: the randomised controlled trial. In: Knottnerus AJ, ed. *The evidence base of clinical diagnosis*. London: BMJ Books, 2002: 61–80.
41. Loesche WJ, Svanberg ML, Pape HR. Intraoral transmission of *Streptococcus mutans* by a dental explorer. *J Dent Res* 1979; **58**: 1765–70.
42. Lussi A. Comparison of different methods for the diagnosis of fissure caries without cavitation. *Caries Res* 1993; **27**: 409–16.
43. Machiulskiene V, Nyvad B, Baelum V. Prevalence and severity of dental caries in 12-year-old children in Kaunas, Lithuania. *Caries Res* 1998; **32**: 175–80.
44. Machiulskiene V, Nyvad B, Baelum V. A comparison of clinical and radiographic caries diagnoses in posterior teeth of 12-year-old Lithuanian children. *Caries Res* 1999; **33**: 340–8.
45. Machiulskiene V, Nyvad B, Baelum V. Comparison of diagnostic yields of clinical and radiographic caries examinations in children of different age. *Eur J Paediatr Dent* 2004; **5**: 157–62.
46. Manji F, Fejerskov O, Baelum V. The pattern of dental caries in an adult rural population. *Caries Res* 1989; **23**: 55–62.
47. Manji F, Fejerskov O, Baelum V, Luan W-M, Chen X. The epidemiological features of dental caries in African and Chinese populations: implications for risk assessment. In: Johnson NW, ed. *Dental caries. Markers of high and low risk groups and individuals*, Vol. 1. Cambridge: Cambridge University Press, 1991: 62–99.
48. Mejàre I, Källestål C, Stenlund H. Incidence and progression of approximal caries from 11 to 22 years of age in Sweden: a prospective radiographic study. *Caries Res* 1999; **33**: 93–100.
49. Merriam-Webster. http://www.merriam-webster.com/dictionary/diagnosis. Accessed October 27, 2014.
50. Mjör IA. Clinical diagnosis of recurrent caries. *J Am Dent Assoc* 2005; **136**: 1426–33.
51. Nyvad B, Fejerskov O. Active root surface caries converted into inactive caries as a response to oral hygiene. *Scand J Dent Res* 1986; **94**: 281–4.
52. Nyvad B, Fejerskov O. Assessing the stage of caries lesion activity on the basis of clinical and microbiological examination. *Community Dent Oral Epidemiol* 1997; **25**: 69–75.
53. Nyvad B, Machiulskiene V, Baelum V. Reliability of a new caries diagnostic system differentiating between active and inactive caries lesions. *Caries Res* 1999; **33**: 252–60.
54. Nyvad B, Machiulskiene V, Baelum V. Construct and predictive validity of clinical caries diagnostic criteria assessing lesion activity. *J Dent Res* 2003; **82**: 117–22.
55. Nyvad B, Machiulskiene V, Fejerskov O, Baelum V. Differential diagnosis of dental caries, dental fluorosis and localized opacities of non-fluoride origin. *Eur J Oral Sci* 2009; **117**: 161–8.
56. Pitts NB. The use of bitewing radiographs in the management of dental caries: scientific and practical considerations. *Dentomaxillofac Radiol* 1996; **25**: 5–16.
57. Pitts NB. Modern concepts of caries measurement. *J Dent Res* 2004; **83** (Spec Iss C): C43–7.
58. Pitts NB, Fyffe HE. The effect of varying diagnostic thresholds upon clinical caries data for a low prevalence group. *J Dent Res* 1988; **67**: 592–6.
59. Pitts NB, Rimmer PA. An *in vivo* comparison of radiographic and directly assessed clinical caries status of posterior approximal surfaces in primary and permanent teeth. *Caries Res* 1992; **26**: 146–52.
60. Raper HR. Practical clinical preventive dentistry based upon periodic roentgen-ray examinations. *J Am Dent Assoc* 1925; **12**: 1084–100.
61. Sellos MC, Soviero VM. Reliability of the Nyvad criteria for caries assessment in primary teeth. *Eur J Oral Sci* 2011; **119**: 225–31.
62. Thylstrup A, Fejerskov O. Clinical appearance of dental fluorosis in permanent teeth in relation to histologic changes. *Community Dent Oral Epidemiol* 1978; **6**: 315–28.
63. Thylstrup A, Fejerskov O. Clinical and pathological features of dental caries. In: Thylstrup A, Fejerskov O, eds. *Textbook of clinical cariology*. Copenhagen: Munksgaard, 1994: 111–57.
64. Thylstrup A, Bruun C, Holmen L. *In vivo* caries models – mechanisms for caries initiation and arrestment. *Adv Dent Res* 1994; **8**: 144–57.
65. Weerheijm KL, Jälevik B, Alaluusua S. Molar–incisor hypomineralisation. *Caries Res* 2001; **35**: 390–1.
66. WHO. *Oral health surveys. Basic methods*. 4th edn. Geneva: World Health Organization, 1997.
67. Wulff HR. What is understood by a disease entity? *J R Coll Physicians Lond* 1979; **13**: 219–20.
68. Wulff HR, Gøtzsche PC. *Rational diagnosis and treatment: evidence-based clinical decision-making*. 3rd ed. Oxford: Blackwell Science, 2000.
69. Zubcevic M, Nyvad B. Invasiv cervikal rodresorption – et overset klinisk problem? In: Holmstrup P, ed. *Odontologi 2007*. Copenhagen: Munksgaard Danmark, 2007: 127–40.

12

Additional caries detection methods

H. Hintze, A. Lussi, F. Cuisinier, and B. Nyvad

Introduction

Because of the less than perfect visual–tactile caries examination – visual–tactile inspection having a rather good ability to rule out a caries lesion but a moderate ability to rule in a lesion (see Chapter 10) — several detection tools have been developed to improve the efficiency and accuracy of caries diagnosis. Radiography is the most commonly used additional diagnostic tool for such purposes. More recently, caries diagnostic principles based on light and electrical current have been introduced in an attempt to further improve the accuracy of caries detection. The basic philosophy behind the use of these additional diagnostic tools is to help the dentist to identify caries lesions that are difficult to detect clinically. However, as we shall learn, every diagnostic method has benefits and limitations, and it is not obvious that methods based on new technologies are better than old and well-established ones. The aim of this chapter is to describe the performance of some commonly available additional diagnostic tools for caries detection and to discuss their application and usefulness in clinical practice.

Radiography

Indications for radiography

Prescription of a radiograph requires that there is an indication that the *additional diagnostic information (additional to clinical examination) obtained by the radiographic examination is likely to benefit the patient and outweigh the potential disadvantages of the method* [24]. This implies that radiographs should not be taken without a prior clinical examination indicating a problem that needs further consideration before final diagnosis or treatment can be decided. Such a strategy may sound rather restrictive. However, radiographs are not harmless. There is always an exposure to ionizing radiation. X-ray photons can damage the DNA in the chromosomes and ultimately lead to the formation of a tumor, particularly related to the brain, salivary glands, and thyroid gland. The risk of a tumor caused by a particular X-ray dose is dose dependent, and since individual doses for basic dental radiography are low, being equivalent to a few hours/days of natural background radiation, the risk connected with dental radiology is considered to be very low. Nevertheless, identical radiographs taken in the same

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd

individual during a long life might increase the radiation risk. In that context, it should be remembered that radiation risk is lower in elderly persons than it is in young persons with a high cell turnover and in whom dental radiography is most frequently performed.

Based on the above, it is clear that radiographs should always be taken on the basis of individual needs. Similarly, it is apparent that the use of radiography for screening purposes in large patient groups is not recommended [24].

What does the dental radiograph show?

Dental radiographs show differences in mineral content of the dental hard tissues. Since demineralizations such as dental caries do not absorb X-ray photons to the same extent that sound enamel and dentin do, mineral losses might appear only when the tooth has lost a certain amount of mineral (Fig. 12.1). Intraoral radiographs represent a summation of all structures passed by X-ray photons. Owing to the summation phenomenon, very shallow initial caries lesions and small cavities in the enamel are not visible in dental radiographs. Another important shortcoming of dental radiographs is that they cannot show activity because caries lesion activity is a surface texture phenomenon (see Chapter 11). From *one* radiograph it is possible only to disclose and estimate the depth of a caries lesion. If a *second* radiograph taken at a later time shows that the depth of an existing lesion has progressed, it may be concluded that the lesion was active. However, based on radiographic lesion depth alone, it cannot be predicted whether the lesion might progress in the future.

Figure 12.1 Bitewing radiograph showing radiolucencies in nearly all approximal surfaces due to caries.

Radiographic technique

The most effective radiographic technique for caries diagnostics is the bitewing technique, which is an intraoral, paralleling technique. However, other techniques – even undertaken with extraoral X-ray units – might also be used. Whichever technique is used, the requirement for radiographs used to detect caries is that they have a dark density and a good contrast, ensuring optimal differentiation of the various hard tissues. In radiographs with light density and poor contrast, existing lesions might be overlooked (false-negative diagnoses) (Fig. 12.2), whereas the opposite – that nonexistent lesions are detected (false-positive diagnoses) – might be the case in radiographs with a very dark density [81]. Furthermore, radiographs used for caries detection should image the relevant teeth with optimal sharpness and without overlaps between approximal surfaces.

Intraoral bitewing technique

The bitewing technique depicts the crowns of the maxillary and mandibular teeth and the top of the alveolar crest on the same image receptor (Fig. 12.1). To place the image receptor correctly in relation to the teeth in need of the examination, it is necessary to position the receptor in a

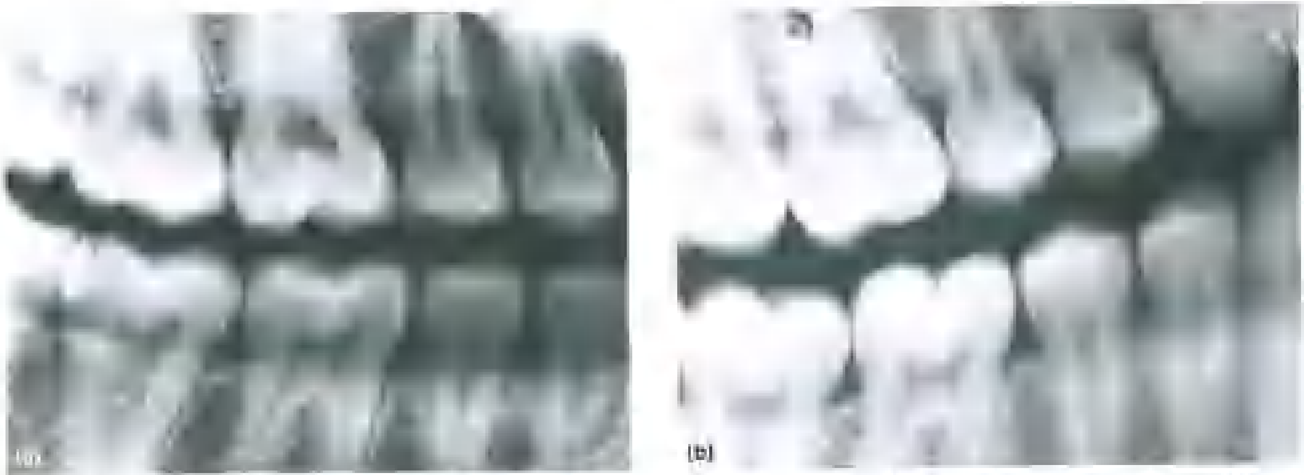


Figure 12.2 (a) A 25-year-old presenting with toothache in the lower right first molar (46). The bitewing radiograph reveals a deep occlusal dentin lesion in 46. (b) Bitewing radiograph taken less than 2 years previously. It is far too light, without contrast, and useless for caries diagnosis.

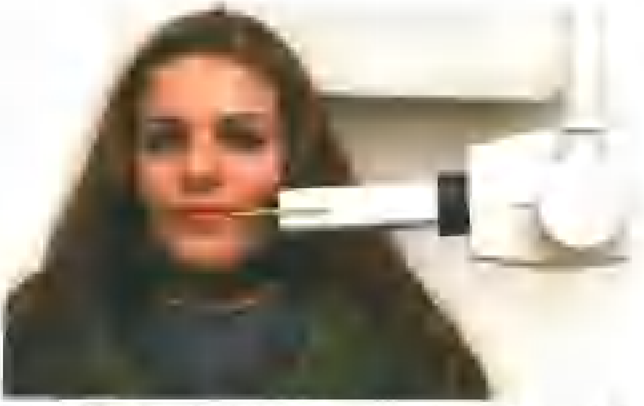


Figure 12.3 A bitewing radiograph is being taken. A film holder supports the film lingually and the patient closes together on a part of this holder. A beam-aiming device helps the operator to position the tube so that the beam is directed at right angles to the film.

Figure 12.4 A bitewing radiograph on a size 2 image receptor covering as many surfaces as possible when the receptor is placed with its middle behind the upper first molar. Dentin caries is present in the distal surface of the upper right first premolar. Note also lesion in enamel.

holder with a bite part placed often right in the middle of the receptor. When the receptor is placed in the holder, both parts should be placed in a comfortable position orally to the teeth/surfaces to be examined (Fig. 12.3). The X-ray beam should be aligned between the maxillary and mandibular teeth and parallel with the occlusal plane. To succeed predictably it is desirable to use a holder with a beam-aiming device which ensures that the X-ray beam passes perpendicular through the interproximal tooth spaces and ensures that the X-ray beam is oriented correctly in relation to the image receptor to avoid cone-cuts. The long axis of the image receptor for bitewings in the posterior part of the mouth is usually oriented horizontally, but it can be oriented vertically if the incisors are examined.

To obtain the best contrast in intraoral bitewing radiographs, a rectangular collimator (tube) with a size fitting the size of the image receptor should be used instead of the traditional circular tube. The usual smaller size of a rectangular tube reduces the amount of scattering radiation produced from the tissue in front of the receptor compared with a circular tube and thereby improves the image contrast. Rectangular collimation of the X-ray beam will further reduce the effective dose to the patient by up to 50% [76].

In teenagers and adults, a size 2 image receptor is traditionally used for bitewings of premolars and molars, whereas in young children a size 1 receptor might be more useful for comfortable placement of the receptor in close contact with the teeth to be examined. A large size 3 receptor specifically designed for bitewing radiography is not recommended, however, as it often results in several overlaps between neighboring approximal surfaces and cone-cuts where a rectangular collimation fitting the size of a size 2 receptor is used. In adults, two size 2 bitewing radiographs are needed to cover all surfaces of premolars and molars from one side of the mouth. However, because of the relatively low caries prevalence in many contemporary populations it may be appropriate to perform bitewing examination of only those surfaces that are assumed to be carious based on the clinical examination, or surfaces that are assumed to have a high risk of caries progression [30] (see later in this chapter). This will often result in the use of only one radiograph per side (Fig. 12.4).

Image receptors

Image receptors for intraoral radiography consist of conventional films and digital receptors consisting of either a sensor or a phosphor plate. Conventional films have been in use for more than a century, but these will without doubt disappear from the market in the near future in favor of receptors for digital radiography, which has advantages such as:

- being dynamic – meaning that the radiograph can be altered in relation to a number of parameters influencing the interpretation of specific tissue/disease characteristics;
- being fast – meaning short time from exposure to image display;
- being reusable – meaning that the receptor is useable again and again after a simple cleaning in between different patients;
- offering possibilities of working with programs for automated caries detection and subtraction technology for monitoring lesion progression, although at the moment no such accurate facilities are available;
- facilitating easy exchange of radiographs between colleagues, meaning that a radiograph can be sent electronically to, for example, a specialist for a second opinion while the patient is seated in the dental chair waiting for the answer;
- storage might be easier as it requires only a minimum of space on a computer hard disc with a safe back-up.

Many studies have shown that caries lesions can be detected as accurately from digital radiographs as from conventional film-based radiographs [31, 34]; however, less is known about how digital images should be displayed, enhanced [25, 26], and viewed to obtain the highest diagnostic quality. In addition, little is known about the costs of digital radiographs in comparison with film radiographs. Even though digital radiography does not make use of developing machines and chemicals, it requires image receptors (which are much more expensive than conventional films) and computers and monitors instead of light boxes. Whether investment and current expenditures for the different techniques are comparable and how they might influence the patient, the dentist, and society remain to be established.

Conventional film

A conventional film captures only a small percentage of the X-ray photons that reach it, it needs chemical processing (which is time consuming), and it represents a static image in which the radiographic characteristics (density, contrast, magnification, and sharpness) cannot be changed once the film has been developed. The fastest film on the market today is the F-speed film. This film requires a 25% lower radiation dose than the second fastest film type (the E-speed film) and should be preferred because the diagnostic capability does not differ between the two films [62].

It is recommended that, after developing, film radiographs are mounted in frames with dark borders and are interpreted on a light box with high luminance by the use of an X-ray viewer with built-in magnification. This should result in optimal conditions for assessment.

Digital receptors

Sensors

A sensor displays the radiographic image directly on a monitor almost immediately after exposure. The analogue electronic signal produced in the sensor is carried along a wire or as a radio signal (wireless sensor) to the computer where it is converted into a digital signal. Today, several sensor systems for intraoral radiography are available on the market, but all sensors are characterized by being much thicker than films. This makes them uncomfortable and difficult to position correctly in the mouth, resulting in more retakes. The largest sensor size is size 2, but often the active image area is smaller than the standard size 2, resulting in a smaller area depicted per sensor exposure compared with conventional film exposure. Some sensors are more sensitive to X-rays and require a lower radiation dose than conventional films do [31, 99], whereas others should be exposed with the same amount of radiation as conventional films.

It is generally recommended that digital radiographs are displayed on a monitor in their full resolution and that the monitor is placed in a room with subdued light for the ideal interpretation. From one study evaluating whether the quality and cost of the monitor has an influence on the diagnostic outcome, it was concluded that caries can be detected as accurately on a cheap monitor as on an expensive medical monitor [27].

Phosphor plates

An alternative digital receptor system consists of plates containing storage phosphor particles embedded in a polymer binder coated onto a plastic base with dimensions similar to the common conventional films. After exposure, information is stored in the phosphor particles. The information can thereafter be transferred to a computer and displayed as a digital dynamic radiograph by a read-out device based on a laser light scanner. In general, phosphor plates are more sensitive to radiation than conventional films are, but owing to the requirement of short scanning times the radiation dose used for intraoral image plates are often comparable to those needed for conventional films. Image plates are also sensitive to visible light and should, therefore, be protected in light-safe plastic envelopes. The protection material needed for each exposure on intraoral phosphor plates raises the costs of such digital radiographs.

Digital phosphor-based radiographs should be displayed and analyzed in the same way as sensor-based radiographs (see earlier).

Extraoral bitewing technique

In some newer-fashion panoramic units, programs for bitewing radiography are available. These bitewings are obtained on a conventional large film or digital receptor (sensor/phosphor plate) placed extraorally. Extraoral bitewings are characterized by large magnification and often they have substantial approximal overlaps since the X-ray beam cannot be aligned individually to the various approximal spaces (Fig. 12.5). Thus, they often demonstrate an inferior quality in comparison with intraoral bitewings, but they can be obtained in patients who are unable to open their mouth (e.g., fixtured because of jaw fracture) and in patients who are unable to have an intraoral image receptor behind the relevant teeth because of severe retching reflexes. Furthermore, they show the roots of the teeth, which raises the possibility also to examine the teeth's periapical conditions, which might be relevant in case of deep lesions or fillings and root canal treatments.

Radiographic detection of caries lesions

As said before, a certain amount of mineral must be lost before a carious demineralization can be perceived in the radiograph. The minimum amount of mineral loss to be detected will depend on the thickness of the surrounding soft and hard tissues and a number of physical and technical radiographic factors, such as receptor resolution, image density and contrast, projecting angles, and examiners' skills.

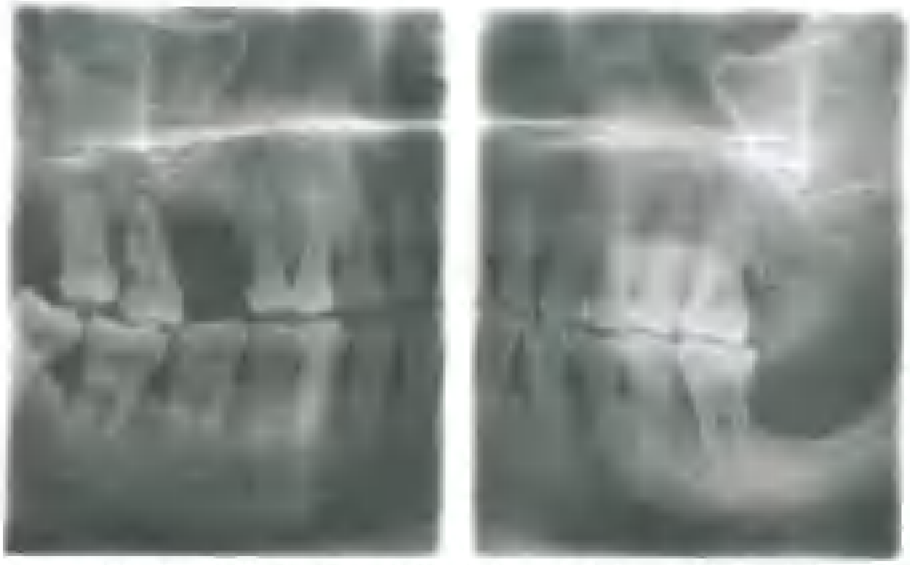


Figure 12.5 Bitewing radiographs obtained with a panoramic unit. Note distinct radiolucencies in the upper right second molar and premolar.

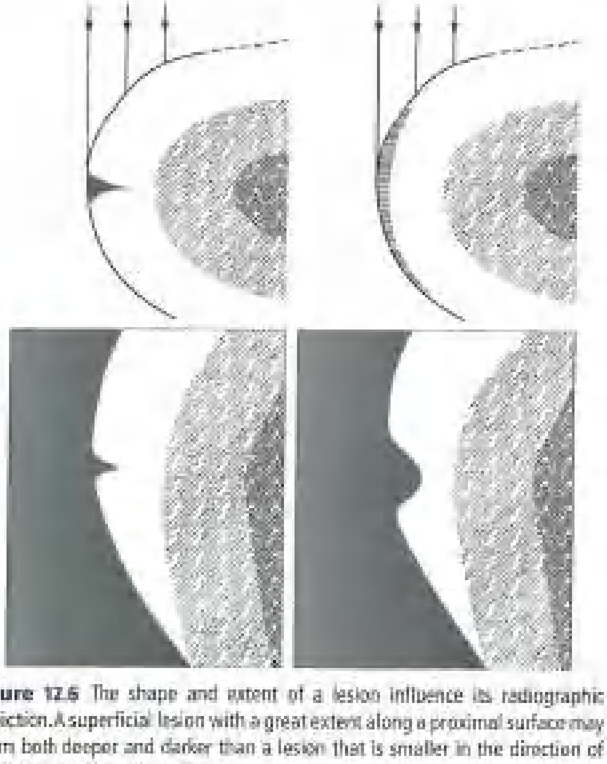


Figure 12.6 The shape and extent of a lesion influence its radiographic depiction. A superficial lesion with a great extent along a proximal surface may seem both deeper and darker than a lesion that is smaller in the direction of the X-rays but actually deeper.

Figure 12.7 Magnified radiograph of approximal caries lesions in enamel in lower left premolar and molar. The enamel lesions are depicted as radiolucent triangles with their bases towards the tooth surface. Note also 'cervical burnout' in the cervical part of the premolar.

Approximal surfaces

A caries lesion in a contacting approximal surface starts cervical to the contact point. The depth and extent of an approximal caries lesion will influence its radiographic appearance. Thus, a relatively deep but localized demineralization in enamel may result in a lesion that appears less severe than a superficial but widespread demineralization encircling the entire approximal surface (Fig. 12.6). Typically, the lesion in enamel presents as a radiolucent triangle with its broad base at the tooth surface and its apex towards the enamel–dentin junction (Fig. 12.7). When the lesion affects the dentin, another radiolucent area with its base towards the enamel–dentin junction and its vertex towards the pulp may be observed (Fig. 12.8).

From a radiograph it might be possible to estimate the depth of an approximal lesion fairly accurately [38], but it is impossible, based on radiography alone, to determine whether such

Figure 12.8 Magnified radiograph of approximal caries lesions in enamel and outer dentin in lower left molars.

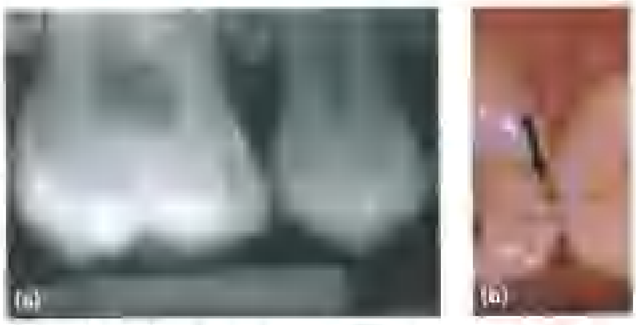


Figure 12.9 (a) Magnified radiograph showing dentin caries lesion in mesial surface of upper right molar and enamel caries lesion in distal surface of neighboring premolar. (b) Stepwise drilling of the dentin lesion revealed the presence of a micro cavity (arrow). This case illustrates that micro cavitation cannot be detected by radiography.

lesions are cavitated (Fig. 12.9). This is a serious drawback of the radiographic method because this means that radiographs cannot be used for deciding whether an operative or nonoperative intervention is required (see Chapters 11 and 19). Based on comparative clinical and radiographic studies, it has been possible to estimate the probability that defined radiographic stages of caries lesions may have developed a cavity (Table 12.1). According to these results, the probability of detecting a cavity at stages of radiographic enamel caries is low, in many studies in the order of less than 20% (Table 12.1). When the lesion has entered the outer third of the dentin the probability for detecting a cavity clinically increases to about 40% in recently examined populations [33, 68], depending on caries prevalence and the examiners conducting the examinations. Only when a lesion has penetrated into the inner two-thirds of the dentin does the chance of observing a cavity clinically increase to about 100% (Table 12.1). While such information is quite valuable for the clinician in helping to decide whether or not a lesion should be treated operatively, it has to be emphasized that radiography is merely an adjunctive diagnostic aid that must never stand alone. No caries lesion should be treated operatively before it has been affirmed clinically that such a decision may be justified. For example, it would be wrong to drill an outer dentin lesion that has presented as an inactive noncavitated lesion for years.

To assess properly whether an approximal carious lesion is cavitated or not, direct visual inspection and/or tactile examination are required. Although dentists may improve their clinical skills in visual–tactile caries examination, it is often impossible to get sufficient access to contacting approximal surfaces to perform an accurate diagnosis. Therefore, it has been suggested to separate the surfaces from their natural contacts, either by the use of orthodontic separation springs or elastics (see Fig. 11.29a and b). This procedure requires an extra dental visit and may be uncomfortable for the patient; therefore, it is not used routinely. Hence, dentists will always have to live with a certain uncertainty for a correct diagnosis in its entirety of approximal caries.

Occlusal surfaces

Enamel lesions in occlusal surfaces rarely result in perceptible radiographic changes. Usually, an occlusal lesion should have penetrated beyond the enamel–dentin junction before it can be imaged as a radiolucent spot or line in the dentin. Deep dentinal caries may be seen as a semicircular radiolucency with its base towards the enamel–dentin junction or as a manifest radiolucency between the enamel–dentin junction and the pulp (Fig. 12.10). The deeper the occlusal lesion, the easier it is to identify the lesion in a radiograph.

Contrary to some approximal surfaces, the caries status (activity and cavity) of occlusal surfaces may be determined directly by clinical examination. This is fortunate, because bitewing radiography does not add much supplementary information to the detection of occlusal caries [55, 36] (Fig. 11.30). Owing to the projection of the X-rays, the mineral loss of shallow noncavitated enamel lesions may simply be too small to be depicted in the radiograph. Deeper lesions, clinically identified because of the presence of dark shadows or microcavities, will usually manifest themselves as dentin lesion by radiography and thereby confirm the clinical diagnosis. However, this does not automatically imply that lesions should be drilled. In such lesions, radiography might be needed to estimate the depth of the lesion in relation to the pulp. It is self-evident that all occlusal surfaces imaged in bitewing radiographs should be examined for caries just as carefully as approximal surfaces.

'Hidden caries'

Several studies from the 1990s (e.g. [40, 98]) have shown that radiography can reveal a high number of occlusal and approximal caries lesions that remain undetected from a

Table 12.1 Percentages of cavitations in permanent teeth with radiographic approximal enamel and dentin caries found in *in vivo* studies [28].

Authors	Study sample, no. of surfaces	Validation method	Radiographic lesions clinically cavitated (total no. of surfaces)		
			Enamel	Outer dentin	Inner dentin
Rugg-Gunn [77]	Children (mean 13.9 yrs; $n = 460$), 370	Direct visual inspection of open contacts[a]	27% ($n = 75$)	100% ($n = 8$)	100% ($n = 4$)
Bille and Thylstrup [16]	Children (8–15 yrs), 158	Clinical assessment during cavity preparation[a]	16% ($n = 85$)	52% ($n = 58$)	100% ($n = 9$)
Mejàre *et al.* [59]	Children (14–15 yrs; $n = 63$), 598	Visual inspection after tooth extraction[b]	13% ($n = 129$)	100% ($n = 6$)	100% ($n = 6$)
Mejàre and Malmgren [57]	Children (7–18 yrs; $n = 43$), 60	Photographs taken during drilling and stepwise excavation following tooth separation[b]	61% ($n = 28$)	78% ($n = 32$)	—
Thylstrup *et al.* [95]	Children and adults, 660	Clinical assessment during cavity preparation[a]	10% ($n = 215$)	52% ($n = 330$)	88% ($n = 102$)
Pitts and Rimmer [65]	Children (5–15 yrs; $n = 211$), 1468	Direct visual examination following tooth separation[a]	2% ($n = 119$)	41% ($n = 22$)	100% ($n = 4$)
De Araujo *et al.* [20]	Students ($n = 168$), 77	Direct visual examination following tooth separation[b]	19% ($n = 58$)	90% ($n = 19$)	90% ($n = 19$)
Akpata *et al.* [1]	Adults (17–48 yrs), 108	Clinical assessment during cavity preparation and clinical examination of adjacent approximal surface after class II preparation[b]	13% ($n = 47$)	79% ($n = 43$)	100% ($n = 18$)
Lunder and von der Fehr [47]	140 teenagers (17–18 yrs; $n = 140$), 96	Assessment of stone dyes made from impressions following tooth separation[a]	30% ($n = 23$)	65% ($n = 23$)	—
Hintze *et al.* [33]	Adults (21–38 yrs; $n = 53$), 277–320	Direct visual examination following tooth separation Four individual examiners	Obs1: 6% ($n = 95$) Obs2: 3% ($n = 73$) Obs3: 4% ($n = 74$) Obs4: 4% ($n = 71$)	Obs1: 29% ($n = 28$) Obs2: 42% ($n = 19$) Obs3: 37% ($n = 35$) Obs4: 22% ($n = 32$)	Obs1: 50% ($n = 4$) Obs2: 100% ($n = 1$) Obs3: 80% ($n = 5$) Obs4: 44% ($n = 9$)
Ratledge *et al.* [68]	Adults (>16 yrs; $n = 32$), 54	Assessment of impressions following tooth separation[a]	—	64% ($n = 14$)	93% ($n = 40$)

[a] One examiner performed the validation.

[b] Two or more examiners performed the validation in consensus.

Figure 12.10 Magnified radiograph of deep occlusal dentin caries lesion in lower left first molar. The lesion appears as a semicircular radiolucency in dentin. No radiolucency is seen in enamel.

traditional clinical examination. However, the additional radiographic diagnostic yield of caries is strongly influenced by the choice of the clinical diagnostic criteria. When cavitation, is the threshold for recording a clinical caries diagnosis, radiography will often result in detection of a higher number of lesions than if noncavitated stages of caries are included in the clinical diagnosis [32, 55, 56]. Hence, the high prevalence of 'hidden' occlusal caries reported in some studies [97] may partly represent a bias due to inadequate clinical examination.

Radiographic detection of recurrent caries lesions

When caries develops in a surface with a restoration it is termed recurrent caries, even if it is a new lesion that occurs adjacent to a restoration (see Chapter 11). Recurrent caries is most frequently located cervical to an approximal restoration and radiographically it appears as a diffuse, radiolucent

Figure 12.11 *Recurrent caries on the distal surface of an upper left second molar (arrow).*

change without sharp borders (Fig. 12.11). Such a lesion might be easier to detect adjacent to a metallic restoration – which is imaged as a white, sharply demarcated object – as opposed to a composite restoration – which may have the same density as the lesion itself. Recurrent caries can sometimes be difficult to distinguish from a composite restoration. In such cases it may be helpful to look at the margins of the radiolucent change. The margins of a restoration will often be sharp and well defined, reflecting the borders of the preparation, whereas recurrent caries will show diffuse and ill-defined margins.

Recurrent caries should not be confused with *residual* caries, which is caries overlooked by excavation of the original lesion. However, in some cases residual caries is purposely left behind, such as during stepwise excavation (see Chapter 20). This underscores again the importance of not making treatment decisions on the basis of radiographs alone.

False-positive caries diagnoses in radiographs

Not every radiolucency observed in a dental radiograph represents caries. For example, incorrect horizontal and vertical angulation of the X-ray beam can result in an illusion of a caries lesion – a so-called false-positive diagnosis leading to misclassification. Similar errors may occur in cases where radiolucencies caused by anatomical variations of teeth (pits and groves), developmental defects in enamel, composite restorations without contrast, residual caries, and incorrect exposure or processing parameters are misinterpreted as caries (Fig. 12.12). Furthermore, it is important to distinguish 'cervical burnout' from dental caries to avoid false-positive caries diagnoses. Cervical burnout is a radiolucent band located in the cervical part of the mesial and distal aspects of a tooth, in the area between the enamel–cementum junction and the upper crest of the marginal bone (Fig. 12.7). This phenomenon occurs because the X-ray photons are absorbed differently by different parts of the tooth. As the crown and the root covered by bone absorb a high number of X-ray photons these areas are imaged rather radiopaque. By contrast, the cervical part of the tooth, being less compact, allows more X-ray photons to penetrate, resulting in an illusion of a radiolucency that sometimes might look like an approximal caries lesion. To distinguish cervical burnout from an approximal caries lesion it is important to remember the localization of the two different phenomena. Cervical burnout is always localized in the cervical part of the tooth – far below the approximal contact point – whereas an approximal caries lesion is localized just below the approximal contact point.

Figure 12.12 Bitewing radiograph of a patient with active caries lesions diagnosed clinically. The radiograph shows several radiolucencies in enamel in approximal surfaces of lower molars and premolar. Large radiolucency in dentin in distal surface of upper right first premolar resembling caries appeared clinically to be a composite filling without detectable caries (false-positive radiographic diagnosis). Note also the radiolucent area in the distal part of the occlusal surface of lower right second molar that might be caries.

To avoid false-positive caries diagnoses it is important that the radiographic caries diagnosis is always supported by a careful clinical examination.

Diagnostic validity of radiography for caries lesion detection

All diagnostic methods have inherent errors. In the examination for caries this means that lesions are sometimes diagnosed as being present in situations where no caries exists and that existing lesions are not diagnosed. The former error is termed a false-positive diagnosis, whereas the latter error is termed a false-negative diagnosis. In addition, the interpretation of bitewings is subject to variation both between and within examiners.

Accuracy

In a diagnostic process the aim is to diagnose diseased sites as diseased – termed 'true positives' – and healthy sites as healthy – termed 'true negatives' (Table 12.2). But with most diagnostic methods it is not possible to separate perfectly

Table 12.2 Expression of diagnostic accuracy for diseased and healthy surfaces.

Gold standard			
Test	Diseased	Healthy	Total
Diseased	True positive (TP)	False positive (FP)	TP + FP
Healthy	False negative (FN)	True negative (TN)	FN + TN
Total	TP + FN	FP + TN	*N*

Sensitivity TP/(TP + FN). Specificity TN/(FP + TN). *N* = TP + FP + TN + FN.

diseased sites from healthy sites. In the diagnosis for caries this means that sometimes carious surfaces are diagnosed as sound – termed 'false negatives' – and sound surfaces are diagnosed as carious – termed 'false positives' (Table 12.2). To express the extent the diagnostic test reflects the correct caries status the term *accuracy* is used. To test the accuracy of radiography for caries detection the 'true' caries status should be known. The true diagnosis is often called 'the gold standard.'

A highly accurate diagnostic method will be characterized by a receiver operating characteristic (ROC) curve that is high in the left side of the ROC space, resulting in a high ROC area (see Chapter 10). From *in vitro* studies, wide ranges of ROC areas for radiographic caries detection have been reported. Thus, ROC areas ranging from 0.55 to 0.88 have been found for the detection of approximal caries, whereas ROC areas of about 0.80 have been reported for the detection of occlusal caries. From the literature, there might be a tendency for ROC areas for occlusal caries detection to be somewhat higher than for approximal caries. The most obvious reason for this difference is the various thresholds for caries, since it may be easier to diagnose deep lesions in dentin (which is usually the threshold for occlusal lesions) more correctly than to diagnose shallow lesions in enamel (which is usually the threshold for approximal lesions) [101].

Reliability

For the detection of caries it is expected that two different dentists examining the same patient will perform identically – meaning that they can reproduce each other's results. This expectation, however, is not obtainable since all caries diagnostic methods are influenced by *inter-examiner* variation, which is the term used for expressing the performance of different examiners using the same method on the same patients. Hintze and Wenzel [29] evaluated the reliability for three dentists who examined 336 conventional bitewing radiographs for the presence and depth of caries lesions. The results showed large variations in the number of enamel and dentinal lesions recorded by each dentist (Fig. 12.13). One dentist found 42% more enamel lesions than another. The dentist who detected the highest number of dentinal lesions recorded nearly 88% more such lesions than the dentist who found the lowest number.

If the inter-examiner reliability for the three dentists referred to in Fig. 12.13 was calculated for the examiners two by two for the detection of dentinal lesions, the κ values (see Chapter 10) ranged from 0.25 to 0.50, expressing agreements varying from 'slight' to 'moderate' [43]. This is not impressive and is comparable to results found in several other studies about examiner performance for caries lesion detection in radiographs [62, 63]. It can be expected, however, that the deeper the lesions are the higher the examiner reliability is because such lesions will show themselves more clearly.

Factors determining the progression of caries in radiographs

Approximal caries

Over the years a number of studies have evaluated the progression of caries as observed in radiographs. Most of these studies have been conducted in children and adolescents. In particular, the studies by Mejàre and coworkers, who followed Swedish school children in the 1980s and 1990s offered clinically relevant information about a broad variety of parameters that may influence the progression of approximal lesions [58, 60, 61]. Such parameters include post-eruptive age of teeth; previous caries experience; primary vs. permanent teeth; tooth and surface types; lesion depth at baseline; risk of cavitation; caries/restoration status of neighboring surfaces.

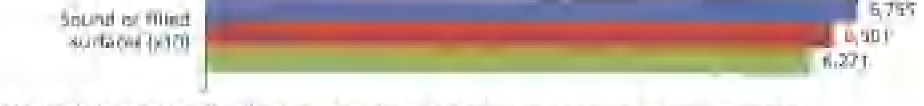


Figure 12.13 Number of caries lesions in enamel and dentin recorded from 336 bitewing radiographs by three dentists [29].

Post-eruptive age of teeth

The post-eruptive age of the teeth plays a significant role for the caries risk, possibly because over time the enamel becomes more resistant to caries along with its adaptation to the oral environment [12]. From studies in Swedish and American children, the median time for progression through the approximal enamel was estimated to be about 4 years for 10–11-year-olds and about double that in 17–22-year-olds [80]. The same tendency has been found in other studies [58]. Thus, the progression expressed in surfaces per 100 surfaces at risk per year for approximal enamel to outer dentin lesions was 7.4 in 13–15-year-olds, 4.9 in 16–19-year-olds, and 3.6 in 20–22-year-olds. The corresponding figures for outer dentin to inner dentin lesions in the same age groups were 32.5, 17.6, and 10.9 respectively [61]. These figures indicate that lesion progression is about two to three times faster among the youngest than among the eldest group.

These results might well be valid also for even younger individuals, as it has been observed that caries progression from the inner half of the enamel to the outer half of the dentin in the mesial surface of the first permanent molar in 8–11- and 12–22-year-olds is almost four times faster in the youngest than in the eldest age group [58]. The difference in caries development from sound to caries in the inner half of the enamel in the two age groups, however, was not found to be significantly different.

Previous caries experience

In general, individuals with a high number of lesions or restorations at baseline run a higher risk of rapid lesion progression than individuals with few or no lesions or restorations [84]. Thus, in Swedish children it was found that individuals with more than one approximal lesion/restoration at the age of 12–13 years had a two-and-a-half times higher risk for the development of new approximal enamel lesions over a 10-year period than individuals with one or no baseline lesions [60]. Therefore, information about previous caries history is important for the prediction of the patient's future caries risk.

Primary vs. permanent teeth

In general, caries lesion progression is faster in approximal surfaces in primary teeth than in permanent teeth, possibly because the enamel of primary teeth is considerably thinner than in permanent teeth. In 6–12-year-old children the lesion progression rate – expressed as the number of surfaces found to progress out of 100 surfaces at risk in 1 year – from sound to outer enamel demineralization was found to be 11.3 in primary second molars compared with 4.6 in permanent molars. Corresponding values for lesion progression from the inner enamel to the outer dentin were found to be 32.6 for primary molars and 20.5 for permanent molars [58]. These values demonstrate convincingly that lesion progression through the primary teeth is more rapid than in permanent teeth because of the smaller thickness of the enamel.

Tooth and surface types

In the permanent dentition, approximal caries lesion progression may vary considerably for the different tooth and surface types. Mejàre *et al.* [60] showed that the risk of caries development from sound to caries in the inner part of enamel for first molars was 1.3 times higher than for second molars and 1.4 times higher than for second premolars. In first molars, the risk of caries development was significantly higher in the distal than in the mesial surfaces irrespective of whether the molar was placed in the maxilla or the mandible. Also, a difference between teeth was found for lesion progression from the inner half of the enamel to the outer half of the dentin. Among maxillary teeth the mesial surface of the second molar was the surface with the highest risk (about 8.5 surfaces per 100 at risk per year) (Fig. 12.14a),

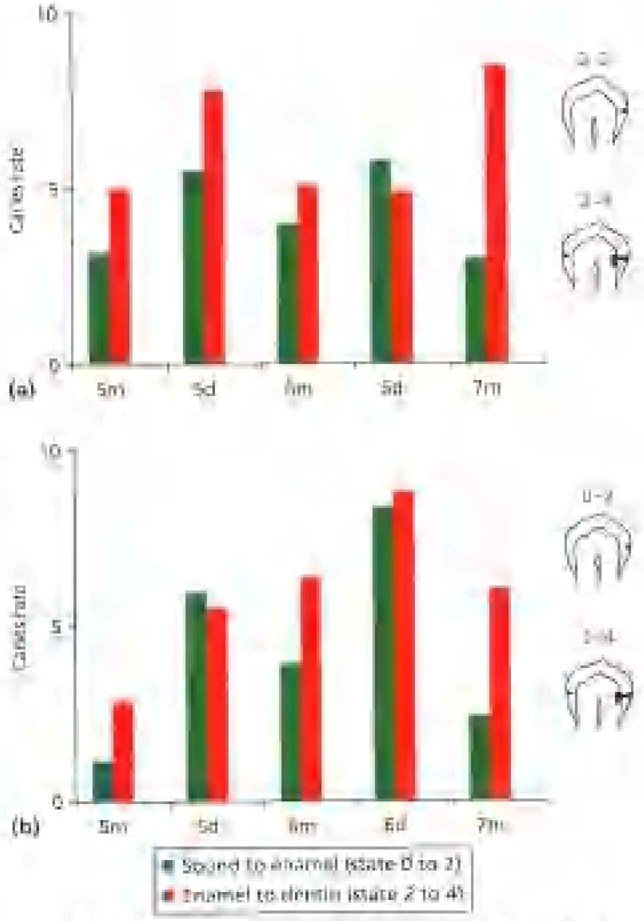


Figure 12.14 Annual caries rates (number of new lesions/100 tooth surface years) of (a) upper and (b) lower posterior approximal surfaces from 12 to 22 years of age by tooth surface. From [60]. Reproduced with permission of Karger Publishers.

whereas among mandibular teeth the distal surface of the first molar was the surface with the highest risk (8.3 surfaces per 100 at risk per year) (Fig. 12.14b). Comparison of lesion progression between distal surfaces in the two premolars showed a significantly higher rate for second than for first premolars, and for second maxillary premolars the distal surface had a progression rate that was 1.7 times higher than the rate for mesial surfaces. This information may be useful for the dental practitioner when searching for noncavitated lesions during the clinical examination and when timing radiographic follow-up of previously observed lesions.

Lesion depth at baseline

It is generally agreed that deep lesions progress faster than superficial lesions, indicating that the progression through enamel is slower than through dentin. This is probably a reflection of the fact that dentin lesions are more likely to be cavitated than are enamel lesions (Table 12.1). In individuals 11–22 years of age the mean progression rates for new and established enamel and dentin caries lesions were 3.9, 5.4, and 20.3 per 100 surface-years respectively [60], meaning that 3.9 of 100 sound surfaces at baseline developed enamel caries during 1 year, 5.4 of 100 surfaces with enamel caries at baseline progressed into the outer dentin during 1 year, and 20.3 of 100 surfaces with outer dentin caries at baseline progressed into the inner dentin during 1 year (Fig. 12.15). The mean progression values varied significantly, however, for the different teeth and for the different surfaces in the same tooth.

Risk of cavitation

Higher progression rates for dentin lesions than for enamel lesions and sound surfaces may be connected with the higher occurrence of cavitations in deep lesions. The frequency of cavitated approximal lesions detected radiographically has been evaluated by various validation methods in several studies (Table 12.1). For radiographic enamel lesions the percentages of cavitation range from 2 to 61, whereas the percentages of radiographic inner dentin lesions with cavitation range from 44 to 100. Reasons for the relatively broad ranges in the percentages of cavitations for the various lesion depths may be due to differences in the samples (age, gender, tooth types, caries activity, caries experience, etc.), the radiographic depth scales, the veracity of the gold standard, and examiner recording variations with both the radiographic registration scale and the gold standard. In particular, the latter parameter might have a strong influence on the percentage of radiographic lesions that are identified as clinically cavitated. Furthermore, Lunder and von der Fehr [47] have shown that the risk of cavitation of radiographically detected caries lesions penetrating into the inner enamel and outer dentin depends on the caries activity of the individual. In caries-active adolescents with six or more new dentin lesions during the past 3 years, lesion cavitation was much more frequent than in adolescents with little or no caries activity.

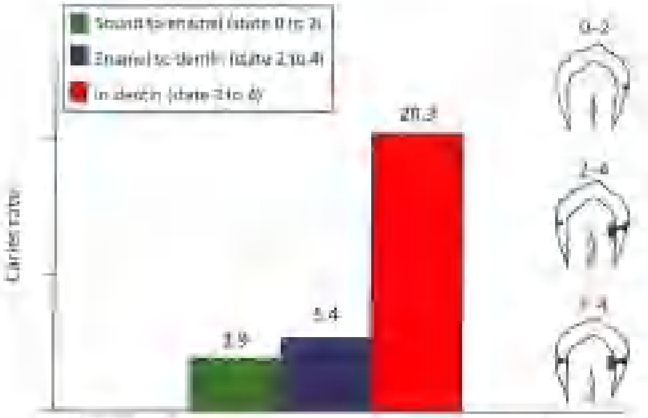


Figure 12.15 Annual caries rates (number of new lesions/100 tooth-surface years) of posterior approximal surfaces from 12 to 22 years of age. Median values of all surfaces. From [60].

Caries/restoration status of neighboring surfaces

Preparation damage of neighboring approximal surfaces in permanent teeth seems to be a frequent phenomenon. Thus, up to 70% of surfaces that are adjacent to a surface with a restoration have been found to show unintended burr damages [67], and such surfaces are subsequently restored four times more frequently than surfaces that are adjacent to a surface without restoration.

In a study by Stenlund *et al.* [85] it was shown that the risk of caries development in an approximal surface – from the distal surface of the first premolar to the mesial surface of the second molar – was several times higher if the surface was adjacent to a carious surface instead of neighbor to a sound surface (Table 12.3). Furthermore, it was documented that if caries (restored/unrestored) was present in the distal surface of the second primary molar the risk of caries in the neighboring mesial surface of the first permanent molar was 15 times higher than if no caries was present in the primary molar (Fig. 12.16).

Table 12.3 Risk of approximal caries development in relation to caries status of the neighboring surface in 11/13–21/22-year olds [85]

Surface	IR[a]	
	Neighbor to a sound surface	Neighbor to a carious surface
7 mesial	1.1	13.5
6 distal	3.7	20.2
6 mesial	3.0	11.1
5 distal	3.6	14.9
5 mesial	1.7	21.7
4 distal	2.1	16.6

Reproduced with permission of John Wiley & Sons.

[a] Number of surfaces showing progression per 100 surfaces at risk per year.

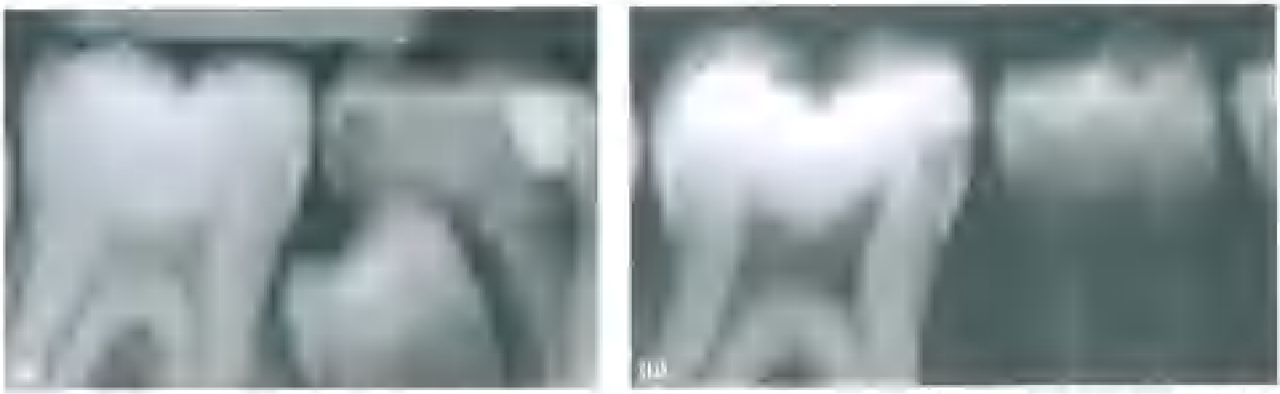


Figure 12.16 Two magnified radiographs showing caries lesion progression over 4 years in the same patient. (a) Dentin caries lesion in the distal surface of lower right primary second molar – a condition that increases the risk of caries development in the neighboring surface. (b) Four years later the second premolar had erupted and the mesial surface of the permanent first molar showed dentin caries.

Table 12.4 Risk of development of new lesions in occlusal surfaces in relation to tooth types [61].

Age/years	Progression of occlusal caries lesions/IR*		
	1st molars	2nd molars	All teeth
12–15	4.4	6.7	2.0
16–19	2.3	3.0	0.9
20–27	1.5	2.7	0.7

Reproduced with permission of Karger Publishers.
*IR: number of surfaces showing progression per 100 surfaces at risk per year.

Occlusal caries

Similar to approximal surfaces, development and progression of caries in permanent occlusal surfaces appears to be highest during the first 5 years after tooth eruption. A longitudinal study in 12–27-year-olds showed that most new lesions in occlusal surfaces developed among 12–15 year-olds (Table 12.4) [61]. No data are available for progression of occlusal lesions in primary teeth.

Timing of radiographic follow-up

There are no fixed rules for how often radiographs should be repeated in different individuals. As stated at the beginning of this chapter, it is important that radiographs are prescribed on the basis of individual needs, following a visual–tactile caries examination. If fixed time intervals between bitewings are used, many individuals might be exposed without any benefit. When Lith and Gröndahl [45] estimated the time interval until the next bitewing examination in Swedish children based on the number and extent of approximal lesions in baseline radiographs, it was found that for most children the usual 1 year interval could be extended without a concomitant risk of missing lesions developing into deep dentin. Hence, the study supported an individualized scheduling of bitewing examinations.

The following clinical situations may call for a bitewing caries examination:

- multiple new active caries lesions (cavitated and/or noncavitated);
- discolorations (e.g., dark shadows) or defects of the teeth that cannot immediately be explained or evaluated on the basis of a clinical examination;
- large/extensive approximal fillings with gingival margins suspected having recurrent caries;
- follow-up of nonoperative caries treatment.

It has been shown that clinical caries increments are correlated with radiographic caries increments in the permanent dentition of young teenagers [64]. This implies that the dentist can be fairly certain that, when there are new/active caries lesions clinically, new lesions may also be detected in radiographs. In such cases it is advised to record the extent and severity of the lesions radiographically as a landmark for future lesion progression. In contrast, it may be presumed that patients with a sound gingival status, no signs of active lesions, and risk factors controlled (Chapter 17) are less likely to benefit from a new bitewing examination. Repeated bitewings with short intervals (e.g., yearly) should only be justified on very rare occasions, for example, in patients with dubious or poor control of caries risk factors and/or sites with increased risk of lesion progression, such as outer dentin lesions. In most patients with clinical signs of caries control, bitewing examination may not be needed for several years.

However, timing of radiographic examinations is challenging because caries activity is not constant. Changes in caries risk may follow lifestyle changes (e.g., dietary changes, changes in social environment, reduction in saliva following the use of medications) or simply periods with less focus on dental hygiene (see Chapter 17). Therefore, it is important that the dentist pays attention to changes in a patient's lifestyle when deciding to perform the next bitewing examination.

Such information should be combined with clinical observations in the patient that are known to influence the rate of lesion progression, for example, patient age, caries prevalence, risk of surface cavitation, caries status of neighboring surface. In some patients, previous bursts of caries activity may be a decisive factor for making a radiographic examination. In other patients, the emergence of a dry mouth may call for radiographic follow-up. Improvement of the clinical status of a patient, such as changes in caries lesion activity and improved control of risk factors, should always delay the time for radiographic follow-up. This may not always come forward when the dentist meets the patient for the first time, but when the dentist gets to know the patient it may become obvious that frequent bitewing examinations are not needed.

In order to meet the difficulties with timing of bitewing examinations, some scientific communities [33] recommend that patients be allocated to risk categories, with each category operating with fixed time intervals for repeated bitewing examinations. However, while such an approach seems attractive and easy to handle, it is hardly justified to prescribe bitewings according to a fixed scheme because of limited additional diagnostic information obtained by mass screening of individuals that have undergone a thorough clinical caries examination [55, 56]. Moreover, it should be appreciated that frequent radiographic examinations may lead to overtreatment because of false-positive diagnoses, particularly in low caries populations. Therefore, patients receiving frequent bitewing examinations might paradoxically end up with a poorer dental status than if such examinations had not been performed (see Chapter 10) [13]. The risk of overtreatment due to false-positive diagnoses can be minimized if the clinician brings together complementary information from both the clinical and the radiographic examination. Clearly, radiographs must never be used as the sole criterion for making treatment decisions.

It is often ignored that the information gained from successive bitewing radiographs is restricted to observing *past* changes in lesion development. Radiographic examination cannot say anything about current caries activity or the probability for future lesion progression, as might be derived from a clinical caries examination using lesion activity assessment (see Chapter 11). Moreover, traditional radiography is based on qualitative evaluations of mineral loss. This has prompted the search for alternative quantitative methods for assessing the progression of caries lesions. Such methods will be addressed next.

Methods based on light and electrical current

Caries detection methods based on light and electrical current have been introduced in the hope that quantitative approaches might overcome some of the problems associated with conventional radiography, such as use of ionizing radiation and the crude categorization of lesions according to depth of penetration. If lesion progression and arrest could be quantified by a device on a continuous scale, longitudinal monitoring might be simple: just apply the device again and observe in which direction the numbers change. The concept is hugely appealing, so no wonder researchers have made much effort to develop, test, and improve such devices.

All quantitative methods for caries detection are based on the interpretation of physical signals. These are causally related to one or more features of a caries lesion. Table 12.5 shows the types of physical principles that may be used and the corresponding diagnostic methods that are going to be described.

Methods based on light

Physico-chemical principles

Sound enamel consists mainly of crystals (Chapters 5 and 9) that are very densely packed, giving the enamel a glass-like, translucent appearance. The yellow–white color of teeth is the result of the dentin shining through the translucent enamel layer. Light that shines on a tooth will, in part, penetrate the tooth and be scattered or absorbed inside. *Scattering* is the process in which the direction of a photon is changed without loss of energy. *Absorption* is the process in which photons lose their energy, mostly by conversion into heat. Since scattering does not cause the light to be lost, scattering may occur many times consecutively along the path, a phenomenon called multiple scattering. After one or more scatter events, a photon may reach the tooth surface again and leave the tooth. *Backscatter* is the phenomenon where photons leave through the surface by which they entered. When photons leave through another surface, the phenomenon is called *diffuse transmission*.

In a sound tooth, scattering is much more probable than absorption. In dentin, both scattering and absorption occur more frequently than in the enamel. The whitish

Table 12.5 Overview of diagnostic methods based on light and electrical current.

Physical principle	Application in caries diagnosis
Light	Laser fluorescence measurement DIAGNOdent®/DIAGNOdent pen Fluorescence VistaProof, SOPROLIFE®, SOPROCARE Quantitative light-induced fluorescence (QLF) Transillumination FOTI, DIFOTI, DIAGNOcam
Electrical current	Electrical conductance measurement (ECM) Electrical impedance measurement

appearance of teeth is due to the fact that absorption is much lower than scattering [87]. Primary teeth show more scattering and, therefore, have a whiter appearance than permanent teeth.

In a white spot caries lesion, scattering is stronger than in sound enamel. The penetrating photons change direction more often in carious enamel than in sound enamel and are generally back-scattered before they reach the dentin. Therefore, such a lesion appears whiter than the surrounding sound parts of the tooth. Brown lesions are due to the presence of light-absorbing material in the lesion and/or exogenous stain.

A slight increase in enamel porosity leads to a change in the optical properties of enamel in such a way that light is increasingly scattered. This is presumed to be primarily due to the fact that the remaining small mineral particles in the lesion are embedded in water rather than in mineral-rich sound enamel [7], thereby increasing the difference in refractive index (RI) between the scattering photon and its environment. The RI of enamel apatite is 1.62, and the RIs of water and air are 1.33 and 1.00 respectively. Thus, when the pores of a white spot enamel lesion are filled with water, the light scattering is less than when the lesion is dry and the pores are filled with air. After dehydration, the enamel lesion looks whiter as a result of more scattered light. This is why a careful clinical examination must be preceded by drying of the teeth (see Chapter 11).

Laser light is composed of electromagnetic waves with equal wavelengths and equal phases. Some materials possess the characteristic of fluorescence when illuminated with light. Fluorescence is a property of some manmade and natural materials that absorb energy at certain wavelengths and emit light at longer wavelengths [69]. By using a filter through which only the fluorescent light may pass, the fluorescent light can be selected and measured. The intensity of the fluorescent light is proportional to the amount of light absorbed and of the amount of material present. Fluorescence of dental hard tissues has been known for a very long time [14], and fluorescence spectra have been presented by several authors [8, 27, 83].

The chromophores causing fluorescence of the dental hard tissues are not clearly identified. The blue fluorescence of enamel was assigned to dityrosine [19]. It seems likely that most of the yellow fluorescence stems from proteinic chromophores' cross-links between chains of structural proteins [78]. Moreover, dental enamel and dentin possess the characteristic of so-called autofluorescence. Caries lesions, plaque, and microorganisms also contain fluorescent substances. The red–infrared fluorescence of caries has been assigned to a protoporphyrin, which is present as a bacterial breakdown product [42]. The difference between the fluorescence of sound tooth tissues and that of a caries lesion can be made visible by laser- or light-induced fluorescence. This is the basis of many detection devices used today, such as QLF, DIAGNOdent, DIAGNOdent pen, VistaProof, SOPROLIFE, and the Spectra system [21, 54, 69, 86, 91].

Devices based on fluorescence (semi-quantitative)

DIAGNOdent

When red light with a wavelength of 655 nm is applied, caries-induced changes in teeth lead to increased fluorescence [27]. The DIAGNOdent (KaVo Biberach, Germany) is based on this principle. The fluorescent light is measured and its intensity is thought to be an indication of the depth of the caries lesion. The intensity of the fluorescent light is displayed as a number ranging from 0 to 99, with 0 indicating a minimum and 99 a maximum of fluorescent light.

Since its first presentation, many studies have extensively investigated this laser fluorescence device for occlusal and smooth surface caries detection. The threshold between occlusal caries limited to enamel and caries into dentin was found to be around 18 under humid conditions [51, 52, 79]. Clinically visible white spot lesions are measurable with this device. However, the very early stages of demineralization with no fluorophores from bacteria present are not captured by the DIAGNOdent. Based on systematic reviews of the performance of DIAGNOdent for detecting caries, it was concluded that DIAGNOdent is more sensitive than traditional diagnostic methods [10, 59, 70] (Table 12.6). However, the higher likelihood of false-positive diagnoses when using the DIAGNOdent means that it should not be relied on as a clinician's primary diagnostic method. The main problem is that bacteria and calculus at the depth of grooves and fissures may generate false-positive results.

Recently, a new laser device (DIAGNOdent pen, DD pen, KaVo Biberach, Germany) was introduced, which, in addition to occlusal surfaces, allows fluorescence from the approximal surfaces of teeth to be captured [54, 88]

Table 12.6 Sensitivities and specificities of different additional caries diagnostic devices when used in occlusal surfaces, compared with visual–tactile caries examination (data retrieved from [11, 68]). *Data reported for enamel level, except for QLF (dentin level).*

Device	Sensitivity	Specificity
Visual examination	0.59	0.72
Visual–tactile examination	0.39	0.94
Bitewing radiography	0.39	0.91
DIAGNOdent	0.87	0.50
SOPROLIFE	0.93	0.63
QLF	0.80	0.86
ECM	0.73	0.87
FOTI	0.21	0.88

(Fig. 12.17). Comparison of the DIAGNOdent pen with the DIAGNOdent on occlusal surfaces revealed a similar detection performance of the two devices [48]. For both DIAGNOdent devices, careful tilting on occlusal surfaces around the spot to be measured is crucial for an adequate detection (Fig. 12.18). When using the instrument approximally it is important to apply it on the oral and facial side of the surface under detection and to move the tip underneath the contact point (Fig. 12.19). This allows the dentist to search for demineralized areas with the highest fluorescence. However, owing to the thickness of the tip (0.4 mm), access to the approximal surface is often impossible.

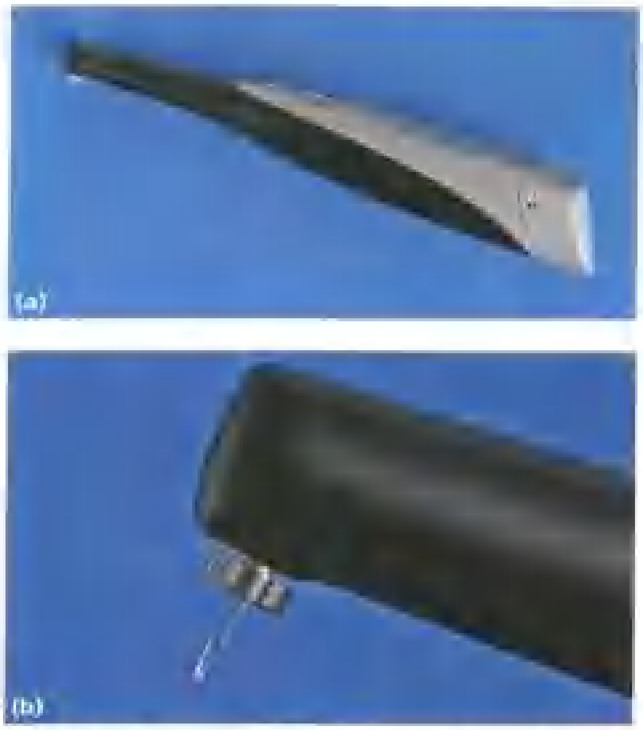


Figure 12.17 (a) The DIAGNOdent pen with the tip for detection of occlusal caries. (b) Close-up of the tip for approximal detection and the knob for turning it around.

The DIAGNOdent devices have shown good intra-examiner reproducibility [52, 54, 94]. This means that the DIAGNOdent can potentially be used for monitoring the carious process. However, it has to be taken into account that monitored differences of four units and below are not clinically relevant [48].

VistaProof

The intraoral fluorescence camera VistaProof (Dürr Dental, Bietigheim-Bissingen, Germany) was developed for caries detection and emits blue light at 405 nm and captures fluorescent images from dental surfaces [91]. The specific software filters and quantifies the fluorescence emitted by the tissue and converts the relationship between green and red fluorescence into numerical values, according to the pixel numbers in each image [91]. This results in numerical values ranging from 0 to 3 with optimal cut-off limits of 0–1.1 (sound surfaces), 1.2–1.7 (enamel caries), and >1.7 (dentin caries). The performance of VistaProof in recent studies was rather similar to the performance of the DIAGNOdent [22, 75, 82].

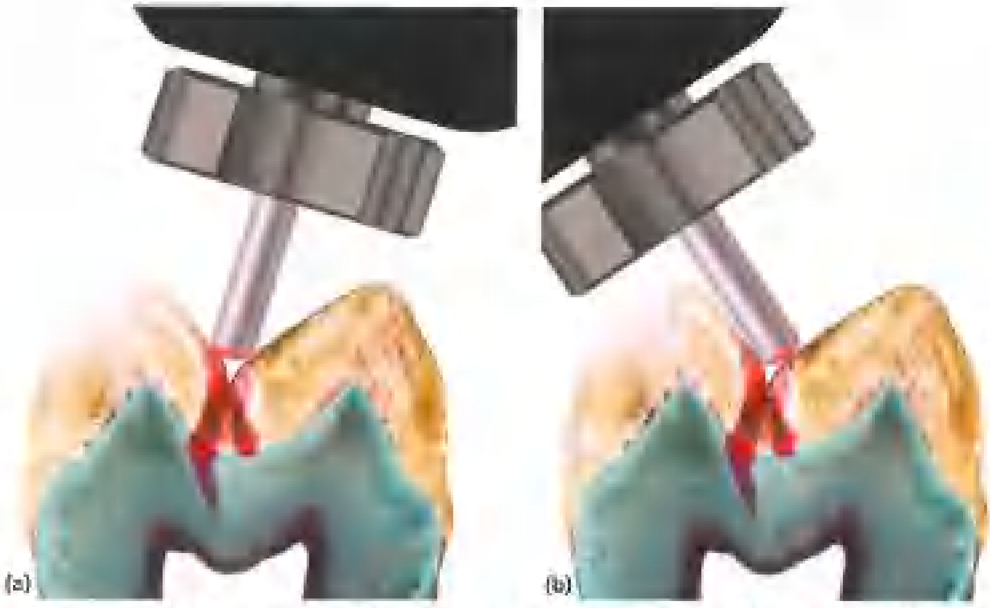


Figure 12.18 Procedure for occlusal detection with the DIAGNOdent pen. The tip has to be rotated around the vertical axis (a, b). This ensures that the tip picks up fluorescence from the slopes of the fissure walls where the carious process may start. The position shown in (b) gives no signal.

Figure 12.19 Procedure for approximal detection with the DIAGNOdent pen. (a) Measurement of the fluorescence (zero value) of a sound spot on the coronal part of the facial surface. (b) Measurement at the approximal site. The approximal space is carefully penetrated.

SOPROLIFE and SOPROCARE

The SOPROLIFE system combines the advantages of a visual detection method with a high-magnification oral camera and a laser fluorescence device. The SOPROLIFE fluorescence tool operates in daylight and blue fluorescence modes. In the daylight mode, the system uses four white light-emitting diodes (LEDs); in the fluorescence mode, it uses four blue LEDs emitting a wavelength of 450 nm. The handpiece allows for collecting pictures at different distances to a tooth, resulting in different magnifications [69, 86]. The SOPROCARE device combines a caries diagnostic mode similar to SOPROLIFE with a perio mode for gingival inflammation assessment. The performance in an *in vivo* study of occlusal surfaces using ICDAS as the gold standard for caries was as follows: DIAGNOdent (sensitivity 87%/specificity 50%), SOPROLIFE (sensitivity 93%/specificity 63%), SOPROLIFE blue fluorescence (sensitivity 95%/specificity 55%) [69] (Table 12.6). Hence, the diagnostic capability of the SOPROLIFE showed a rather similar performance to that of the DIAGNOdent, resulting in a low specificity in return for a high sensitivity.

A clinical advantage of this device compared with similar devices is the image magnification and quality, and the possibility of images to be reviewed over time [69, 86].

In addition to the diagnostic mode, SOPROLIFE has been promoted in a treatment mode for the discrimination of infected and noninfected dentin during caries excavation. It was suggested that when an open caries lesion is illuminated with the fluorescent camera, sound dentin appears acid-green, highly infected dentin appears black–grey–green, affected/demineralized dentin appears bright red, and arrested caries appears dark red [90]. It was hypothesized that the dark red color might reflect modifications of the dentin matrix that correlated with the Maillard reaction [41, 44]. The treatment mode of the SOPROLIFE camera is still at the experimental stage and remains to be validated in clinical and microbiological studies before it can be recommended for use in clinical practice. What will emerge in Chapter 22 is that, intriguingly, the observed color differences of the dentin may be of no clinical consequences, as the dentin, its level of infection and possibly its integrity, changes after the cavity is sealed.

Quantitative light-induced fluorescence

Demineralization of a dental hard tissue results in loss of its autofluorescence: the natural fluorescence. As early as in the 1920s this phenomenon was suggested to be useful as a tool for diagnosing dental caries [15]. More recently, laser light was used to induce fluorescence of enamel [17, 18]. The tooth was illuminated with an argon laser ($\lambda = 488\,\text{nm}$). Demineralized areas appeared as dark areas because the fluorescence of a caries lesion viewed by QLF is lower than that of sound enamel.

The laser fluorescence method was developed further for *in vivo* quantification of mineral loss in natural enamel lesions using a color microvideo charge-coupled device (CCD) camera and computed image analysis [21] (Fig. 12.20). To enable calculation of fluorescence loss in the caries lesion,

Figure 12.20 Clinical use of QLF. Courtesy of S. Tranæus.

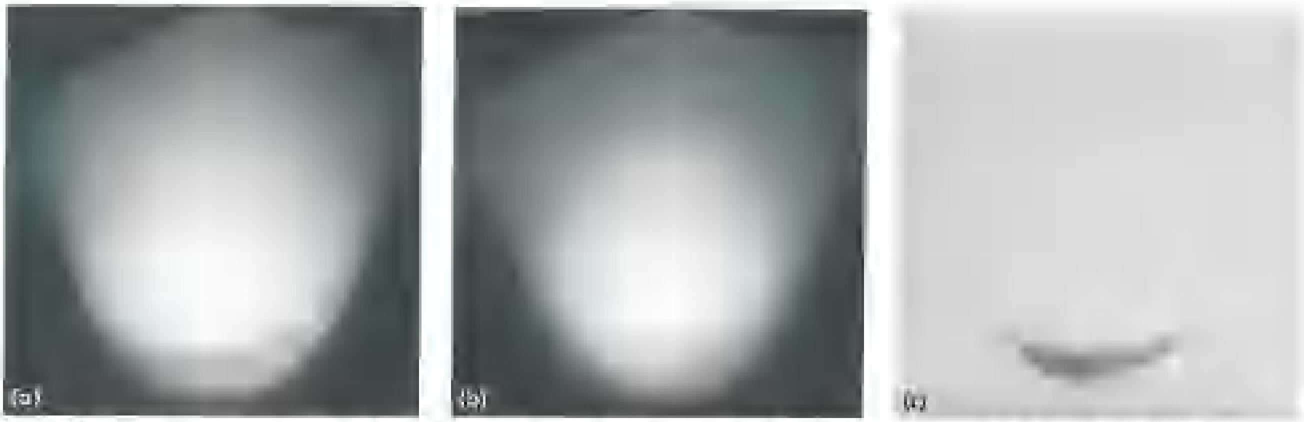


Figure 12.21 Principles of the QLF method for quantification of an enamel caries lesion. (a) The actual fluorescence image of a caries lesion; (b) the reconstructed image in which fluorescence radiance of the original sound enamel at the lesion site was reconstructed by interpolation of values indicating sound enamel around the lesion. (c) The difference between the measured and the reconstructed values gave the resulting fluorescence loss in the lesion.

the fluorescence of the lesion is subtracted from the fluorescence of the surrounding sound tissue. The difference between the actual values and the reconstructed ones gives the resulting fluorescence loss. Figure 12.21a shows the actual fluorescence image of a caries lesion; Fig. 12.21b shows the reconstructed image in which the fluorescence of the original sound enamel at the lesion site was taken from the fluorescence of the sound enamel around the lesion. The difference between the measured and the reconstructed values gave the resulting fluorescence loss in the lesion (Fig. 12.21c). From this, three lesion quantities may be obtained: mean fluorescence loss over the lesion (%), maximum fluorescence loss in the lesion (%), and area of the lesion (mm^2). To facilitate clinical studies at different locations, a small, portable system for intraoral use was developed with a regular light source and filter system to replace the laser source [3]. The illumination system consists of a 50 W xenon microdischarge arc lamp provided with an optical bandpass filter with a maximum wavelength of 370 nm to produce blue light. The light illuminating the tooth is transported through a liquid-filled light guide. The portable QLF device was validated against chemical analysis and microradiography for the assessment of mineral changes in enamel and compared with results from measurements with the laser light equipment [3]. It was concluded that QLF was a sensitive (Table 12.6) and reproducible method for quantification of early enamel lesions.

The QLF method has been applied successfully in a few clinical studies for monitoring remineralization of incipient enamel lesions in smooth surfaces of caries-active adolescents [4, 93].

Attempts to adapt the QLF method for occlusal caries diagnosis have been made. Preliminary results comparing the QLF method with other diagnostic methods showed that QLF was more sensitive than electrical conductance for measurements of shallow occlusal lesions [6, 66, 92]. Discrimination of deeper lesions, however, was not possible. An updated portable QLF device showed good performance on occlusal surfaces when used in a clinical setting [2].

Digital imaging fiber-optic transillumination

Fiber-optic transillumination (FOTI) has been introduced as a qualitative diagnostic method by which teeth are transilluminated. The observation of 'shadows' has been associated with the presence of caries lesions. Use of the method is described in Chapter 11. The major problem associated with the accuracy of FOTI is the low sensitivity [11]. However, the specificity is quite high (88–100%), suggesting that FOTI might be useful for ruling out sound surfaces (Table 12.6).

The technique of digital imaging fiber-optic transillumination (DIFOTI) was introduced to improve the sensitivity by replacing the human eye with a CCD receptor [39] (Fig. 12.22). A clinical validation study determined the ability of DIFOTI to detect caries [5]. Deciduous molars of 119 children (aged 8–12 years) were examined at 6-month intervals throughout a 2-year study period. Exfoliated teeth were collected for the validation of lesion presence and depth using polarized light microscopy as the gold standard. Results indicated that lesions involving the inner half of enamel were better detected than lesions restricted to the outer half of enamel for both approximal and occlusal surfaces. In other words, DIFOTI may not be able to detect very shallow lesions. Such lesions are better detected using a visual examination (Table 12.6).

Another transillumination system, representing a further development of DIFOTI, the near-infrared light transillumination (NILT) (DIAGNOcam, KaVo, Biberach, Germany), was introduced in 2013. This camera uses an illuminating wavelength of 780 nm and it seems to be possible to capture

Figure 12.22 DIFOTI for the detection of occlusal caries. Courtesy of M. Ando.

different stages of approximal carious lesions. DIAGNOcam has not yet been tested and validated in clinical studies.

Methods based on electrical current

When an electrical current passes through a material the electrical properties of this material determine the extent to which the current is conducted. Biomaterials with high concentrations of fluids and electrolytes are more conductive than materials with low concentrations. It follows that immature, porous enamel is more conductive than mature enamel, and dentin is more conductive than enamel. When a current is applied by placing an electrode onto a tooth surface the electrical conductance of all material between this electrode and the contra-electrode, which is generally held in the hand, can be measured. Since all of these materials have high concentrations of electrolytes except for dental enamel, the measurement of the conductance is mainly that of enamel. Demineralized sites in enamel, sites with a high pore volume, and cavities can be detected by measuring the conductance.

Impedance is the measure of the degree to which an electric circuit resists electric-current flow when a voltage is impressed across two electrodes. Impedance, like electrical resistance expressed in ohms, is the ratio of the voltage impressed across a pair of terminals to the current flow between those electrodes. Every material has different electrical impedance determined by its molecular composition: some materials have high electrical impedance, while others have low electrical impedance. Carious tissues have a much lower electrical impedance (conduct electricity much better) than sound tooth tissues.

Electrical conductance measurements

The value of site-specific ECMs in caries diagnosis has been the subject of many *in vitro* [9, 71, 100] and *in vivo* studies [50, 72–74, 96]. The reported sensitivities of ECM in diagnosing dentinal carious lesions of permanent premolar and molar teeth ranged from 0.67 to 0.96, whereas the specificities ranged from 0.71 to 0.98, reflecting an acceptable performance. When analyzing ECM data obtained by different researchers [36] it might be concluded that there was a consistent, systematic, nonrandom measurement variation. This was assumed to be related to factors such as insufficient and unpredictable probe contact (Fig. 12.23), which may explain the aforementioned wide ranges of sensitivities and specificities reported (Table 12.6).

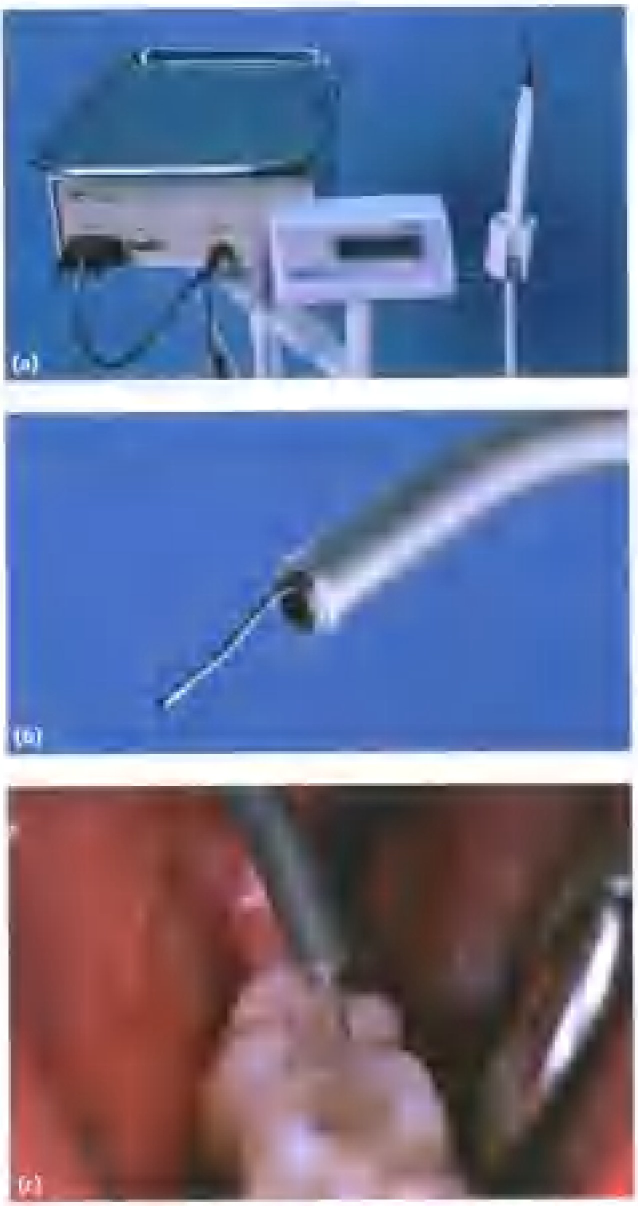


Figure 12.23 (a) ECM. The electrical caries monitor with its tip. (b) Air flows through the tube to dry the tooth surface. (c) The measurement of a spot. To prevent the current from 'leaking' through a superficial layer of moisture to the gingiva, an airflow is applied to dry the occlusal tooth surface around the probe.

Electrical impedance measurements

The principle of electrical impedance has been applied to detect caries lesions at approximal sites of teeth [35, 46]. A system used for electrical impedance is called CarieScan. This device displays numbers giving some information about the severity of the carious process. A recent *in vivo* study judged the device as unsuitable for use in the primary dentition [88]. There are no *in vivo* studies available that have tested the device in the permanent dentition.

Are the additional methods suitable for use in clinical practice?

Having reviewed a broad range of caries detection tools it is apparent that there is no perfect caries diagnostic method. Likewise, no caries diagnostic test evaluated so far can claim superiority over that of a clinical caries examination. Table 12.6 shows an overview of the sensitivities and specificities of the different diagnostic technologies described in this chapter compared with a visual–tactile caries examination. No single test is close to 100% sensitivity and 100% specificity. Some tests are better in ruling in a caries lesion (high sensitivity and low specificity; e.g., QLF, DIAGNOdent, and SOPROLIFE), whereas others are better in ruling out a caries lesion (high specificity and low sensitivity; e.g., visual–tactile caries examination and bitewing radiography). A carefully conducted visual–tactile caries examination has an acceptable balance of a relatively high proportion of true-positive diagnoses while at the same time having a low proportion of false-positive diagnoses that might lead to incorrect treatment decisions. A visual caries examination is superior to bitewing radiography for detecting shallow lesions confined to enamel, whereas radiography may be better in detecting deep/cavitated dentin lesions in approximal surfaces (see Fig. 11.30).

The semi-quantitative devices such as DIAGNOdent, VistaProof, and SOPROLIFE have been launched because of their ease of use and their ability to detect caries in enamel and dentin. However, some of these devices also detect deposits like plaque, calculus, or staining, and all these confounders give false-positive readings. This, in turn, will lead to overtreatment of a patient, as a dentist may falsely intervene operatively. Mechanical approaches to eliminate the deposits/stain from occlusal fissures may by itself lead to false-positive diagnoses because of difficulties in removing fluorescent polishing paste [22, 49] or because of artifacts induced by cleaning with air abrasion [89].

The QLF method offers a combination of quantitative data and display of the fluorescent image of the tooth on the monitor, which makes QLF instructive for demonstrating lesion progression and/or arrest. The high sensitivity of the method makes it an appropriate research tool for *in vivo* monitoring of mineral changes in early white spot enamel lesions. However, like other methods based on fluorescent light, the clinical use of QLF may be complicated by confounding factors such as plaque and stain.

Advantages of DIFOTI and other methods based on transmission of light include a high specificity, the absence of ionizing radiation, and the possibility for images to be reviewed over time. However, training for interpretation of images with this technique is required. Furthermore, there is currently no objective way to quantify caries with these systems.

It is self-evident that any diagnostic method intended for longitudinal monitoring of caries lesions must prove a good reproducibility within and between examiners. Apart from clinical and radiographic examination, only QLF has been used for monitoring lesions longitudinally.

Can the methods serve as adjuncts to a visual–tactile caries examination?

It is often claimed that additional diagnostic methods, despite their lack of accuracy, may be used as an adjunct (or second opinion) to visual inspection for caries. This thinking probably stems from the concept of additional diagnostic yields (see Chapter 10), inferring that the more lesions detected the better the diagnostic performance. However, second opinions on lesion detection may not be as innocent as they sound. In a recent study by Baelum *et al.* [13], the additional effect on the number of treatment decisions of adding a bitewing examination to a visual–tactile caries examination was evaluated. It was shown that while the supplementary use of bitewings resulted in a 40% increase in the number of treatment decisions, the correct number of treatment decisions (operative or nonoperative, as determined by the presence or absence of cavitation) dropped by 10% (from 60% to 50%). Thus, bitewing examination did not correct errors made by the visual–tactile examination but rather added more errors to the faulty visual examination! Clinicians should be aware of the risk of making more erroneous treatment decisions when adding a supplementary diagnostic tool.

References

1. Akpata ES, Farid MR, Al-Saif K, Roberts EAU. Cavitation at radiolucent areas on proximal surfaces of posterior teeth. *Caries Res* 1996; 30: 313–6.
2. Alammari MR, Smith PW, de Josselin de Jong E, Higham SM. Quantitative light-induced fluorescence (QLF): a tool for early occlusal dental caries detection and supporting decision making in vivo. *J Dent* 2013; 41: 127–32.
3. Al-Khateeb S, ten Cate JM, Angmar-Månsson B, de Josselin de Jong E, Sundström G, Exterkate RA, Oliveby A. Quantification of formation and remineralization of artificial enamel lesions with a new portable fluorescence device. *Adv Dent Res* 1997; 11: 502–6.
4. Al-Khateeb S, Forsberg CM, de Josselin de Jong E, Angmar-Månsson B. A longitudinal laser fluorescence study of white spot lesions in orthodontic patients. *Am J Orthod Dentofacial Orthop* 1998; 113: 595–602.
5. Ando M. Performance of digital imaging fiber-optic transillumination (DIFOTI) for detection of non-cavitated primary caries: Preliminary report. In: Stookey GK, Kambara M, eds. *Early detection of dental caries: Proceedings of the 7th Annual Indiana Conference*. Indiana University, Indianapolis, 2006: 41–57.

6. Ando M, Eggertsson H, Isaacs RL, Analoui M, Stookey GK. Comparative studies of several methods for the early detection of fissure lesions. In: Stookey GK, ed. *Early detection of dental caries II. Proceedings of the 4th Annual Indiana Conference*. Indiana University, Indianapolis 2000; 279–99.
7. Angmar-Månsson B, ten Bosch JJ. Optical methods for the detection and quantification of caries. *Adv Dent Res* 1987; 1: 14–20.
8. Armstrong WG. Fluorescence characteristics of sound and carious human dentine preparations. *Arch Oral Biol* 1963; 8: 79–90.
9. Ashley PF, Blinkhorn AS, Davies RM. Occlusal caries diagnosis: an in vitro histological validation of the electronic caries monitor (ECM) and other methods. *J Dent* 1998; 26: 83–8.
10. Bader JD, Shugars DA. A systematic review of the performance of a laser fluorescence device for detecting caries. *JADA* 2004; 135: 1413–26.
11. Bader JD, Shugars DA, Bonito AJ. Systematic reviews of selected dental caries diagnostic and management methods. *J Dent Educ* 2001; 65: 960–8.
12. Baelum V, Machiulskiene V, Nyvad B, Richards A, Vaeth M. Application of survival analysis to carious lesion transitions in intervention trials. *Community Dent Oral Epidemiol* 2003; 31: 252–60.
13. Baelum V, Hintze H, Wenzel A, Danielsen B, Nyvad B. Implications of caries diagnostic strategies for clinical management decisions. *Community Dent Oral Epidemiol* 2012; 40: 257–66.
14. Benedict HC. Note on the fluorescence of teeth in ultra-violet rays. *Science* 1928; 67: 442.
15. Benedict HC. The fluorescence of teeth as another method of attack on the problem of dental caries. *J Dent Res* 1929; 9: 274–5.
16. Bille J, Thylstrup A. Radiographic diagnosis and clinical tissue changes in relation to treatment of approximal carious lesions. *Caries Res* 1982; 16: 1–6.
17. Bjelkhagen H, Sundström F. A clinically applicable laser luminescence method for the early detection of dental caries. *IEEE J Quant Elect* 1981; 17: 266–8.
18. Bjelkhagen H, Sundström F, Angmar-Månsson B, Rydén H. Early detection of enamel caries by the luminescence excited by visible laser light. *Swed Dent J* 1982; 6: 1–7.
19. Booij M, ten Bosch JJ. A fluorescent compound in bovine dental enamel matrix compared with synthetic dityrosine. *Arch Oral Biol* 1982; 27: 417–21.
20. De Araujo FB, Rosito DB, Toigo E, dos Santos CK. Diagnosis of approximal caries: radiographic versus clinical examination using tooth separation. *Am J Dent* 1992; 5: 245–8.
21. de Josselin de Jong E, Sundström F, Westerling H, Tranaeus S, ten Bosch JJ, Angmar-Månsson B. A new method for in vivo quantification of mineral loss in enamel with laser fluorescence. *Caries Res* 1995; 29: 2–7.
22. Diniz MB, Sciasci P, Rodrigues JA, Lussi A, Cordeiro RC. Influence of different professional prophylactic methods on fluorescence measurements for detection of occlusal caries. *Caries Res* 2011; 45: 264–8.
23. Espelid I, Mejàre I, Weerheijm KL. EAPD guidelines for use of radiographs in children. *Eur J Paediatr Dent* 2003; 4: 40–8.
24. Victoria University of Manchester. *Radiation protection 136. European guidelines on radiation protection in dental radiology.* Luxembourg: Office for Official Publications of the European Communities, 2004.
25. Hellén-Halme K, Rohlin M, Petersson A. Dental digital radiography: a survey of quality aspects. *Swed Dent J* 2005; 29: 81–7.
26. Hellén-Halme K, Nilsson M, Petersson A. Digital radiography in general dental practice: a field study. *Dentomaxillofac Radiol* 2007; 36: 249–55.
27. Hibst R, Paulus R, Lussi A. Detection of occlusal caries by laser fluorescence: basic and clinical investigations. *Medical Laser Appl* 2001; 16: 205–13.
28. Hintze H. Radiography for the detection of dental caries lesions. Doctoral thesis. Aarhus University, 2004.
29. Hintze H, Wenzel A. Clinically undetected dental caries assessed by bitewing screening in children with little caries experience. *Dentomaxillofac Radiol* 1994; 23: 19–23.
30. Hintze H, Wenzel A. A two-film versus a four-film bitewing examination for caries diagnosis in adults. *Caries Res* 1999; 33: 380–6.
31. Hintze H, Wenzel A. Diagnostic accuracy of six digital and two conventional radiographic systems for caries detection. Influence of the validation method. *Dentomaxillofac Radiol* 2002; 31: 44–9.
32. Hintze H, Wenzel A. Diagnostic outcome of methods frequently used for caries validation. A comparison of clinical examination, radiography and histology following hemi- and serial tooth sectioning. *Caries Res* 2003; 37: 115–24.
33. Hintze H, Wenzel A, Danielsen B, Nyvad B. Reliability of visual examination, fibre-optic transillumination, and bite-wing radiography, and reproducibility of direct visual examination following tooth separation for the identification of cavitated carious lesions in contacting approximal surfaces. *Caries Res* 1998; 32: 204–9.
34. Hintze H, Wenzel A, Frydenberg M. Accuracy of caries detection with four storage phosphor systems and E-speed radiographs. *Dentomaxillofac Radiol* 2002; 31: 170–5.
35. Huysmans MC, Longbottom C, Pitts NB, Los P, Bruce PG. Impedance spectroscopy of teeth with and without approximal caries lesions – an in vitro study. *J Dent Res* 1996; 75: 1871–8.
36. Huysmans MC, Kühnisch J, ten Bosch JJ. Reproducibility of electrical caries measurements: a technical problem? *Caries Res* 2005; 39: 403–10.
37. Isidor S, Faaborg-Andersen M, Hintze H, Kirkevang LL, Frydenberg M, Haiter-Neto F, Wenzel A. Effect of monitor display on detection of approximal caries lesions in digital radiographs. *Dentomaxillofac Radiol* 2009; 38: 537–41.
38. Jacobsen JH, Hansen B, Wenzel A, Hintze H. Relationship between histological and radiographic caries lesion depth measured in images from four digital radiography systems. *Caries Res* 2004; 38: 34–8.
39. Keem S, Elbaum M. Wavelet representations for monitoring changes in teeth imaged with digital imaging fiber-optic transillumination. *IEEE Trans Med Imaging* 1997; 16: 653–63.
40. Kidd EAM, Naylor MN, Wilson RF. Prevalence of clinically undetected and untreated molar occlusal dentine caries in adolescents on the Isle of Wight. *Caries Res* 1992; 26: 397–401.
41. Kleter GA, Damen JJ, Buijs MJ, ten Cate JM. The Maillard reaction in demineralized dentin in vitro. *Eur J Oral Sci* 1997; 105: 278–84.
42. König K, Flemming G, Hibst R. Laser-induced autofluorescence spectroscopy of dental caries. *Cell Mol Biol* 1998; 44: 1293–300.
43. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977; 33: 159–74.
44. Levallois B, Terrer E, Panayotov Y, Salehi H, Tassery H, Tramini P, Cuisinier F. Molecular structural analysis of carious lesions using micro-Raman spectroscopy. *Eur J Oral Sci* 2012; 120: 444–51.
45. Lith A, Gröndahl HG. Intervals between bitewing examinations in young patients when applying a radiologic algorithm. *Community Dent Oral Epidemiol* 1992; 20: 181–6.
46. Longbottom C, Huysmans MC, Pitts NB, Los P, Bruce PG. Detection of dental decay and its extent using a.c. impedance spectroscopy. *Nat Med* 1996; 2: 235–7.
47. Lunder N, von der Fehr FR. Approximal cavitation related to bitewing image and caries activity in adolescents. *Caries Res* 1996; 30: 143–7.
48. Lussi A, Hellwig E. Performance of a new laser fluorescence device for the detection of occlusal caries in vitro. *J Dent* 2006; 34: 467–71.
49. Lussi A, Reich E. The influence of toothpastes and prophylaxis pastes on fluorescence measurements for caries detection in vitro. *Eur J Oral Sci* 2005; 113: 141–4.
50. Lussi A, Firestone A, Schoenberg V, Hotz P, Stich H. In vivo diagnosis of fissure caries using a new electrical resistance monitor. *Caries Res* 1995; 29: 81–7.
51. Lussi A, Imwinkelried S, Pitts NB, Longbottom C, Reich E. Performance and reproducibility of a laser fluorescence system for detection of occlusal caries in vitro. *Caries Res* 1999; 33: 261–6.
52. Lussi A, Megert B, Longbottom C, Reich E, Francescut P. Clinical performance of a laser fluorescence device for detection of occlusal caries lesions. *Eur J Oral Sci* 2001; 109: 14–9.
53. Lussi A, Hibst R, Paulus R. DIAGNOdent: an optical method for caries detection. *J Dent Res* 2004; 83: C80–3.
54. Lussi A, Hack A, Hug I, Megert B, Stich H. Detection of approximal caries with a new laser fluorescence device. *Caries Res* 2006; 40: 97–103.
55. Machiulskiene V, Nyvad B, Baelum V. A comparison of clinical and radiographic caries diagnoses in posterior teeth of 12-year-old Lithuanian children. *Caries Res* 1999; 33: 340–8.
56. Machiulskiene V, Nyvad B, Baelum V. Comparison of diagnostic yields of clinical and radiographic caries examinations in children of different age. *Eur J Paediatr Dent* 2004; 5: 157–62.

57. Mejàre I, Malmgren B. Clinical and radiographic appearance of proximal carious lesions at the time of operative treatment in young permanent teeth. *Scand J Dent Res* 1986; **94**: 19–26.
58. Mejàre I, Stenlund H. Caries rates for the mesial surface of the first permanent molar and the distal surface of the second primary molar from 6 to 12 years of age in Sweden. *Caries Res* 2000; **34**: 454–61.
59. Mejàre I, Gröndahl H-G, Carlstedt K, Grever A-C, Ottosson E. Accuracy of radiography and probing for the diagnosis of proximal caries. *Scand J Dent Res* 1985; **93**: 178–84.
60. Mejàre I, Källestål C, Stenlund H. Incidence and progression of approximal caries from 11 to 22 years of age in Sweden: a prospective radiographic study. *Caries Res* 1999; **33**: 93–100.
61. Mejàre I, Stenlund H, Zelezny-Holmlund C. Caries incidence and lesion progression from adolescence to young adulthood: a prospective 15-year cohort study in Sweden. *Caries Res* 2004; **38**: 130–41.
62. Nair MK, Nair UP. An in-vitro evaluation of Kodak Insight and Ektaspeed Plus film with a CMOS detector for natural proximal caries: ROC analysis. *Caries Res* 2001; **35**: 354–9.
63. Naitoh M, Yuasa H, Toyama M, Shiojima M, Nakamura M, Ushida M, Iida H, Hayashi M, Ariji E. Observer agreement in the detection of proximal caries with direct digital intraoral radiography. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 1998; **85**: 107–12.
64. Nyvad B. Udvikling og evaluering af en screeningsmetode til identifikation af cariesaktive individer. Master of Public Health Thesis, Aarhus University, 2005.
65. Pitts NB, Rimmer PA. An *in vivo* comparison of radiographic and directly assessed clinical caries status of posterior approximal surfaces in primary and permanent teeth. *Caries Res* 1992; **26**: 146–52.
66. Pretty IA, Edgar WM, Higham SM. A review of the effectiveness of quantitative light-induced fluorescence (QLF) to detect early caries. In: Stookey GK, ed. *Early detection of dental caries III. Proceedings of the 6th Annual Indiana Conference*. Indiana University, Indianapolis, 2003: 253–69.
67. Qvist V, Johannessen L, Bruun M. Progression of approximal caries in relation to iatrogenic preparation damage. *J Dent Res* 1992; **71**: 1370–3.
68. Ratledge DK, Kidd EA, Beighton D. A clinical and microbiological study of approximal carious lesions. Part 1: the relationship between cavitation, radiographic lesion depth, the site-specific gingival index and the level of infection of the dentine. *Caries Res* 2001; **35**: 3–7.
69. Rechmann P, Charland D, Rechmann BM, Featherstone JD. Performance of laser fluorescence devices and visual examination for the detection of occlusal caries in permanent molars. *J Biomed Opt* 2012; **17**: 036006.
70. Ricketts DN. The eyes have it. How good is DIAGNOdent at detecting caries? *Evid Based Dent* 2005; **6**: 64–5.
71. Ricketts DN, Kidd EA, Liepins PJ, Wilson RF. Histological validation of electrical resistance measurements in the diagnosis of occlusal caries. *Caries Res* 1996; **30**: 148–55.
72. Ricketts DN, Kidd EA, Wilson RF. The effect of airflow on site-specific electrical conductance measurements used in the diagnosis of pit and fissure caries in vitro. *Caries Res* 1997; **31**: 111–8.
73. Ricketts DN, Kidd EA, Wilson RF. Electronic diagnosis of occlusal caries in vitro: adaptation of the technique for epidemiological purposes. *Community Dent Oral Epidemiol* 1997; **25**: 238–41.
74. Rock WP, Kidd EAM. The electronic detection of demineralisation in occlusal fissures. *Br Dent J* 1988; **164**: 243–7.
75. Rodrigues JA, Hug I, Diniz MB, Lussi A. Performance of fluorescence methods, radiographic examination and ICDAS II on occlusal surfaces in vitro. *Caries Res* 2008; **42**: 297–304.
76. Rohlin M, White SC. Comparative means of dose reduction in dental radiography. *Curr Opin Dent* 1992; **2**: 1–9.
77. Rugg-Gunn AJ. Approximal carious lesions. A comparison of the radiological and clinical appearances. *Br Dent J* 1972; **133**: 481–4.
78. Scharf F. Über die natürliche Lumineszenz der Zahnhartgewebe 'Schmelz und Dentin'. *Stoma* 1971; **24**: 11–25.
79. Shi X-Q, Welander U, Angmar-Månsson B. Occlusal caries detection with KaVo DIAGNOdent and radiography: an in vitro comparison. *Caries Res* 2000; **34**: 151–8.
80. Shwartz M, Gröndahl H-G, Pliskin JS, Boffa J. A longitudinal analysis from bite-wing radiographs of the rate of progression of approximal carious lesions through human dental enamel. *Arch Oral Biol* 1984; **29**: 529–36.
81. Skodje F, Espelid I, Kvile K, Tveit AB. The influence of radiographic exposure factors on the diagnosis of occlusal caries. *Dentomaxillofac Radiol* 1998; **27**: 75–9.
82. Souza JF, Boldieri T, Diniz MB, Rodrigues JA, Lussi A, Cordeiro RC. Traditional and novel methods for occlusal caries detection: performance on primary teeth. *Lasers Med Sci* 2013; **28**: 287–95.
83. Spitzer D, ten Bosch JJ. The total luminescence of bovine and human dental enamel. *Calcif Tiss Res* 1976; **20**: 201–8.
84. Stenlund H, Mejàre I, Källestål C. Caries rates related to approximal caries at ages 11–13: a 10-year follow-up study in Sweden. *J Dent Res* 2002; **81**: 455–8.
85. Stenlund H, Mejàre I, Källestål C. Caries incidence rates in Swedish adolescents and young adults with particular reference to adjacent approximal tooth surfaces: a methodological study. *Community Dent Oral Epidemiol* 2003; **31**: 361–7.
86. Tassery H, Levallois B, Terrer E, Manton DJ, Otsuki M, Koubi S, Gugnani N, Panayotov I, Jacquot B, Cuisinier F, Rechmann P. Use of new minimum intervention dentistry technologies in caries management. *Aust Dent J* 2013; **58** (Suppl 1): 40–59.
87. ten Bosch JJ. Light scattering and related methods. In: Stookey GK, ed. *Early detection of dental caries. Proceedings of the 1st Annual Indiana Conference*. Indiana University, Indianapolis 1996: 81–90.
88. Teo TK, Ashley PF, Louca C. An *in vivo* and *in vitro* investigation of the use of ICDAS, DIAGNOdent pen and CarieScan PRO for the detection and assessment of occlusal caries in primary molar teeth. *Clin Oral Investig* 2014; **18**: 737–44.
89. Terrer E, Koubi S, Dionne A, Weisrock G, Sarraquigne C, Mazuir A, Tassery H. A new concept in restorative dentistry: light induced fluorescence evaluator for diagnosis and treatment. Part 1: diagnosis and treatment of initial occlusal caries. *J Contemp Dent Pract* 2009; **10**: 1086–94.
90. Terrer E, Raskin A, Koubi S, Dionne A, Weisrock G, Sarraquigne C, Mazuir A, Tassery H. A new concept in restorative dentistry: LIFEDT – light-induced fluorescence evaluator for diagnosis and treatment: part 2 – treatment of dentinal caries. *J Contemp Dent Pract* 2010; **11**: E095–102.
91. Thoms M. Detection of intraoral lesions using a fluorescence camera. In: Rechmann P, Fried D, eds. *Lasers in dentistry XII. Proceedings of SPIE*, Vol. 6137. Bellingham, WA: SPIE Press, 2006: 1–7.
92. Tranæus S, Lussi A, de Josselin de Jong E, Angmar-Månsson B. Quantification of occlusal caries – an in vitro study with laser fluorescence, electrical resistance measurement and histologic examination. *J Dent Res* 1997; **76**: 101.
93. Tranæus S, Al-Khateeb S, Björkman S, Twetman S, Angmar-Månsson B. Application of quantitative light-induced fluorescence to monitor incipient lesions in caries-active children. A comparative study of remineralisation by fluoride varnish and professional cleaning. *Eur J Oral Sci* 2001; **109**: 71–5.
94. Tranæus S, Lindgren L-E, Karlsson L, Angmar-Månsson B. *In vivo* validity and reliability of IR fluorescence measurements for caries detection and quantification. *Swed Dent J* 2004; **28**: 173–82.
95. Thylstrup A, Bille J, Qvist V. Radiographic and observed tissue changes in approximal carious lesions at the time of operative treatment. *Caries Res* 1986; **20**: 75–84.
96. Verdonschot EH, Bronkhorst EM, Burgersdijk RCW, König KG, Schaeken MJM, Truin GJ. Performance of some diagnostic systems in examinations for small occlusal carious lesions. *Caries Res* 1992; **26**: 59–64.
97. Weerheijm KL. Occlusal 'hidden caries'. *Dent Update* 1997; **24**: 182–4.
98. Weerheijm KL, Groen HJ, Bast AJ, Kieft JA, Eijkman MA, van Amerongen WE. Clinically undetected occlusal dentine caries: a radiographic comparison. *Caries Res* 1992; **26**: 305–9.
99. Wenzel A, Gröndahl HG. Direct digital radiography in the dental office. *Int Dent J* 1995; **45**: 27–34.
100. White GE, Tsamtsouris A, Williams DL. Early detection of occlusal caries by measuring the electrical resistance of the tooth. *J Dent Res* 1978; **57**: 195–200.
101. White SC, Hollender L, Gratt BM. Comparison of xeroradiographs and film for detection of proximal surface caries. *J Am Dent Assoc* 1984; **108**: 755–9.

Part IV
Controlling dental caries

13

The caries control concept

B. Nyvad and O. Fejerskov

Why the caries control concept should replace caries prevention

For more than half a century the term 'caries prevention' has been considered synonymous with 'primary prevention'; that is, *prevention* by reducing the incidence of disease (reducing the development of new disease). For example, the results of the water fluoridation studies in the USA in the 1940s were interpreted such that fluoride prevents the development of carious cavities because about 50% fewer cavities could be recorded in a given cohort in fluoridated communities (see Chapter 14 for details). This phenomenon was ascribed to fluoride being incorporated into enamel, thereby making the tooth more resistant to acid attacks.

However, based on a critical review of the epidemiological evidence and a series of laboratory studies on enamel chemistry [21], Fejerskov *et al.* [14] promoted a new paradigm on the mode of action of fluoride in 1981. According to this new paradigm, fluoride does not *prevent* the development of cavities by forming a more 'resistant enamel' but rather exerts its cariostatic effect by interfering with the de-and remineralizing processes during lesion development whereby it *treats* active caries lesions as they progress. This discovery meant a radical shift in our way of thinking about 'caries prevention.' As a consequence, fluoride was redefined as *a therapeutic agent that operates by controlling the initiation and development of dental caries at precavitated stages of lesion formation* (see Chapter 9). At the time, precavitated stages of caries were usually not recorded clinically, as classical caries epidemiologists claimed that noncavitated enamel lesions could not be recorded with any certainty. However, reanalyses of the original Tiel–Culemborg data on the effect of water fluoridation [16] – which in fact included observations of noncavitated lesions – showed that the new paradigm [14] was justified. Subsequently, in 2003, analyses

Dental Caries: The Disease and its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

of caries lesion transitions in a controlled clinical trial of supervised brushing with fluoride toothpaste demonstrated that fluoride promotes lesion arrest more than it inhibits lesion development [6, 29], thereby controlling (or delaying) the formation of cavities.

Fluoride is not the only agent that may have a therapeutic effect on the caries processes. However, fluoride is the only agent so far that has been proven to significantly influence caries incidence rates (see Chapter 14). As shown in Chapter 14, fluoride has an effect only when it is present during periods of 'active disease': that is, when pH decreases and fluctuates as a result of biofilm metabolism. Understanding this fact is essential for understanding why we talk about *caries control*.

Interventions that are capable of modifying the metabolic activity of the biofilm (Chapter 7) may also possess therapeutic properties because of their potential to restore the physiological equilibrium at the biofilm–tooth interface, but the clinical effect of such strategies is less clear. The caries-controlling effect of interventions could occur on any tooth surface that is covered by a biofilm, whether the surface is noncavitated or cavitated. Therefore, we now propose a shift from the concept of 'caries prevention' to a broader evidence-based concept of 'caries control' when attempting to interfere with the dynamic processes of caries at all stages of lesion development. This is not merely a question about semantics. A more precise terminology should preferably be reflected in better promotion of dental health. Our line of thinking behind this change of terminology is illustrated in Fig. 13.1.

Adoption of the caries control paradigm necessitates that clinicians have the proper diagnostic tools to monitor lesion progression over time. In 2003, when we first introduced the caries control concept in a well-hidden publication [13], the criteria for detecting active and inactive caries lesions [24, 28] were not validated. The caries control concept matured gradually as it became obvious that the clinical criteria for assessing lesion activity were capable of predicting lesion outcomes [29] and help clinicians in making informed treatment decisions (Fig. 10.1). The caries control concept was successfully implemented in the cariology curriculum at Aarhus University as an integrated part of the course on restorative dentistry. The goal was that students should appreciate that a patient who disturbs the biofilm mechanically (brushing), chemically (fluoride), or by behavioral change (diet) is performing caries control.

Both nonoperative and operative treatments are part of the caries control concept (Fig. 13.1), but operative treatments should never be the only treatment offered to patients presenting with active caries lesions. A filling is sometimes the only option for arresting an active cavitated caries lesion because of poor access to cleaning, but fillings alone do not cure a caries-active patient without the ancillary help of improved caries control (see also Chapters 17 and 19).

In this chapter we will now demonstrate the effects of applying the caries control concept in clinical settings.

How caries control was managed in the past

Already a century ago, Dr G.V. Black, reported about his clinical successes in the prevention and treatment of smooth surface caries after recommending self-performed toothbrushing. In his textbook [7], he wrote that

> *even in cases of marked whitening of the enamel in several teeth, my experience shows plainly that the decay of the enamel can be effectively checked in any case in which the enamel has not been penetrated. The brush and water are all that is needed, but these must be correctly used to be effective.*

Dr Black observed that his treatments were less effective at the cavitation stage. This may not come as a surprise

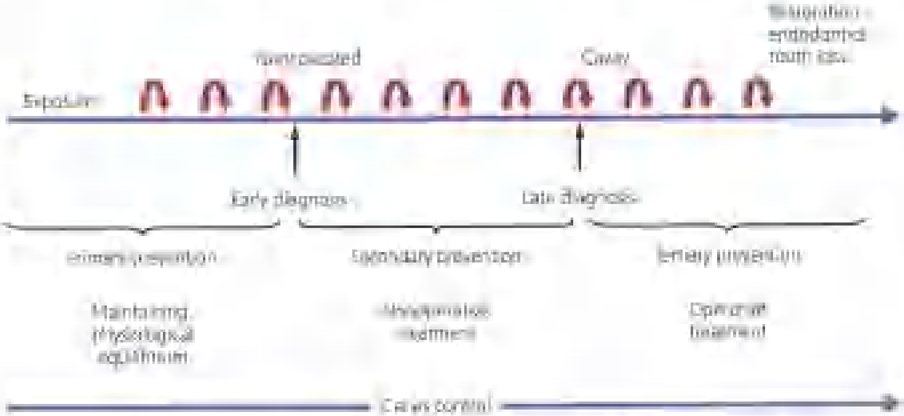


Figure 13.1 Schematic illustration of the caries control concept. Because of continuous exposure to the metabolically active biofilm, disease control must be maintained lifelong. Both nonoperative and operative treatments are part of the caries control concept, but operative treatments should never be the only treatment provided for patients with active caries lesions. See text for a detailed explanation. Modified from [13].

because it is much more difficult to clean a carious cavity with undermined enamel than a smooth tooth surface. In deciduous teeth, where he had no suitable restorative material and small nervous patients who must not be frightened, he advocated opening the lesions to allow cleaning. Two decades later, Anderson [1] published a case series of experimental arrest of 20 large occlusal dentin cavities following 'gross excavation of decay' and elimination of margins of unsupported enamel that made the lesion inaccessible to biofilm removal. All the treated cavities experienced either partial or complete arrest of the carious process after the chewing function was reestablished. These historical observations, combined with more recent clinical observations, suggest that caries lesion progression can be arrested at any stage of lesion development, provided that clinically plaque-free conditions are obtained [26].

To fully understand the concept of lesion arrest it is important to appreciate the dynamic nature of caries lesion development (see Fig. 5.2), and the dynamics of de- and remineralization processes (see Chapter 9). Clinicians may experience that caries lesions exhibit different pathways of lesion arrest, depending on the patient's ability to perform oral hygiene and control of risk factors. In some cases individual lesions may alternate between active and inactive stages over time. In other cases of efficient biofilm removal, lesions may show clear signs of arrest within a few months.

Why has the caries control concept/nonoperative caries treatment not been broadly adopted by dental practitioners? One obvious reason could be that the fee structure does not reimburse for this treatment. However, even in countries where there is an accepted fee for nonoperative interventions (such as in Denmark), dentists are often reluctant to perform this treatment. This may be due to the fact that dentists feel insecure about how to monitor caries control, or this type of treatment does not fit with the dentist's perception of their professional role of 'drilling and filling,' or simply that dentists do not think that the method works. The examples presented in this chapter should help to overcome this barrier when combined with the information presented in Chapter 20 on reactions of the pulpo-dentinal complex to caries.

Arrest of active enamel caries

Several clinical experimental studies have confirmed the original observations of Black [7]. When active enamel caries lesions are cleaned regularly, the surface features change from chalky-white to a more diffuse opacity, particularly in the peripheral shallow parts of the lesion; see Figs 5.25 and 5.26 [3, 4, 19]. The total area of the lesion may be reduced, and occasionally lesions may completely disappear [5]. It has also been suggested that localized ruptures of the surface layer of demineralized enamel may induce the formation of microcavities during lesion arrest [3]. Altogether, these changes were interpreted to be mainly a result of surface wear (toothbrushing and mastication) rather than a result of 'remineralization' of the demineralized tissue [31]. The very surface layer of the lesions may take up some mineral, but the porous tissue deep to the surface is unlikely to 'repair' completely because of restricted diffusion of ions in and out of the lesion (Chapters 8 and 9). Therefore, arrested lesions remain as lifelong whitish or brownish scars in the enamel.

Enamel lesion development and arrest was also observed in *in vivo* studies on experimental gingivitis and caries carried out at Aarhus University in the late 1960s [30, 32]. Clinically detectable noncavitated enamel caries lesions developed unexpectedly rapidly in the natural dentitions of dental students by abstention of oral hygiene for 3 weeks and supplementation with nine daily mouthrinses with a 50% sucrose solution (Fig. 9.17a). Fortunately, these lesions were arrested after resuming oral hygiene practices and performing daily mouthrinses with a 0.2% NaF solution for 2 months (Fig. 9.17b). With today's knowledge this clinical experiment may seem fairly unethical, but it should be appreciated that at the time the rapid development of visible lesions came as a surprise to the researchers. As a result of this experiment, it is no longer ethical to perform prolonged *in vivo* studies in humans by applying frequent mouthrinses with sucrose solutions.

Some dentists are doubtful about the effect of caries control in occlusal surfaces because of the difficulties encountered in proper cleaning of the fissures, particularly during tooth eruption. However, a substantial body of evidence shows that it is indeed possible to control the development and progression of caries in occlusal surfaces of erupting molars when children are subjected to an individualized program of intensified oral hygiene, including professional tooth cleaning and use of topical fluorides [8]. After 1 year of the program the proportion of arrested lesions increased at the expense of a decrease in the proportion of active lesions. At the same time, the proportion of surfaces with visible biofilm decreased significantly (Fig. 13.2a–c). These results were maintained over time, and after 3 years almost 90% of the sites had remained clinically stable [9]. Only 9% of the occlusal surfaces were sealed and 1% filled during the follow-up period, compared with 66% sealed and 8% filled surfaces in a control group from the same community. The authors suggested that the nonoperative program, now referred to as the 'Nexø method,' might be particularly advantageous for controlling caries at the very early stages of tooth eruption during which sealing cannot be performed due to lack of moisture control.

However, the original Nexø study [9] did not involve a concurrent control group for comparison. A subsequent trial performed in Moscow, based on the Nexø method, involved a concurrent control group and confirmed the positive effects of nonoperative treatments on oral hygiene levels and caries control of occlusal surfaces, without using sealants [11]. More than half (54%) of the noncavitated active lesions in occlusal surfaces were converted into inactive lesions over the course of 2.5 years. This was in contrast to the control group, where no lesions regressed. A nonoperative treatment approach based on professional tooth cleaning and dental health education has also been tested in newly erupted first molars in Australia and was found to be equivalent to a conventional preventive program comprising selective fissure sealing and application of topical fluorides [2]. Common to the above nonoperative programs for occlusal caries was that the recall visits and allocation of resources had to be more frequent during the first year, but the frequency of recall visits decreased with time as the molars reached full occlusion and compliance improved.

Arrest of active root caries

Increased aging of populations and associated difficulties with operative treatment of root caries has prompted a series of studies exploring the possibilities for lesion arrest of root caries lesions. In all cases of sustained meticulous oral hygiene the clinical features of root caries lesions change relatively rapidly. Formerly plaque covered, active yellowish lesions with soft surface texture may convert into harder inactive discolored lesions, the surface of which might eventually appear glossy smooth (Fig. 13.3a–c) or contain microcavities (Fig. 13.4a–d) [24].

Arrest of root caries is particularly interesting from the point of view that, in contrast to enamel caries, bacteria have been shown to invade the superficial layers of carious root dentin at an early stage [25]. But we need not be concerned about these bacteria because when the superficial

Figure 13.2 Nonoperative control of caries progression on occlusal surface of erupting first molar. (a) Thick biofilm before and (b) after plaque removal. Note the presence of active noncavitated lesions in the groove–fossa system after plaque removal and drying. (c) After 3 months of nonoperative treatment the translucency of the enamel in the central part of the groove–fossa system appears normal, but opaque lesions are still visible next to gingiva distally. Courtesy of Joanna C. de Carvalho.

Figure 13.3 Arrest of root-surface caries. (a) Active root-surface caries lesion in upper canine presenting a softened surface. (b) Same lesion after 1 year of nonoperative caries control by improved toothbrushing with fluoride toothpaste. The lesion has turned into an inactive stage as evidenced by the hard and shiny surface. (c) After 4 years the lesion is still inactive and has taken up stain. Note also the inactive lesion in the gingival part of enamel.

Figure 13.4 Consecutive stages of nonoperative treatment of active noncavitated root-surface caries lesion on the buccal surface of upper left canine. The figure shows changes in the clinical appearance of the lesion after 3, 6, and 18 months. Note that, within the observation period, improved oral hygiene leads to gradual changes in color and surface structure of the lesion, from soft and yellowish to hard and darkly discolored. Also note changes in the topography of the marginal gingiva. From [24]. Reproduced with permission of John Wiley & Sons.

biofilm – the main driving force of the carious process – is removed repeatedly, caries progression is reduced by a change in the ecology of the microbial communities in the demineralized dentin. This hypothesis was subsequently confirmed by experimental studies of root caries in which it was shown that the mineral loss did not increase during lesion arrest, in spite of bacteria being present in the carious tissue. The thickness and mineral density of the surface layer of the arresting root caries lesions increased over time. Furthermore, a certain redistribution of mineral took place within the lesion body (see Fig. 5.22) [27]. The latter phenomenon was probably a result of the topical fluoride treatments given to the lesions.

One case series of root caries arrest demonstrated the fate of particularly deep dentin lesions with obvious cavity formation in the buccal surfaces (Fig. 13.5a–d) [26]. Most dentists would immediately treat such lesions with fillings. However, the patient was willing to try a nonoperative treatment under the premise that the treatment would not endanger the pulp. The nonoperative treatment turned out to be so successful that the patient did not ask for a filling within the 10-year follow-up. The lesions turned harder over time, and they became almost black. But cosmetic appearance was not an issue for the patient in this part of the mouth. At the 4-year examination (Fig. 13.5c) a rim of unsupported enamel facilitating biofilm retention was removed along the occlusal aspect of the lesion in the first premolar to facilitate plaque removal. During this procedure, utmost care was used not to damage the very surface layer of the lesion as this might potentially create larger pathways for bacterial invasion into the body of the lesion and hamper continued lesion arrest. The 10-year follow-up (Fig. 13.5d) reveals that this mechanical adjustment of the lesion borders was effective.

Nonoperative treatment may not only be a useful strategy for controlling root caries in individual patients in the dental office. A recent clinical trial has demonstrated that this treatment concept may also be successfully applied in elderly nursing-home residents who have their teeth brushed professionally twice a day by the nursing staff [12]. Significantly more active root caries lesions arrested in an intervention group that brushed with 5000 ppm fluoride toothpaste compared with a control group brushing with 1450 ppm fluoride paste for 8 months. Since no differences were recorded in plaque levels and other relevant caries determinants at the end of the study, the authors concluded that the 5000 ppm fluoride toothpaste was more effective than the 1450 ppm fluoride paste in arrest of root caries lesions in this program of professional daily toothbrushing, which is not surprising in view of our knowledge about the cariostatic mechanisms of fluoride (see Chapter 14).

Arrest of active cavitated caries

Many dentists are skeptical about arrest of cavitated dentin caries because they worry that the pulp may suffer permanent damage. However, it should be remembered that dentin is a vital tissue, and during caries lesion development the pulpo-dentinal complex will react with a biological response trying to 'seal off' the destroyed tissue to protect the pulp (see Chapter 20). These positive reactions are facilitated by regular removal of the microorganisms and may result in pain relief. Figure 13.6a and b shows such a case in which improved plaque control resolved sensitivity to cold and sweet over 2–3 weeks. The bacteria-infiltrated soft dentine is gradually removed by the toothbrush and the surface layer of the lesion takes up mineral from saliva in a manner similar to that described for arrest of root caries. It is not recommended to remove the softened dentin by

Figure 13.5 Consecutive changes of nonoperative treatment of active cavitated root-surface caries lesions on the buccal surfaces of lower first and second premolars. The illustrations show the clinical appearance of the active lesions after (b) 2, (c) 4, and (d) 10 years. The successful treatment was achieved through careful daily plaque removal with a fluoride toothpaste. After 4 years an overhanging rim of unsupported enamel at the occlusal aspect of the lesion was removed to facilitate cleaning. Although cosmetically a problem to most patients, these lesions did not need operative treatment, which may weaken the teeth substantially and, in the long run, reduce their survival. From [26]. Reproduced with permission of John Wiley & Sons.

Figure 13.6 (a) Active cavitated lesions filled with microbial deposits in anterior teeth. The dark brown appearance of the lesions is a result of discoloration of the softened dentin. This is obvious when most of the dental plaque is removed with a toothbrush, as seen in (b). Such cavitated lesions can be converted into arrested lesions by nonoperative interventions using a fluoride-containing tooth paste. In this patient, after 2–3 weeks of plaque control, the lesions were no longer sensitive to cold and sweet, and 4 months later they were hard on probing.

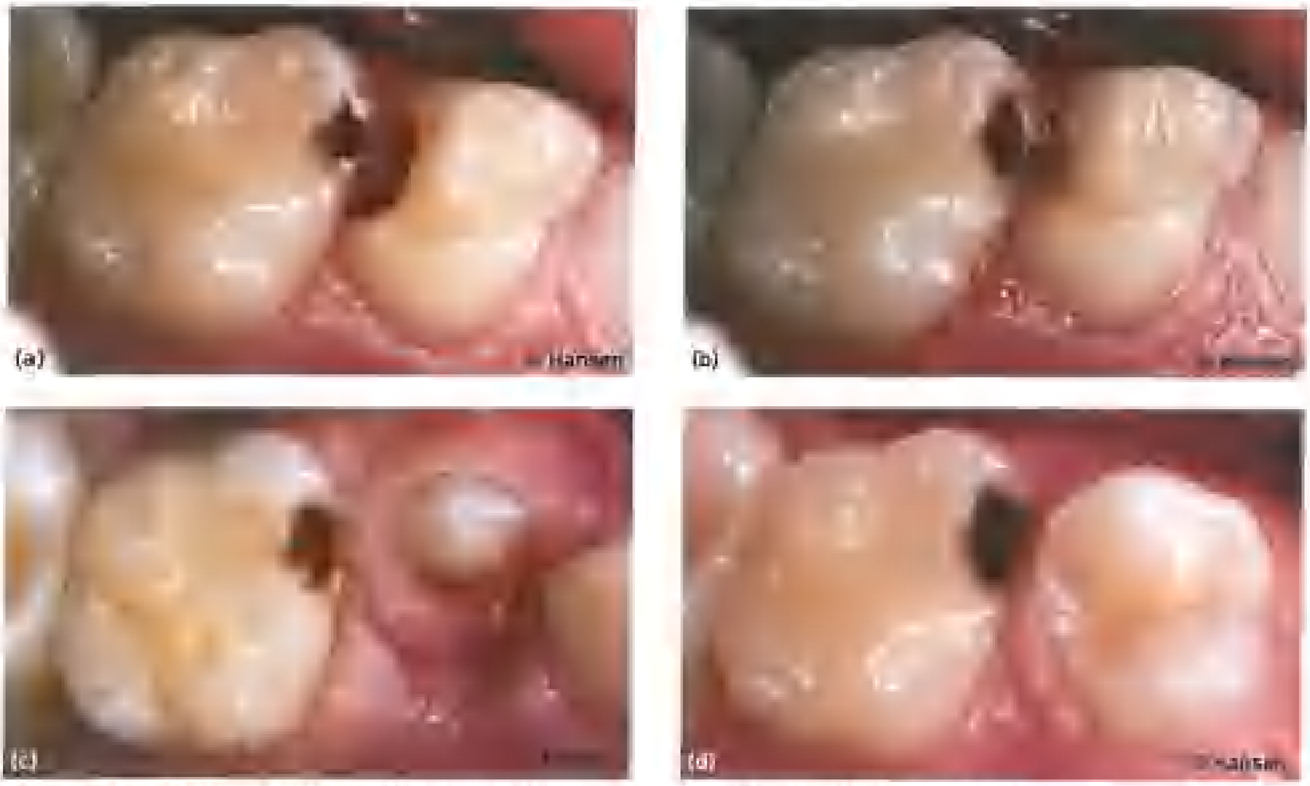


Figure 13.7 Sequential stages of nonoperative caries control in active cavitated primary teeth. The cavity in the first molar had previously been filled, but the filling was lost. (a, b) Active carious cavities before and after 'slicing' of unsupported enamel to make the cavities cleansable with a toothbrush. (c, d) Successive stages of lesion arrest in the second molar after 3 months and 6 months respectively. The floor of the dentin cavity became harder and darker over time. Note that the first permanent premolar erupts into a clean environment! Courtesy of Niels V. Hansen.

instrumentation – the trick is to slowly abrade the softened dentin to stimulate the biological response.

Repeated *re*-restoration of fillings in primary teeth has prompted some pedodontists to advocate nonoperative treatment as an alternative strategy for cavity treatment in the primary dentition [17, 18]. The principle is simply that open cavities are kept free from biofilm on a daily basis by using a toothbrush and fluoride toothpaste. If the cavity cannot be properly cleaned because of undermined enamel, the lesion is made cleansable by 'slicing' unsupported enamel away with a bur (Fig. 13.7a and b). Empirical evidence suggests that if compliance with oral hygiene measures is maintained, formerly soft and active cavitated lesions become harder and inactive over time (Fig. 13.7c and d). As with root caries, these processes should be supported by professional applications of topical fluorides. The slicing procedure is well tolerated by even small children because it does not hurt to momentarily trim the enamel borders. Therefore, most parents prefer this nontraumatic treatment procedure to traditional filling therapy for the deciduous teeth of their children – if they are given the choice.

When selecting lesions for nonoperative cavity treatment it is implicit that the patient/parent should understand the importance of daily plaque control. Teeth must not show signs of spontaneous pain (chronic pulpitis) or problems with food impaction, which could hinder effective plaque control. For anatomical reasons, carious cavities in primary teeth are shallower and easier to clean than cavities in permanent teeth. Hence, it is not surprising that a simple caries control program based on daily supervised toothbrushing using fluoride toothpaste (1000 ppm fluoride) conducted in 3–5-year-old kindergarten children in China resulted in substantial arrest/rehardening of open dentin lesions [23]. After 3 years about 28% of the active dentin caries lesions in the test group had arrested and most of the arrested cavities were found on anterior teeth (45%) compared with posterior teeth (7%). A remarkable observation of this study was that in the control group not receiving organized preventive care as many as 19% of the active cavitated lesions arrested! This suggests that a considerable amount of active cavitated lesions in primary teeth may arrest without operative intervention and could partly explain why 84% of unrestored carious deciduous teeth in a retrospective practice-based study exfoliated without symptoms [22]. Altogether, these findings call for a reconsideration of the benefits of nonoperative caries control in the primary dentition, as also voiced by others [20].

Role of fluoride in lesion arrest

Most of the aforementioned studies of lesion arrest were carried out in an era during which regular use of fluoride toothpaste was the basic caries preventive method. In some studies professional fluoride applications were added on top of the fluoride paste. It should be remembered, however, that fluoride treatment, irrespective of how aggressive it may be, cannot stop the development of caries but only reduce the speed of lesion progression. Moreover, fluoride will predominantly exert its cariostatic effect in active lesions subjected to periods of low pH (Chapters 9 and 14). Therefore, the caries-controlling effect of brushing with a fluoride toothpaste during lesion arrest relies mainly on removal of the microorganisms and their harmful metabolic products. It has been suggested that there might be an additive effect on caries control of fluoride exposure and biofilm removal (Chapter 15). However, the magnitude of such interactions during lesion arrest has not been resolved definitively.

Benefits and limitations of the caries control approach – and some recommendations

The nonoperative caries control approach that we promote in this chapter can be applied for all types and stages of dental caries, as long as the pulp remains vital. Even after a filling therapy, nonoperative care is essential to prevent the development of secondary caries at the margins of restorations. Nonoperative caries control is a biological treatment at the very root of the disease as opposed to treatment of the symptoms by insertion of fillings. Because of the continuous metabolic processes in the dental biofilm it should be appreciated that caries cannot be managed by a single cure. However, by way of balancing the de- and remineralization processes in the dental biofilm, the individual may be taught to maintain lifelong control of the disease [15].

For some specialists the highest possible dental care is uniquely associated with a filling therapy and they shamefully refer to unrestored caries lesions as 'untreated disease' or 'supervised neglect' [10]. However, nonoperative treatment is not passive neglect, it is a biological treatment modality that requires active feedback. It is true that for a number of reasons some patients may not be able to comply fully with the preventive advice given. But this does not mean that the well-documented concept of nonoperative caries control should be abandoned altogether. Nonoperative treatments should be offered to receptive persons for the right reasons. Therefore, we recommend that the clinical practice of nonoperative caries control becomes an obligatory part of the dental curriculum in all universities.

With the knowledge gathered for more than 100 years, the time has come to apply an evidence-based mode of caries treatment that will allow most individuals to maintain a natural dentition for life. Nonoperative caries control offers such opportunities to all populations, but its implementation necessitates a total rethinking of the way in which dentistry is organized and remunerated in order to depart from the classical concept of restorative dentistry [15].

References

1. Anderson BG. Clinical study of arresting dental caries. *J Dent Res* 1938; 17: 443–52.
2. Arrow P. Oral hygiene in the control of occlusal caries. *Community Dent Oral Epidemiol* 1998; 26: 324–30.
3. Årtun J, Thylstrup A. Clinical and scanning electron microscopic study of surface changes of incipient caries lesions after debonding. *Scand J Dent Res* 1986; 94: 193–201.
4. Årtun J, Thylstrup A. A 3-year clinical and SEM study of surface changes of carious enamel lesions after inactivation. *Am J Orthod Dentofac Orthop* 1989; 95: 327–33.
5. Backer Dirks O. Posteruptive changes in dental enamel. *J Dent Res* 1966; 45: 503–11.
6. Baelum V, Machiulskiene V, Nyvad B, Richards A, Vaeth M. Survival modelling of caries lesion transitions in community intervention trials of preventive interventions. *Community Dent Oral Epidemiol* 2003; 31: 252–60.
7. Black GV. *A work on operative dentistry*. Vol. 2. *The technical procedures in filling teeth*. Chicago: Medico-Dental Publishing Co., 1914: 188–92.
8. Carvalho JC, Ekstrand KR, Thylstrup A. Results after 1 year of non-operative occlusal caries treatment of erupting permanent first molars. *Community Dent Oral Epidemiol* 1991; 19: 23–8.
9. Carvalho JC, Thylstrup A, Ekstrand KR. Results after 3 years of non-operative occlusal caries treatment of erupting permanent first molars. *Community Dent Oral Epidemiol* 1992; 20: 187–92.
10. Curzon M. Supervised neglect – again! *Eur Arch Paediatr Dent* 2010; 11: 51–2.
11. Ekstrand KR, Kuzmina IN, Kuzmina E, Christiansen MEC. Two and a half year outcome of caries preventive programs offered to groups of children in the Solntsevsky district of Moscow. *Caries Res* 2000; 34: 8–19.
12. Ekstrand KR, Poulsen JE, Hede B, Twetman S, Qvist V, Ellwood RP. A randomized clinical trial of the anti-caries efficacy of 5,000 compared to 1,450 ppm fluoridated toothpaste on root caries lesions in elderly disabled nursing home residents. *Caries Res* 2013; 47: 391–8.
13. Fejerskov O, Nyvad B. Is dental caries an infectious disease? Diagnostic and treatment consequences for the practitioner. In: Schou L, ed. *Nordic dentistry 2003 yearbook*. Copenhagen: Quintessence, 2003: 141–52.
14. Fejerskov O, Thylstrup A, Larsen MJ. Rational use of fluorides in caries prevention. A concept based on possible cariostatic mechanisms. *Acta Odont Scand* 1981; 39: 241–9.
15. Fejerskov O, Escobar G, Jøssing M, Baelum V. A functional natural dentition for all – and for life? The oral health care system needs revision. *J Oral Rehabil* 2013; 40: 707–22.
16. Groeneveld A, Van Eck AAMJ, Backer Dirks O. Fluoride in caries prevention: is the effect pre- or post-eruptive? *J Dent Res* 1990; 69 (Spec Iss): 751–5.
17. Gruythuysen RJM. Non-restauratieve cavitebehandeling. Cariësactiviteit beheersen in plaats van maskeren. *Ned Tijdschr Tandheelkd* 2010; 117: 173–80.
18. Gruythuysen RJM, van Strijp AJP, van Palenstein Helderman WH, Frankenmolen FW. Non-restauratieve behandeling van cariës in het melkgebit: doelmatig en kindvriendelijk. *Ned Tijdschr Geneeskd* 2011; 155: A2689.
19. Holmen L, Thylstrup A, Årtun J. Surface changes during the arrest of active enamel caries lesions in vivo. A scanning electron microscope study. *Acta Odontol Scand* 1987; 45: 383–90.
20. Kidd E. Should deciduous teeth be restored? Reflections of a cariologist. *Dent Update* 2012; 39: 159–66.
21. Larsen MJ. Enamel solubility. Caries and erosion. Doctoral dissertation. Aarhus: Royal Dental College, 1974.

22. Levine RS, Pitts NB, Nutgent ZJL. The fate of 1,587 unrestored carious deciduous teeth: a retrospective general practice based study from northern England. *Br Dent J* 2002; **193**: 99–103.
23. Lo ECM, Schwarz E, Wong MCM. Arresting dentine caries in Chinese preschool children. *Int J Paediatr Dent* 1998; **8**: 253–60.
24. Nyvad B, Fejerskov O. Active root surface caries converted into inactive caries as a response to oral hygiene. *Scand J Dent Res* 1986; **94**: 281–4.
25. Nyvad B, Fejerskov O. An ultrastructural study of bacterial invasion and tissue breakdown in human experimental root surface caries. *J Dent Res* 1990; **69**: 2218–25.
26. Nyvad B, Fejerskov O. Assessing the stage of caries lesion activity on the basis of clinical and microbiological examination. *Community Dent Oral Epidemiol* 1997; **25**: 69–75.
27. Nyvad B, ten Cate JM, Fejerskov O. Arrest of root surface caries in situ. *J Dent Res* 1997; **76**: 1845–53.
28. Nyvad B, Machiulskiene V, Baelum V. Reliability of a new caries diagnostic system differentiating between active and inactive caries lesions. *Caries Res* 1999; **33**: 252–60.
29. Nyvad B, Machiulskiene V, Baelum V. Construct and predictive validity of caries diagnostic criteria assessing lesion activity. *J Dent Res* 2003; **82**: 117–22.
30. Theilade E, Wright WH, Jensen SB, Loe H. Experimental gingivitis in man. II. A longitudinal clinical and bacteriological investigation. *J Periodontal Res* 1966; 1: 1–13.
31. Thylstrup A, Bruun C, Holmen L. *In vivo* caries models – mechanisms for caries initiation and arrestment. *Adv Dent Res* 1994; **8**: 144–57.
32. Von der Fehr FR, Löe H, Theilade E. Experimental caries in man. *Caries Res* 1970; **4**: 131–48.

14

Fluorides in caries control

O. Fejerskov, J.A. Cury, L.M. Tenuta, and V.C. Marinho

Introduction

The role of fluorides in the control of dental caries represents one of the most successful stories in general public health. However, as with many successful programs, this success is not without cost, and it is a story which at times has resulted in strong emotional debates within the dental profession that have not always been based on scientific evidence.

We will in this chapter base our views on what is currently known about the effects of fluorides on developing and erupted teeth to derive at a rational way of advocating the use of fluorides in contemporary populations. Fluoride (F^-) can have both beneficial and detrimental effects on the dentition. The beneficial effect is due primarily to the local (topical) effect of F^- on the tooth surfaces whenever these are covered by a biofilm after the teeth have erupted into the oral cavity (for mechanisms of action see later in this chapter and also Chapter 9). In contrast, the detrimental effects of F^- are due to its systemic absorption during tooth development, resulting in dental fluorosis, which is a hypomineralization of the enamel the degree of which is a direct reflection of F^- ingestion during tooth formation. If we can maximize the intraoral exposure throughout life and minimize systemic absorption during the period when the dentition is developing, F^- can be used to maximize the benefits of fluorides in caries control whilst at the same time minimizing the risk of fluorosis.

This chapter is divided into the following major headings:

- Fluoride in caries prevention and control
- Cariostatic mechanisms of fluoride
- Dental fluorosis and metabolism of fluoride
- The effectiveness of fluorides in the control of dental caries: evidence from systematic reviews
- Rational use of fluorides in caries control: recommendations

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

Fluoride in caries prevention and control

It was in fact the detrimental effects of F^- on the appearance of tooth enamel (dental fluorosis) that prompted the initial detailed investigations and ultimately the discovery of its anticaries benefits [73]. Probably black, discolored teeth have been found as long as man has been living in areas with elevated F^- content in soil and water. For example, Galen (131–201 AD) noted that dental caries 'do not attack teeth having a dark yellow colour, although one would have expected the contrary' according to a translated text by late professor D Lambrou from Thessaloniki.

But the association between F^- and 'mottled enamel,' as it was first designated, became clear in the beginning of the 20th century, thanks to two American dentists: Dr Fredrick McKay and US Public Health Officer H Trendley Dean. Subsequently, the positive association between elevated exposure to F^- and decreased prevalence of caries cavities became known. In Europe, however, Denninger in the latter part of the 19th century prescribed calcium fluoride (CaF_2) to children and pregnant women and observed 'great benefits' to their teeth [38].

In 1901, McKay worked in Colorado Springs, Colorado, USA, and noticed that some of his patients had what was locally known as 'Colorado brown stain.' In subsequent years he turned for help to Dr Greene Vardiman Black (see Chapter 19), one of America's most eminent experts on tooth enamel. His histological investigation of the condition 'Mottled teeth. An endemic imperfection of the enamel of the teeth heretofore unknown in the literature of dentistry' [17] drew the attention of the dental research community to the condition. One thing that puzzled both Black and McKay was that although mottled enamel was clearly hypocalcified, and therefore theoretically more susceptible to decay, this did not appear to be case [119]. Coincidentally, Ainsworth [2] in England made a similar observation.

It became clear that the condition was localized to children born in specific geographical areas and McKay suspected that the water supplies of these districts might be an important etiological factor. In Bauxite, changes to a water supply resulted in children having mottled enamel [99], and chemical analysis of the water supply revealed an unexpectedly high level of F^- in the drinking water (14.7 ppm F^-). These high levels were later confirmed in other towns where mottled enamel occurred [34]. These observations did not establish a cause-and-effect relationship. However, when McCollum *et al.* in 1925 reported that rats fed a diet with added F^- developed hypomineralized teeth, the etiology of mottled enamel was clearly established [117].

In the 1930s, systematic animal experiments and human epidemiological studies established both the association and cause–effect relationship between fluorides in drinking waters and mottled enamel (since referred to as dental fluorosis). The epidemiological studies were performed by a team led by Dean [44, 47, 48]. Dean was also interested in the apparent anomaly that although the enamel appeared to be hypomineralized it did not appear to be any more susceptible to decay. He initially undertook a small study involving 114 children who had used water containing 0.6–1.5 ppm F^- and found only 4% were caries free compared with 22% of 122 children in an area with drinking water containing 1.7–2.5 ppm F^- [45]. A further larger study suggested that caries experience in two cities with water supplies containing 1.7 and 1.8 ppm F^- was half that of two similar adjacent cities with only 0.2 ppm F^- in the drinking water [49].

The association between the F^- level in the drinking water and caries levels was then characterized in the '21 city study' (actually a series of studies [50, 51]). Children from cities with natural F^- concentrations in their drinking water ranging from around zero up to 2.6 ppm were examined and the results of this classic piece of epidemiological investigation of both fluorosis and caries experience are summarized in Figs 14.1 and 14.2 [46].

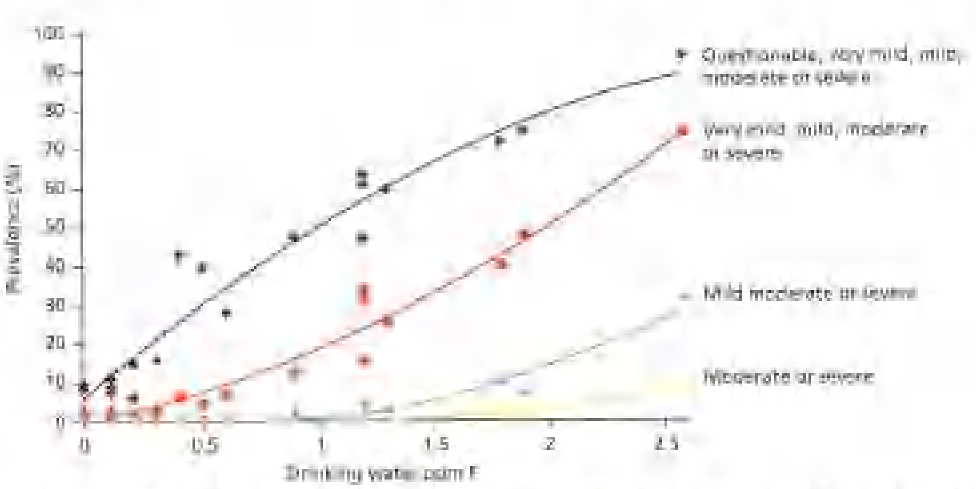


Figure 14.1 Prevalence and severity of mottled enamel in 21 cities in the USA with varying levels of F^- in their drinking water [46]. (Public domain.)

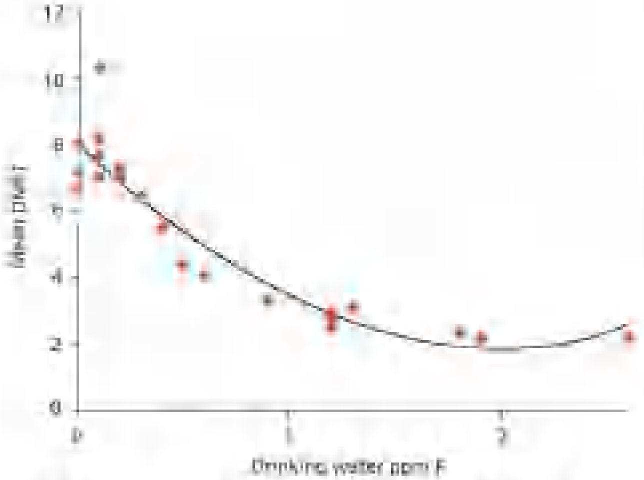


Figure 14.2 Mean number of decayed, missing, and filled teeth (DMFT) and F^- concentration of the drinking water from the 21 city study [46]. (Public domain.)

Dean's index [43, 45, 46] classifies fluorosis as questionable, very mild, mild, moderate, and severe. The prevalence of subjects with lesions of any severity is about 60% at the level of 1 ppm F^- or less in the drinking water (Fig. 14.1). However, it is also interesting to note that the less severe forms of fluorosis (questionable and very mild) account for most cases and there is a very clear dose–response relationship between the F^- level in the drinking water and the prevalence of fluorosis even at levels of F^- in the drinking water below 1 ppm. Therefore, even at low levels of F^- in the drinking water there was some risk attached to use of F^- (for details, see later in this chapter).

The use of the term 'questionable' to describe the earliest classification level in Dean's index has been the source of much controversy over the years as the dental profession has tried to eliminate this category, claiming that it reflected a variety of other types of enamel changes not caused by F^-. However, Fig. 14.1 clearly demonstrates that there is a strong dose–response relationship between this category of defects and the F^- concentration of the drinking water. Moreover, in 1983, Myers reviewed the available literature regarding the 'questionable' category of dental fluorosis and demonstrated that it was a distinct entity associated with F^- [124].

The association between F^- levels in the drinking water and dental caries in the 21 cities is shown in Fig. 14.2. At the time there was a dramatic reduction in caries as the F^- level in the drinking water increased up to 1 ppm. Beyond this level, the mean decayed, missing, and filled teeth (DMFT) continued to decrease but at a much lower rate. At the level of F^- of 1 ppm the average number of decayed, missing, or filled teeth had reduced by more than 50%. However, when studying this graph we should consider whether the apparent plateau is an artefact of the recording method or population observed. The recording method was DMFT, but the average DMFT (see Chapter 4) is a very crude measure and by its nature not able to reflect sensitively changes at the lower end of the scale. It only records caries when lesions have reached cavity level; as such, it is insensitive in identifying benefits in arresting enamel lesions.

Dean gave much thought to the question of what might constitute 'the optimum level of F^-' in drinking water supplies: that is, the concentration of F^- that would result in maximum 'caries protection' while causing minimal dental fluorosis. Based on his studies on 'the minimal threshold of chronic endemic dental fluorosis,' Dean concluded that 'amounts not exceeding 1 part per million expressed in terms of fluorine are of no public health significance' [47]. As was stressed when dealing with Fig. 14.1, Dean's personal assessment 'of no public health significance' was not synonymous with saying that no dental fluorosis occurs in the population. Also, the relationships between perceptions of dental appearance and oral health-related quality of life and dental fluorosis were not assessed at that time. Nevertheless, these reflections resulted in the widespread adoption of 1–1.2 ppm F^- in the USA as an 'optimal' level in the drinking water (for further discussion, see later).

The strong association between the F^- level in the drinking water and caries levels were based on cross-sectional study designs. Therefore, in order to establish a cause-and-effect relationship, intervention studies were required, and these commenced in the Lake Michigan area in 1944. Two towns were selected, Grand Rapids and Muskegon, and baseline caries levels in children aged 4–16 years were recorded. In addition, caries levels were recorded in Aurora, Illinois, an area with naturally occurring F^- in the drinking water at the level of 1.4 ppm. At the start of the study caries levels in the two Michigan cities were similar [52]. F^- at the level of 1 ppm was then added to the drinking water of the city of Grand Rapids in January 1945, and caries levels were recorded again after 6½ years of fluoridation. In 'non-fluoride' Muskegon, the average number of teeth with decay experience was 5.7, compared with 3.0 in 'fluoridated' Grand Rapids [7]. The study was deemed so successful that it was decided to fluoridate the drinking water of Muskegon. After 15 years of fluoridation in Grand Rapids (Fig. 14.3) the number of teeth with cavities had fallen from 12.5 in 1944 to 6.2 in 1959, a reduction of approximately 50% [8]. Caries levels in Grand Rapids were now very similar to those experienced in Aurora, the naturally fluoridated city. This outcome was replicated in a number of studies throughout the USA and a few in other parts of the world. The Dutch Tiel–Culemborg studies by Otto Backer-Dirks and his collaborators were of particular importance [9] because the original data were available decades later when the artificial fluoridation of the drinking water had to cease. As we shall see, reanalyses of these data many years later confirmed the changed concepts on the mechanisms of F^- action.

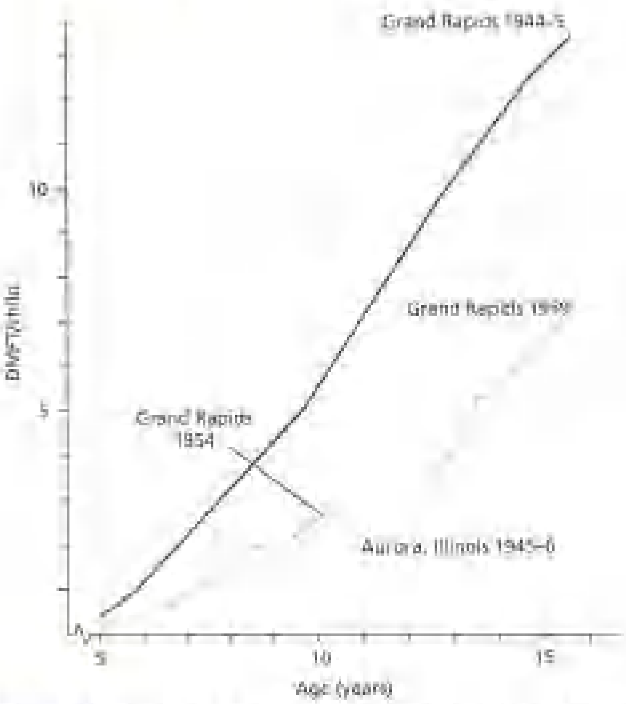


Figure 14.3 Dental caries in Grand Rapids children after 10 and after 15 years of fluoridation (– – – – –), in Grand Rapids before fluoridation (——) and in the natural fluoride area Aurora (——).

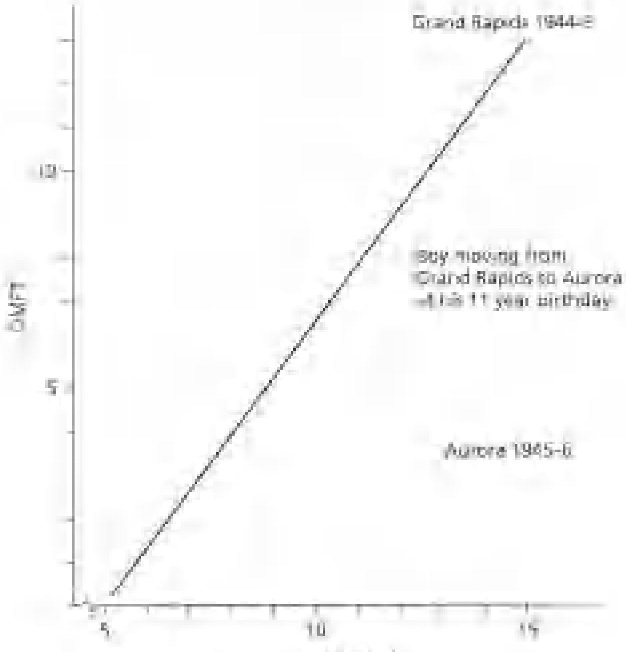


Figure 14.4 Dental caries in Grand Rapids before water fluoridation and in Aurora with fluoride in the water supply. The dashed line indicates caries progression in a boy moving from the non-fluoride to the fluoride area on his 11th birthday [107]. Reproduced with permission of John Wiley & Sons.

Although it is hard to think how these original studies in the USA could have been improved, some criticism can be made of the approach taken by Dean and his coworkers. Probably the most important is the possible bias introduced by the fact that the F^- level of the site investigated was known before the examinations were conducted (a problem which of course has been present in most other studies of the same kind). This might have resulted in a tendency to underscore fluorosis in later studies in different parts of the world, in particular when applying Dean's classification without including the 'questionable' category – or having had examiners not trained in the diagnostic characteristics of early signs of dental fluorosis. A similar bias could also be made in relation to the caries studies and the benefits may have been overestimated.

By the middle of the 20th century there was thus much enthusiasm about the possibilities for caries prevention using fluorides. During that period, in Europe in particular, the caries situation was overwhelming, with numerous tooth extractions amongst children, so attempts to introduce 'the American concept' of adding F^- to the water supplies were made in a few countries as exemplified in Holland. Similarly, it was introduced in Brazil. The concept of an 'optimum F^-' consumption was further advanced.

During these attempts, Hodge [91] presented the results of logarithmic transformations of Dean and coworkers' caries data and averaged index values of Dean's original scores of dental fluorosis (Fig. 14.4). It is now appreciated that this way of manipulating data is inappropriate (see later and Fig. 14.19). In a personal discussion (OF) with Hodge in 1982 he fully appreciated that, at the time, he was carried away when making this transformation of the data. However, from a public health point of view (and it appealed to the layman) it gave rise to a very convincing plot of data which indicated that children born and reared in areas with a F^- content in water supplies below 1 ppm would only experience a prevalence and severity of fluorosis that was considered of 'negligible biologic (aesthetic) significance'. Moreover, the mean caries experience recorded from the 21 city studies indicated that a maximum caries reduction was obtained around the concentration of about 1–1.2 ppm F^- in water supplies (Figs 14.5 and 14.6), so the 'optimum level' was determined as the level of concentration of F^- in water supplies that gave maximum caries reduction while causing minimal dental fluorosis of no concern from a public health point of view. This estimate of the optimal water F^- concentration was subsequently used to determine the amount of F^- that should be given in other systemic F^- regimens, such as tablets, vitamin drops, salt, and so on that became introduced in populations where health authorities would not allow artificial fluoridation of water supplies. For dose considerations and consequences, see later in this chapter.

The concept of the necessity of ingesting F^- was based on the belief that F^- exerted its anticariogenic effect predominantly by becoming incorporated into the crystals in

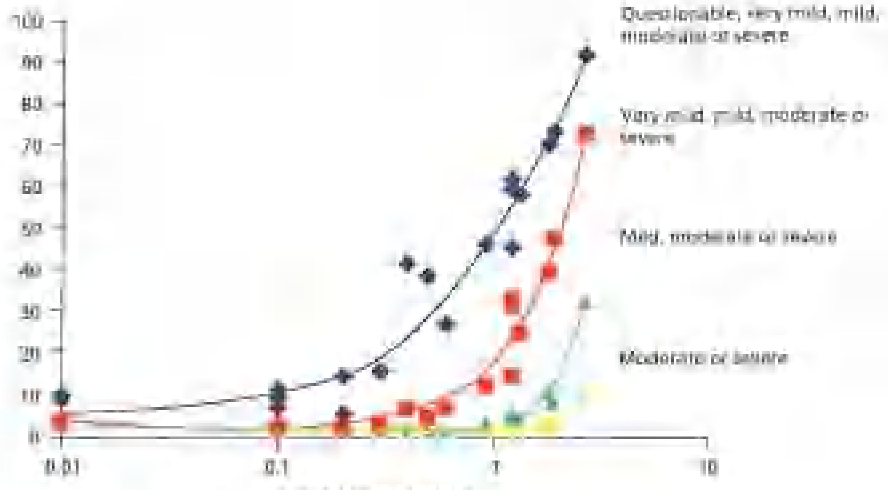


Figure 14.5 Log transformation of the fluoride level in the drinking water and the prevalence and severity of mottled enamel in 21 cities in the USA with varying levels of fluoride in their drinking water [46]. Reproduced with permission of Public Health Reports.

the dental hard tissues during enamel formation. This, it was believed, would make the enamel more 'resistant' to the acid attack on tooth surfaces. With this paradigm it was therefore logical that public health dentists would have to argue that as much F^- as possible should be ingested during tooth formation in order to increase the 'resistance of the tooth.' Therefore, early signs of dental fluorosis – considered an undesirable side effect to the beneficial use of F^- in water – were looked upon only from the point of view of 'cosmetic disturbances.' In attempts to downplay the significance of a toxicological effect of F^-, there was much interest in questioning whether it was possible to diagnose the early stages of dental fluorosis, and arguments that 'optimal F^- concentrations in water supplies result in more perfect mineralized teeth with pearl shine appearance' or 'teeth formed in low F^- areas are F^- deficient' were common. Also, based on this old concept, F^- was considered a micronutrient to control caries, and it is still considered by some as 'essential in diet' [16, 92], although this is surprising taking into account how the concepts on cariostatic mechanisms of F^- have changed (see later in this chapter).

It is clear when reading about the cariostatic mechanisms of F^- later in this chapter and in Chapter 9 that F^- predominantly exerts its anticaries effect through its local action on tooth surfaces in the oral cavity [72]. F^- can therefore be used in caries control based on modern scientific evidence of the mechanisms of action and its toxicological effect. Dental caries can be controlled with little risk of dental fluorosis. It is clear that oral health advice recommending the necessity to ingest F^- is extremely misleading as it is clearly not necessary to ingest F^- to receive its benefits. Nevertheless, it is striking how many of the recommendations about use of fluorides are still based on past paradigms and old beliefs from the 1930s and 1960s.

The introduction of F^- into drinking water was followed by the development of other oral care products, such as toothpaste, gels, varnishes, and so on, and these have had an impact on the prevalence and severity of dental caries throughout the world (see later). For example, the widespread addition of F^- in toothpaste in Europe in the 1960s and 1970s has been claimed to be responsible for a change in the pattern of dental disease in many parts of Europe, particularly in Scandinavia and the UK. This is well illustrated by national census data collected for England and Wales in 1973, 1983, and 1993 (Fig. 14.6). Most health professionals agree that although F^- cannot alone account for these dramatic reductions [77, 127], an increased availability of F^-, mainly in toothpaste, has played a major part in the process in developed [19] and developing countries [41]. Often, however, fluoridated toothpastes were thought to be less efficient than water fluoridation, but the following should be taken into account.

The maximum benefit is achieved if F^- is available from the time of eruption and exposure continues during the entire lifetime of the tooth. However, children may not have continuous exposure to F^-. For example, consider an 11-year-old 'average' boy with a DMFT of 8 from Grand Rapids before fluoridation was introduced, who then moved to Aurora where F^- in the drinking water was present (Fig. 14.4). On average, we would expect that progression rate of lesions would be similar to other children in Aurora, but he would of course already have a higher caries experience than his new contemporaries. Clearly, we would not expect to see a 50% reduction in caries compared with children from Grand Rapids when he is 15 years old. This phenomenon has caused some confusion in the past related to the post- and pre-eruptive effects of F^-, as it was postulated that the difference could largely be attributed to a pre-eruptive F^- effect. However, if we examine Fig. 14.7, it is

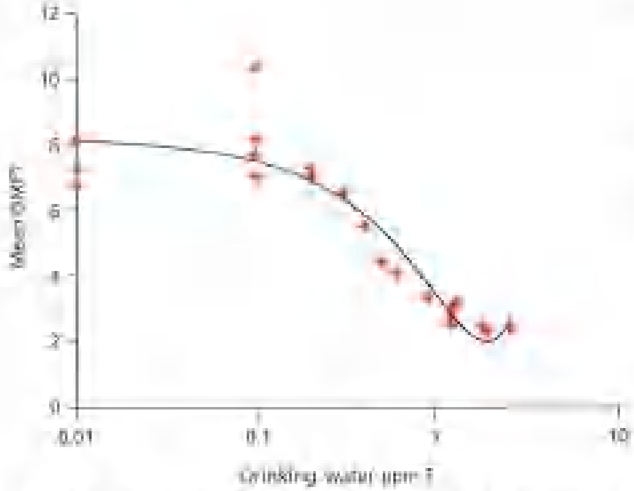


Figure 14.6 Log transformation of the fluoride level in the drinking water and caries prevalence in 21 cities in the USA with varying levels of fluoride in their drinking water [46]. Reproduced with permission of Public Health Reports.

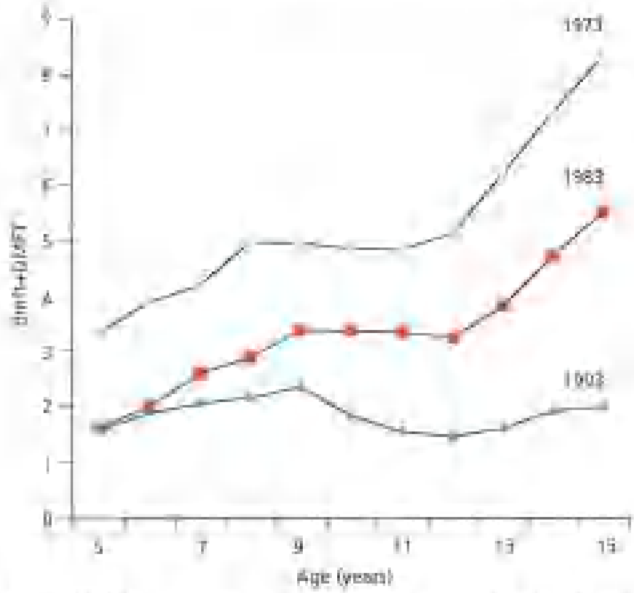


Figure 14.7 Caries experience of children from England and Wales in 1973, 1983 and 1993 [131]. Reproduced with permission of The National Archives.

clear that what we are probably seeing is the influence of the time of initiation and duration of F^- exposure posteruptively on the caries processes. Likewise, on average, a child born and reared in a F^- area will experience an increased caries incidence if moving to live in a low F^- area. So F^- has to be available in the oral environment to interfere with the caries process, and its incorporation in enamel during formation is of much less significance [72]. Therefore, the caries reduction obtained during a 2–3-year clinical trial cannot be compared uncritically with the effect of water fluoridation!

The dramatic decline in caries prevalence and incidence has had far-reaching implications for the practice of dentistry – although not being reflected in the number of dentists being produced [77] – but has had a significant impact on the quality of life of the majority of individuals who avail themselves of this simple preventive and therapeutic intervention.

In the following pages we shall introduce the basic principles of how F^- exerts its cariostatic effect – for details, refer to Chapter 9.

Cariostatic mechanisms of fluoride

It is clear from the discussion above that many of the debates have arisen because of the misunderstanding that F^- had to be ingested to exert its cariostatic effect, although this was shown not to be the case decades ago [72]. The mechanism of action of F^-, irrespective of vehicle used (water, toothpastes, salt, tablets, rinses, gels, varnishes, etc.), is based on the availability of the ion in the oral fluids (saliva, biofilm fluid) to interfere with the caries process.

In order to understand this mechanism, it is crucial to understand the caries process as a progressive loss of minerals from the tooth structure caused by biofilm metabolism, leading over time to the development of a cavity (see Chapters 2, 5, and 9). The effect of F^- on the caries process is not fully understood despite years of research. Nevertheless, while available in the oral cavity even at micromolar concentrations, F^- has a tremendous effect on the stability of tooth minerals, since it is a potent enhancer of mineral precipitation (Chapter 9). The ultimate effect will be a reduction in the progression of caries lesions (Fig. 14.8).

The concept that F^- delays caries progression by reducing demineralization and enhancing remineralization has to be understood in order to discuss the mode of action of each method of F^- delivery. It is clear that tooth minerals are very stable because saliva under normal pH conditions has calcium and phosphate concentrations high enough to be supersaturated with respect to the mineral phases of teeth (mainly hydroxyapatite) – see Fig. 9.3. It is only under certain conditions when this supersaturation is disturbed (i.e., when the biofilm metabolism produces acid from sugar fermentation) that dental demineralization can occur. Therefore, it is not surprising that caries is ubiquitous in the modern society, which lives on a sucrose-rich diet. Sucrose fermentation results in proton production, which reduces the supersaturation of the biofilm fluid with respect to tooth minerals and leads to mineral dissolution in order to maintain the saturation condition (Fig. 9.6). If this demineralization episode is repeated many times a day, over a period of weeks or months, a visible caries lesion develops [68]. Although F^- does not affect biofilm formation and sugar metabolism in concentrations available in saliva and biofilm fluid, dental demineralization is reduced by the concomitant precipitation of fluorhydroxyapatite, a mineral

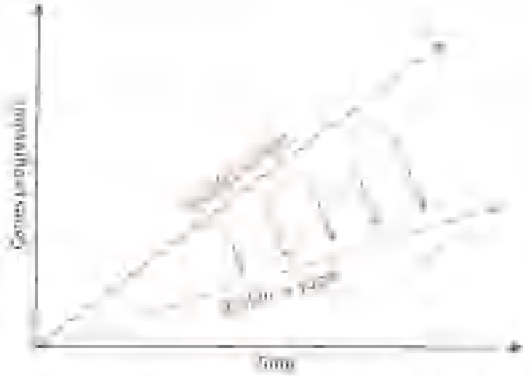


Figure 14.8 Schematic representation of the effect of F⁻ available in oral fluids on the dynamics of caries progression over time.

phase that is more stable than hydroxyapatite at any given pH – see Fig. 9.11. Therefore, while hydroxyapatite from inside the tooth enamel is dissolving during a cariogenic challenge, a fluoridated apatite can precipitate in the very surface layers. The net result is the reduction of the total mineral loss, accompanied by the gradual formation of a F⁻-enriched mineral (a consequence, and not cause, of the F⁻ effect). During the period of time that biofilm pH is high enough to prevent any mineral dissolution, F⁻ available in the oral fluid will enhance mineral precipitation as fluorhydroxyapatite (see Chapter 9).

The reduction of demineralization and enhancement of remineralization is the basis of F⁻ use irrespective of the vehicles used. Since the effect is always local, there is no reason to continue to classify F⁻ methods as either 'systemic' or 'topical'. Nevertheless, given the wide range of F⁻ vehicles available, and the change in the epidemiology of caries in the last decades (partly as a result of F⁻ use), it is of utmost importance that the role and mode of action of each of these methods is understood so that they may be logically recommended. Methods of F⁻ application can be considered as collective to the whole population (e.g., water), individual (e.g., toothpaste, mouthwash), or professionally applied (e.g., topical 2% sodium fluoride (NaF) solution, F⁻ gel, varnish).

F⁻ ingestion is not needed for the anticaries effect of any F⁻. Fluoridated water controls caries because it is drunk regularly and present in cooking preparations and the F⁻ levels in the oral fluids increase regularly during the day [130, 132]. This moderate increase explains the effect on the caries process. Table 14.1 shows that the concentration of F⁻ in dental biofilm of children drinking 'optimally' fluoridated water decreased almost 20 times when the ingestion was temporarily interrupted [129]. When water fluoridation was restarted 6 months later, the F⁻ concentration in the dental biofilm returned to the level found previously [39]. These fluctuations in F⁻ concentration in the biofilm were observed irrespective of the calcium concentrations, which did not decrease significantly during this period (unpublished data). These data show there is no homeostatic mechanism to control F⁻ in the oral environment and explain epidemiological data showing an increase in caries progression rate when children living in areas with high F⁻ concentration in the water moved to low F⁻ areas [72].

Table 14.1 F⁻ concentration in dental plaque from schoolchildren according to the status of water fluoridation (Piracicaba, SP, Brazil, 1986–1987).

Condition of water fluoridation	μgF/g biofilm wet weight
Fluoridated (0.8 ppm F⁻)	3.2 ± 1.8
Interrupted (0.06 ppm F⁻)	0.2 ± 0.09
Refluoridated (0.7 ppm F⁻)	2.6 ± 1.9

From [39, 129].

Table 14.1 shows that constant exposure to F⁻ is needed to maintain elevated F⁻ concentration in the oral fluids. However, F⁻ levels in the dental biofilm can be maintained, even after interruption of water fluoridation, if a F⁻ dentifrice is being used daily [155]. Water fluoridation is unique as a public health measure of F⁻ delivery because it does not depend on individual compliance and is a passive 'mass medication'. Other fluorides (supplements, toothpaste, gels, varnishes, etc.) rely on active patient involvement. The irrelevance of the ingestion (systemic effect) of F⁻ became apparent when attempts were made to substitute the F⁻ in water by adding the same amount to F⁻ tablets [1]. In this study, a caries reduction was obtained but the children developed rather extensive dental fluorosis. However, when similar studies were performed in Denmark and Holland and multivariate analytical methods applied to control for confounders, these F⁻ supplement programs only resulted in development of dental fluorosis in the children without any caries reduction [98, 171]. It is possible that in the Aasenden and Peebles study [1] the caries reduction was a consequence of the mothers who provided the supplements being well educated and motivated for individual health care for their children.

F⁻ dentifrice has been considered the most rational way of F⁻ use because it is associated with the mechanical removal of the dental biofilm – if toothbrushing is performed in the right way. F⁻ may be available in toothpastes as different salts, such as NaF, stannous fluoride (SnF_2), sodium monofluorophosphate (Na_2PO_3F, MFP), and amine fluoride (in which F⁻ is the anion and a long hydrocarbon chain-substituted amine is the cation). F⁻ is available in the ionic form in all formulations except in MFP, which relies on intraoral hydrolysis by biofilm unspecific phosphatases to provide ionic F⁻ [136].

Toothpaste, and any F⁻-containing vehicle, sharply increases F⁻ concentration in the oral fluids (Fig. 14.9). However, the oral cavity acts as an open sink, and these high F⁻ concentrations decrease as saliva runs down the sink. After 1–2 h the F⁻ concentration in mixed saliva has returned to its original value. The F^- concentration in the toothpaste and the post-brushing habits, such as spitting or rinsing, determine the mean F^- levels in whole saliva and how rapidly salivary levels return to normal [24].

During toothbrushing, F^- is spread throughout the oral cavity, and soft tissues adsorb F^- that is released into saliva during subsequent minutes/hours [183, 184]. Moreover, F^- can be stored temporarily [61] on enamel surfaces and in dental biofilm. Indeed, salivary F^- levels may be maintained above resting levels for several hours [59]. Table 14.2 shows that 10 h after toothbrushing the F^- concentration in dental biofilm of the group using F^- dentifrice was higher than that found in a control group [29]. It is important to avoid water rinsing after toothbrushing to increase the available F^- in saliva, and avoiding vigorous rinsing (spit, do not swallow) seems to be important for the caries-reducing effect [56, 57].

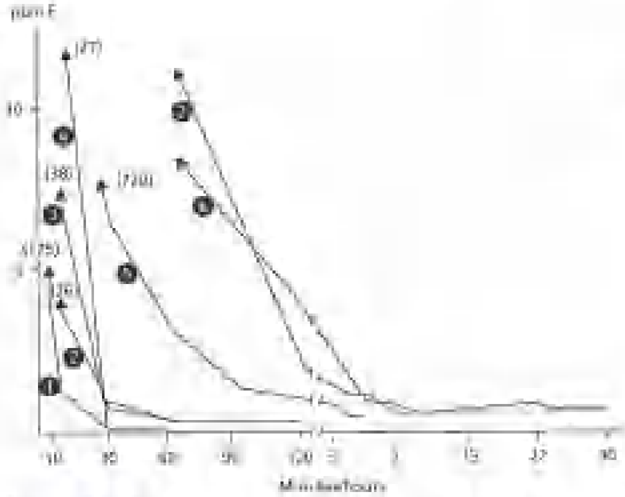


Figure 14.9 Mean F^- concentration in whole saliva after various topical F^- treatments. (1) Toothbrushing with NaF dentifrice (0.50 mg F^-) followed by 10 s mouth rinse with water. (2) Chewing of chewable F^- tablets (0.42 mg F^-). (3) Chewing of plain F^- tablets (0.50 mg F^-). (4) Chewing of F^--containing chewing gum (0.50 mg F^-) for 15 min. (5) A 2 min mouth rinse with 0.2% NaF solution. (6) Topical application of APF (1.2% F^-, pH 3.2). (7) Topical application of neutral 2% NaF solution. Figures in parentheses denote initial F^- concentration after 1–3 min [35]. Reproduced with permission from Wiley.

Table 14.2 F^- concentration in cariogenic dental biofilm formed in situ, according to the toothpaste used (mean ± SD, n = 14).

Toothpaste	Biofilm fluid (ppm F^-)	Biofilm solids (µmol F^-/g biofilm wet weight)
Nonfluoridated (placebo)	0.03 ± 0.01	0.4 ± 0.7
F^- toothpaste (1100 ppm F^-, as NaF, silica based)	0.05 ± 0.04*	0.7 ± 0.7*

From [29].
Toothpastes used three times/day over 14 days; analysis after overnight fasting 10 h after last exposure to toothpastes. Biofilm exposed to sucrose 10 times/day.
*Significantly higher than the respective values for the nonfluoridated group.

The relative importance of F^- taken up by enamel as CaF_2-like products during toothbrushing or simply absorbed into remaining biofilm as F^- ion on the caries process has been studied experimentally [168]. Results suggest that F^- dentifrice does not form sufficiently large reservoirs of CaF_2 on enamel to be effective in controlling caries [167].

Mouth rinsing with F^- solutions (0.05% or 0.2% NaF) gives rise to higher initial peak concentrations in whole saliva and longer lasting elimination periods than seen after use of F^- dentifrices (Fig. 14.9). Despite this, the transient increase of F^- implies that these treatments would need to be performed frequently to maintain elevated F^- levels in the oral fluids. Continued daily mouth rinsing with NaF/MFP solutions has shown sustained levels of markedly increased F^- concentrations in both saliva and dental plaque up to 18 h after last treatment [58, 82]. However, these are treatments that are not needed in individuals using F^- dentifrices unless we are dealing with very caries-active patients.

When dental health personnel apply concentrated topical fluorides (2% NaF painting, F^- gels or varnishes) the major product resulting from the reaction of F^- with dental apatite is a CaF_2-like mineral. The formation of CaF_2 is possible when F^- concentrations are above 100 ppm, although modest concentrations of CaF_2 may be formed after using toothpastes or rinses. The amount of CaF_2 formed will increase with increasing F^- activity, increasing exposure time, and decreasing pH in the treatment solution. Therefore, an acidulated fluorophosphates (APF) solution will enhance the availability of calcium ions dissolved from the dental apatite. The following equation illustrates that a low pH enhances CaF_2 precipitation due to the release of calcium from the tooth mineral:

$$Ca_{10}(PO_4)_6(OH)_2 + 20F^- + 8H^+ \rightarrow 10CaF_2 + 6HPO_4^{2-} + 2H_2O$$

This explains why high concentrations of CaF_2-like minerals form rapidly (1–4 min) during the application of APF, which contains around 12,300 ppm F^-, pH of 3.5. CaF_2 is also formed within caries lesions where the reaction area is increased by lesion porosity.

The formation of CaF_2 from F^- varnishes is not rapid because most of the F^- in varnishes is insoluble, as NaF particles in the varnish matrix. Therefore, to react with the tooth structure, the varnish must be kept on the surface for hours, allowing for the continuous solubilization of NaF from the saliva-imbedded varnish matrix. This is why the patient should not rinse or eat immediately after varnish application.

Saliva is unsaturated with respect to CaF_2 (see Chapter 9) and the salt gradually dissolves after a treatment. During a cariogenic challenge the pH is lowered and more CaF_2 is dissolved so that more ionic F^- is available to slow down lesion progression. The more porous an enamel surface, the deeper the porosities where CaF_2 may form. These inaccessible microporous environments in enamel caries lesions may thus act as reservoirs for CaF_2 for prolonged periods (i.e., months) [22]. This slow-release mechanism probably explains the caries-reducing effect of concentrated topical F^- treatments provided by dental personnel.

We can conclude that to obtain a significant caries reduction using F^- the ion has to be present in the oral fluids at slightly elevated levels regularly during the day. This may be obtained from water, toothpastes, and several other vehicles – but remember, caries is not the result of F^- deficiency. F^- alone is not sufficient to obtain maximum caries control (see Chapters 9 and 16). Because F^- in toothpaste is applied concomitantly with removal/disturbance of the biofilms – if used appropriately, which is a major obstacle – it is the best possible way of obtaining maximum caries control. As will be apparent from the efficiency considerations later in this chapter, other vehicles (and protocols) may be chosen depending on the populations you are serving. *Therefore, there is not one – and only one – program to be recommended to all individuals, and in all communities.*

Dental fluorosis and metabolism of fluoride

In order to appreciate the clinical characteristics of dental fluorosis, it is important to understand the underlying histological features of the pathological changes in the tooth. The earliest manifestation of dental fluorosis is an increase in enamel porosity along the striae of Retzius [69]. With an increased exposure to F^- during tooth formation, the enamel exhibits an increased porosity in the tooth surface along the entire tooth surface (Fig. 14.10).

This porosity, which is a result of a hypomineralization of the enamel, can be seen in microradiographs, mainly in the subsurface enamel (Fig. 14.11). Hypomineralization is very different from hypoplasia. The normal structure of the enamel remains but the tissue is less well mineralized. The extent and degree of hypomineralization increases with increasing F^- exposure during tooth development. In humans, the most severe forms of the hypomineralized lesion extend throughout the enamel almost to the enamel–dentine junction in the cervical third of the crowns (Fig. 14.10c), whereas in the occlusal two-thirds of the teeth the band of hypomineralization extends more than halfway through the enamel. Such severely hypomineralized enamel will be very fragile; hence, when the tooth erupts, surface damage may occur due to mastication, attrition, and abrasion (Fig. 14.12). It is important to appreciate that in humans F^- has not been documented to cause true

Figure 14.11 Microradiograph showing extensive hypomineralization of fluorosed enamel deep to a well-mineralized surface zone. Note incremental lines of Retzius. This represents a score of 4 according to the TF index.

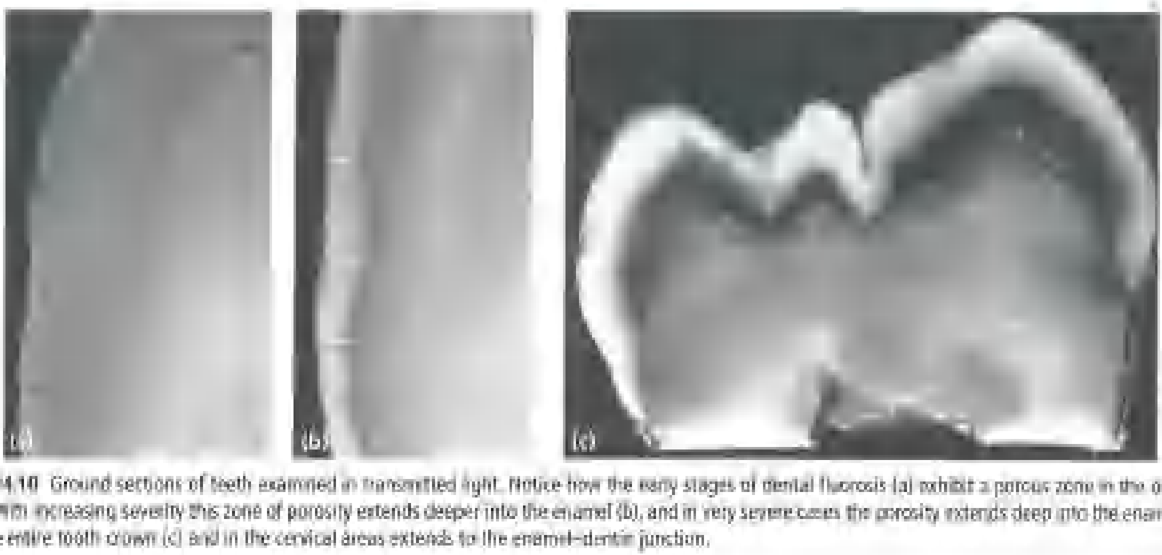


Figure 14.10 Ground sections of teeth examined in transmitted light. Notice how the early stages of dental fluorosis (a) exhibit a porous zone in the outermost enamel. With increasing severity this zone of porosity extends deeper into the enamel (b), and in very severe cases the porosity extends deep into the enamel tissue along the entire tooth crown (c) and in the cervical areas extends to the enamel–dentin junction.

hypoplastic changes; the characteristic pits, bands, and loss of extensive areas of enamel occur posteruptively and are not true hypoplasias.

Clinically, the porosity of the fluorosed enamel reflects itself as opacity of the enamel. Thus, F^--induced enamel changes at tooth eruption range from thin, white, opaque lines corresponding to the perikymata running across the tooth surface, to an entirely chalky white surface (Figs 14.13, 14.14, and 14.15). Depending upon the degree of hypomineralization, this chalky white enamel may then change posteruptively, due to mechanical damage, resulting in the more severe forms of fluorosis.

Dean's way of classifying dental fluorosis was based entirely on his interpretation of clinical appearance. In 1978, Thylstrup and Fejerskov proposed a way of recording dental fluorosis (TF-index) based on the histopathological features of the various degrees of dental fluorosis [169]. It is important to stress that the TF-index is a logical extension of the classification principles originally proposed by Dean; but, as would be expected, with a greater understanding of the underlying pathology, it is a more precise description of how to record early signs of fluorosis, as well as the more severe grades. Thylstrup and Fejerskov have ranged the severity of fluorosis in scores from 0 to 9 (Table 14.3 and Fig. 14.16).

This so-called TF-index represents a measurement on an ordinal scale and, therefore, should be considered only as an arbitrary point along a continuum of changes of the enamel. It is useful to compare the description found in Table 14.3 with the illustrations in Figs 14.12, 14.13, 14.14, 14.15, 14.17, and 14.18, where we can see that each score encompasses a small spectrum of fluorotic changes. It should be appreciated that if a child has been exposed to highly varying levels of F^- during the long-lasting period of tooth development, the intraoral distribution of fluorosis severity will be different to one who has been exposed to more constant F^- levels throughout the first 10–12 years of life [73, 102, 170]. The TF-index is the most appropriate

Figure 14.12 TF score 4 represents entirely white opaque enamel (see lower canine). As a reflection of the extension of subsurface hypomineralization, part of the surface enamel may break away posteruptively, creating TF scores 5–7. Brown discoloration of the porous enamel, which has occurred posteruptively, is also visible.

Figure 14.13 TF score 1: the earliest clinical sign of dental fluorosis appears as thin, white, opaque lines running across the tooth surface corresponding to the position of the perikymata.

Figure 14.14 In addition to the thin, white, opaque lines, the earliest signs of dental fluorosis may include small, opaque, white areas along cusp tips, incisal edges, or marginal ridges.

Figure 14.15 In TF score 2 the opaque white lines are more pronounced and frequently merge to form wider bands.

Table 14.3 The Thylstrup–Fejerskov index.

TF score	
0	The normal translucency of the glossy creamy-white enamel remains after wiping and drying of the surface
1	Thin white lines are seen running across the tooth surface. Such lines are found on all parts of the surface. The lines correspond to the position of the perikymata. In some cases, a slight 'snowcapping' of the cusps/incisal edges may also be seen
2	The opaque white lines are more pronounced and frequently merge to form small cloudy areas scattered over the whole surface. 'Snowcapping' of the incisal edges and cusp tips is common
3	Merging of the white lines occurs, and cloudy areas of opacity occur spread over many parts of the surface. In between the cloudy areas, white lines can also be seen
4	The entire surface exhibits a marked opacity, or appears chalky white. Parts of the surface exposed to attrition or wear appear to be less affected
5	The entire surface is opaque, and there are round pits (focal loss of the outermost enamel) that are less than 2 mm in diameter
6	The small pits may frequently be seen merging in the opaque enamel to form bands that are less than 2 mm in vertical height. In this class are also included surfaces where cuspal and facial enamel has chipped off, and the vertical dimension of the resulting damage is less than 2 mm
7	There is a loss of the outermost enamel in irregular areas, and less than half the surface is so involved. The remaining intact enamel is opaque
8	The loss of the outermost enamel involves more than half the enamel. The remaining intact enamel is opaque
9	The loss of the major part of the outer enamel results in a change of the anatomical shape of the surface/tooth. A cervical rim of opaque enamel is often noted

From Fejerskov et al. [73], as modified from the original work by Thylstrup and Fejerskov [169].

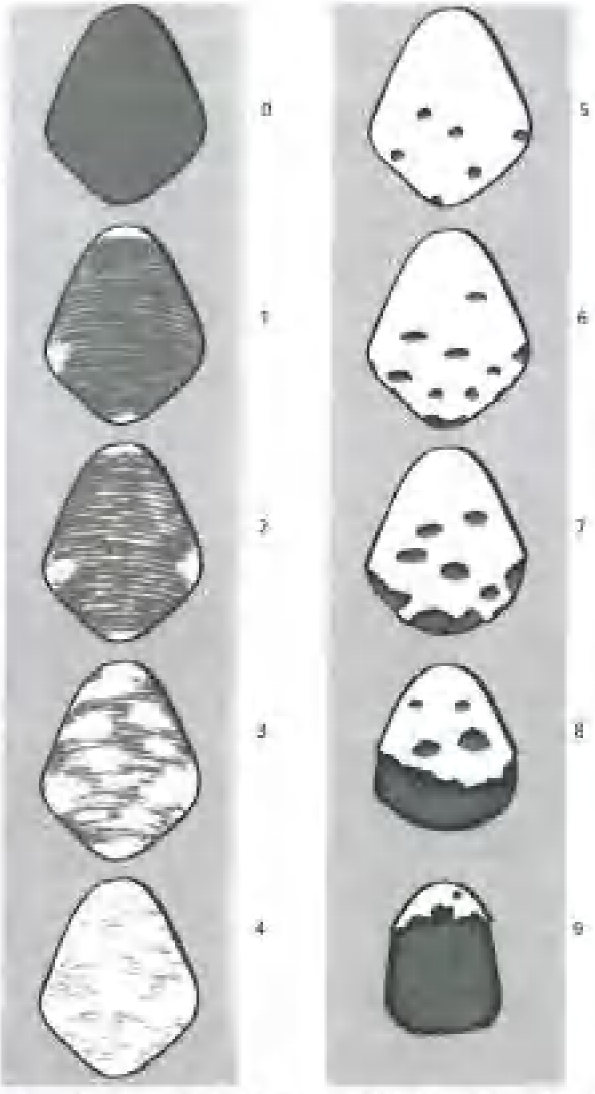


Figure 14.16 Diagrammatic illustration of the clinical features of dental fluorosis from the mildest form (TF 1) to the most severe (TF 9). Compare with Table 14.3.

Figure 14.17 In TF score 3 the entire tooth surface exhibits cloudy, white, opaque areas between which accentuated perikymata lines are evident.

Figure 14.18 Another example of TF score 3 with the addition of posteruptive staining of the porous enamel.

way to classify the *biological severity* of fluorosis as it accurately reflects past F^- exposure. In a later section of this chapter on effectiveness of fluorides the term *fluorosis of aesthetic concern* is introduced. This is highly subjective and reminiscent of the days where Dean talked about 'no public concern.' What is considered an aesthetic concern varies extensively from country to country – and often it is different in girls and boys. Therefore, when included in reviews it may give doubtful information which may lead to later misinterpretation and debates which should be prevented. An example: once, the first author was invited to a department of pediatric dentistry in the USA to calibrate the staff on how to record dental fluorosis – which the staff claimed was very rare in the county. He took with him a small handbook for health-care workers [73], and when the staff was looking at the pictures one said: 'we thought that it was natural to have these white teeth because everyone here looks like this – if this is the case we are having a high prevalence!'

Fluoride dose and dental fluorosis

It is remarkable that Dean's original data showed that the systemic effects of F^- on dental enamel were manifest even in communities exposed to concentrations of F^- below 1 ppm. Thus, the claim that water F^- concentrations around 1 ppm are 'of no public health significance' was for Dean not synonymous with saying that no dental fluorosis occurs in such populations.

Generally, any pharmaceutical product should be prescribed in relation to the body weight of the individual if its effect is systemic, but this does often not apply to F^- because its anticaries effect is local and not immediately concentration dependent, although the higher the concentrations in a toothpaste the longer time elevated F^- concentrations prevail (see 'Cariostatic mechanisms of fluoride' section). However, the F^- effect causing *fluorosis* is systemic and a dose–response effect would be expected. The use of water F^- concentrations has made attempts to produce valid estimates of a dose–response relationship between F^- ingestion and dental fluorosis difficult if weight and consumption are not considered. An accurate estimate of fluorosis severity can only be made in children when the permanent dentition erupts; hence, there is a considerable time lag between the F^- exposure during tooth formation and the measurement of the effect (dental fluorosis). In addition, no firm agreement exists as to how much F^- ingested from foods is in fact absorbed [166]. The bioavailability of F^- once ingested is relatively uncertain since the F^- compound in question and the contents of the stomach will determine the relative absorption of F^- by the organism. Therefore, the data about dose (expressed as mg F^-/day per kilogram body weight) for children from diet or dentifrice are dose of ingestion and do not reveal the fraction of F^- ingested that is in fact absorbed (bioavailable fraction). Furthermore, the suggested recommendations of 0.05–0.07 mg F^-/day per kilogram body weight [25] to give the anticaries benefit and minimize fluorosis has been shown not to be useful [115, 127].

However, despite all these difficulties, it is highly relevant to make use of the epidemiologic studies throughout the world which have shown a positive relationship between the water F^- content and severity of dental fluorosis [26, 46, 100, 108, 148, 169]. In an attempt to derive at an estimate of average water intake, daily consumption of water was related to air temperature, and Galagan and coworkers developed an equation that could describe the average water intake in relation to body weight in children as a function of air temperature [79–81]. For details on how to use these equations and calculate daily dose of F^- from drinking water, F^- tablets, and so on, the reader is referred to Fejerskov *et al.* [76]. When data from three large American epidemiological surveys conducted in the 1940s, 1960s, and 1980s are presented in such a way that the relationship between the average fluorosis score and daily F^- dose is calculated, a clear dose–response relationship is seen (Fig. 14.19) – for details concerning calculations, see [74, 75]. The following can be seen:

- Regardless of the source of the data, the regression of the fluorosis community index F_{ci} (Dean's way of averaging) on the daily dose of F^- from drinking water clearly demonstrates that even with very low F^- intake from water a certain level of dental fluorosis will be found.
- The dose–response relationship is clearly linear and the data indicate that for *every* increase of the dose of 0.01 mg F^- per kilogram body weight we can anticipate an increase in dental fluorosis in a population. Thus, there exists no 'critical' value for the F^- intake below which the effect on dental enamel will not be manifest.
- When the data originating from three distinctively different generations in the USA are examined – and hence a very different exposure to diet, commodities, and F^--containing dental products – there is no indication that the additional sources of F^- occurring until the mid-1980s have led to an upward shift of the dose–response curve.

When these data are kept in mind, it is to be expected that whenever more F^- is ingested in the form of tablets, salt, drops, toothpaste, and so on that both the prevalence and severity of dental fluorosis in a population will increase. Such an increase is not to be blamed, for example, on the F^- content per se in toothpastes, but is a simple reflection that dental fluorosis is a result of the total ingestion of fluorides during tooth development *irrespective of the source of the* F^-. The consequence of this, of course, is that if the water in any given area contains above 0.5 ppm F^- it is not acceptable uncritically to add further F^- for systemic use in such a population (e.g., salt). Furthermore, the estimation of an 'optimal F^- concentration' based on daily temperature

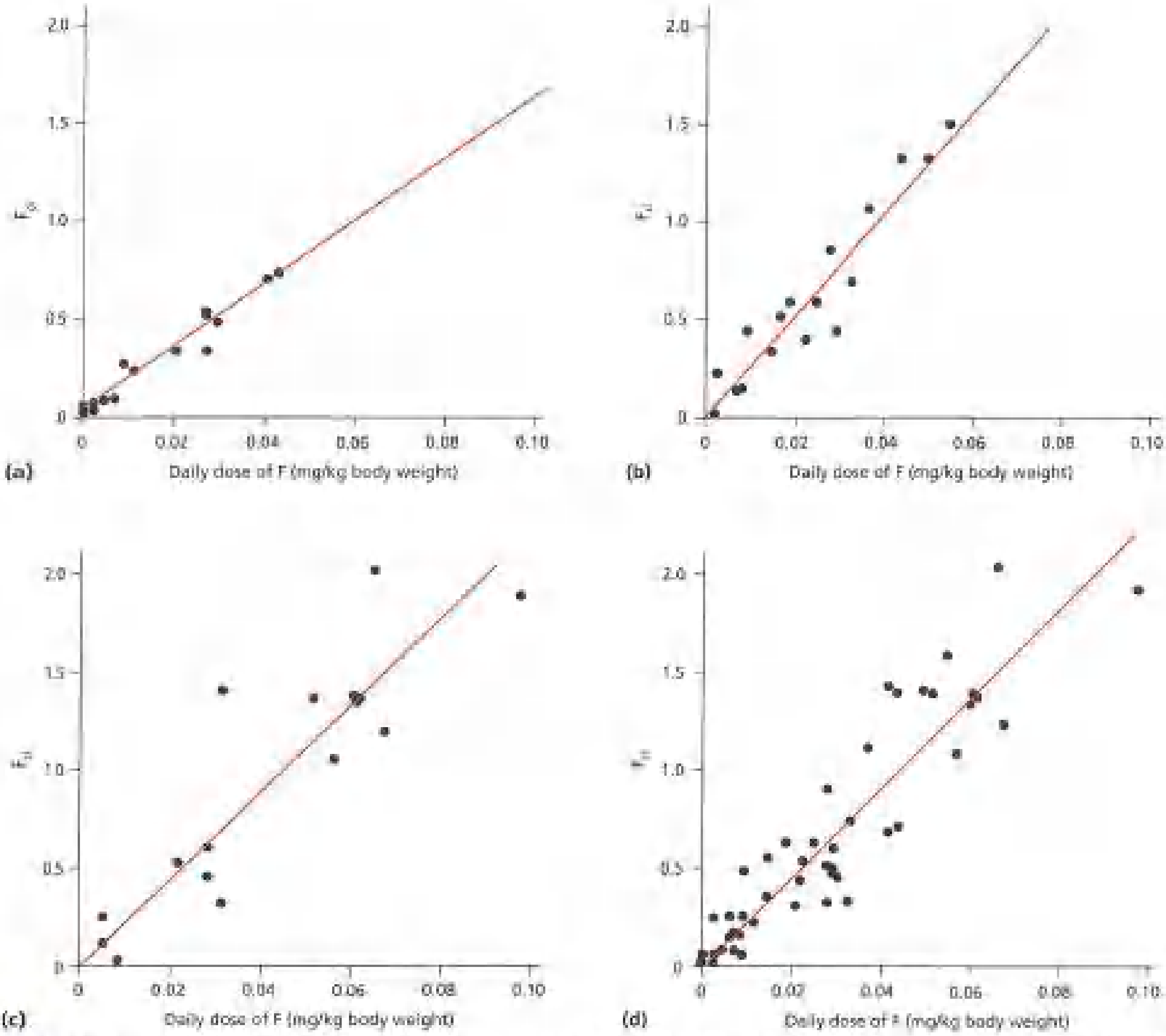


Figure 14.19 Relationship between F_{ci} and daily F^- dose pooling data. Sources: (a) [44, 45]; (b) [26]; (c, d) [148]. All data sets pooled as presented by Fejerskov *et al.* [74, 75].

seems not to be valid for tropical regions when additional fluids are consumed and higher daily F^- intake is estimated [106]. Therefore, in tropical countries having water with natural F^- concentration as low as 0.5 ppm, a higher prevalence and severity of dental fluorosis should be expected if the population simultaneously is using fluoridated salt; Colombia is a good example.

Calculations of this type are useful, for example, when interpreting the effect of giving F^- tablets to a population. Thus, when considering the effect of different F^- tablet dose regimes in the USA [1] and in Sweden [86], it is apparent that, had these dose–response curves been generated at the time when the F^- tablet regimes were developed, it would have been possible to predict the subsequent level of fluorosis.

It is also important to understand that, if we assume a constant dose of F^-, the effects of F^- are cumulative; hence, the longer the teeth undergo mineralization the more severe the fluorosis will be. Figure 14.20 shows data from a very low F^- area [101]. The highest prevalence and severity of fluorosis is seen in the second molar teeth, whilst the prevalence and severity in the first molars erupting 6 years earlier is much lower.

Figure 14.19 shows the linear relationship between daily F^- dose and fluorosis prevalence, over the dose range 0–0.1 mg per kilogram body weight. Therefore, even very low levels of F^- ingestion (0.02 mg F per kilogram body weight) constitute a small risk of fluorosis. We can also see that an ingestion of 0.1 mg F^- per kilogram body weight per day would almost certainly result in a significant risk of

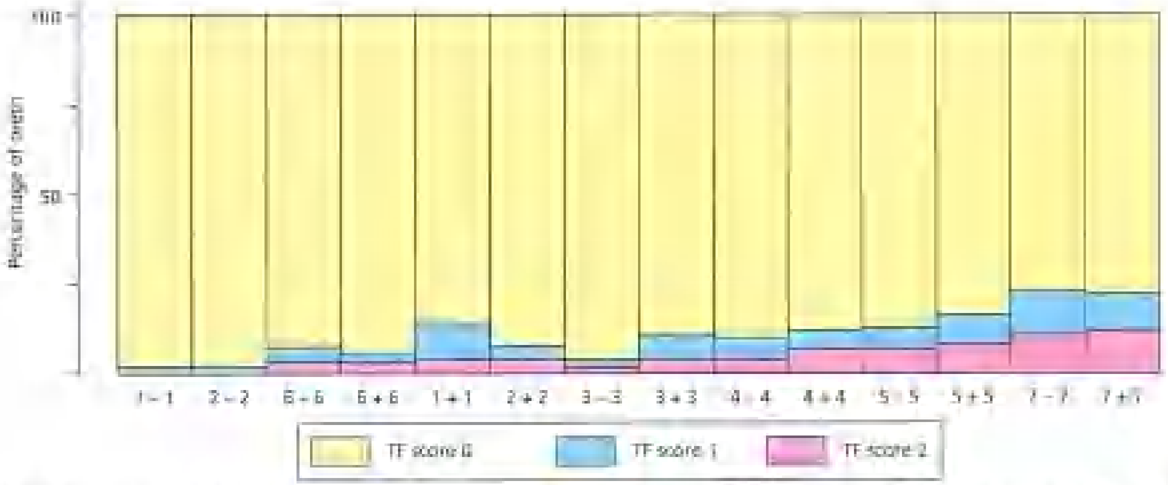


Figure 14.20 Diagram showing the percentage of teeth exhibiting dental fluorosis according to the TF classification. The tooth types are ranked from left to right in the order of mineralization. The data originate from children born and raised in an area of Denmark with less than 0.1 ppm F⁻ in the drinking water [101]. + maxillary teeth, − mandibular teeth.

developing the more aesthetically compromising forms. There is only a risk of developing dental fluorosis when the dentition is developing (from before birth to almost 20 years of age). From a cosmetic point of view, the permanent upper central incisors are particularly at risk between the ages of 15 and 30 months [67]. This can be explained when considering the data from Richards *et al.* [145] suggesting that dental fluorosis in humans results predominantly from a disturbance of enamel maturation. Although the weight of young children is highly variable, a 2-year-old child might be expected to weigh approximately 12 kg. We can therefore estimate that a F⁻ ingestion of 1.2 mg/day would constitute a very high risk of developing aesthetically compromising forms of fluorosis for a 2-year-old. As infants get older and heavier, the risk of fluorosis moves to the more posterior teeth, and because of the greater body weight the dose of F⁻ required to be ingested would be more. For example, a 5–6-year-old weighing approximately 20 kg would need to ingest approximately 2.0 mg. But at the same time, it should be remembered that the steady-state level of F⁻ in plasma will increase with age, so, if a child has been exposed to F⁻ from birth then such a child is likely to be more at risk than a child of the same weight who has not been lifelong exposed.

Calculations of F⁻ ingestion, although useful, are subject to many errors and must be treated with caution. Figure 14.21 represents the amounts of toothpaste (grams) required to be *ingested* to constitute an intake of 0.1 mg F⁻ per kilogram body weight for 12 and 20 kg children. Covering the head of a child's toothbrush would constitute an application of approximately 0.5–1 g of paste, and for a standard-head toothbrush it would be approximately 1–1.5 g of paste. It can be seen, therefore, that children brushing twice daily may be in contact with sufficient F⁻ to constitute a risk of dental fluorosis, particularly when using toothpastes containing the higher levels of F⁻. Young children tend to swallow a greater percentage of toothpaste than older ones [104], with 2-year-olds swallowing, on average half the toothpaste used and 6-year-olds swallowing one-quarter (Tables 14.4 and 14.5). Therefore, we must, on average, multiply the amounts shown by factors of 2 and 4 for the 2-year-old and 5–6-year-old children respectively.

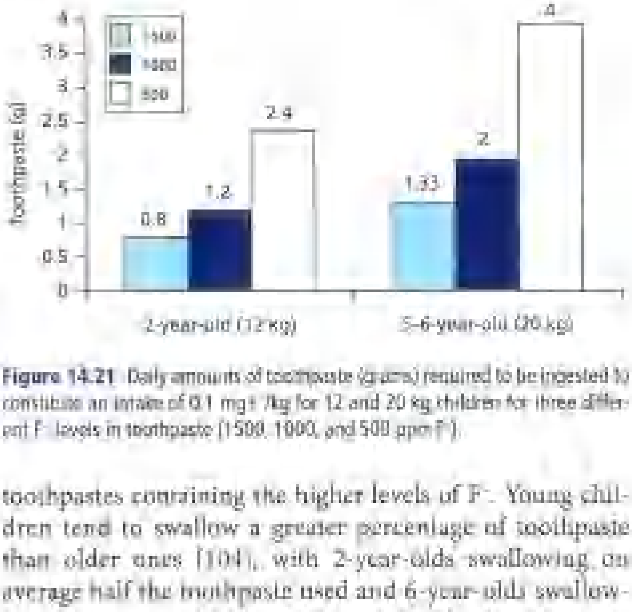


Figure 14.21 Daily amounts of toothpaste (grams) required to be ingested to constitute an intake of 0.1 mg F⁻/kg for 12 and 20 kg children for three different F⁻ levels in toothpaste (1500, 1000, and 500 ppm F⁻).

In addition, the amount of F⁻ absorbed from ingested toothpaste will depend on the gastric contents at time of ingestion and the type of toothpaste. Toothbrushing is usually conducted after meals, and this can significantly reduce F⁻ bioavailability. In fact, F⁻ bioavailability from an 1100 ppm toothpaste ingested after lunch can be very similar to that of a 550 ppm toothpaste ingested on fasting (Fig. 14.22). Regarding toothpaste composition, it should be considered that many affordable toothpastes are formulated with a calcium-based abrasive agent, and with MFP as the F⁻ salt. In these formulations, about 20–30% of F⁻ is

Table 14.4 Amount of dentifrice used per brushing (grams) or F⁻ per brushing (milligrams)[a] by age.

Study	Age range (years)						
	2–3	4	5	6–7	8–10	11–13	16–35
Ericsson and Forsman [65][b]		0.45		0.45			
Hargreaves *et al.* [88][c]			0.38			1.10	
Barnhart *et al.* [11][b]	0.86			0.94			1.39
Glass *et al.* [83][c]					1.04[d]		
Dowell [55][c]	0.55						
Bruun and Thylstrup [21][c]	0.55[d]			0.75[d]	1.10[d]		1.55[d]
Simard *et al.* [156][b]	0.46	0.78	0.65				
Naccache *et al.* [125][b]	0.50		0.47				
Naccache *et al.* [155][b]	0.55	0.45	0.52	0.50			
Mean value (no. of studies)	0.58 (6)	0.56 (3)	0.50 (4)	0.66 (4)	1.02 (3)	1.10 (1)	1.5 (2)

Source: [117].

[a] If one assumes that the dentifrice contains 0.1% (1000 ppm), then the ingestion of *x* g of dentifrice results in the ingestion of *x* mg of fluoride.

[b] Supervised dentifrice use study.

[c] Home-use study.

[d] No attempt was made to control for spillage of dentifrice.

Table 14.5 Percentage ingestion of dentifrice fluoride by age.

Study	Age range (years)						
	2–3	4	5	6–7	8–10	11–13	16–35
Ericsson and Forsman [65][a]		30		25			
Hargreaves *et al.* [88][b]			28				
Barnhart *et al.* [11][a]	35			14		6	3
Glass *et al.* [83][b]					12[c]		
Simard *et al.* [156][a]	59	48	34				
Naccache *et al.* [125][a]	41		30				
Naccache *et al.* [126][a]	57	49	42	34			
Mean value (no. of studies)	48 (6)	42 (3)	34 (4)	25 (3)	12 (1)	6 (1)	3 (1)

Source: [132].

[a] Supervised dentifrice use study.

[b] Home-use study.

[c] No attempt was made to control for spillage of dentifrice.

bound to calcium, being insoluble and not absorbable. Therefore, if total F⁻ in such formulations is considered to calculate the dose to which children are exposed by inadvertent ingestion during toothbrushing, a dose twice as high would be found when compared with a formulation in which all F⁻ is soluble (e.g., a silica base, NaF toothpaste). However, if only the soluble (bioavailable) F⁻ fraction in both types of formulations is considered, the bioavailable dose would be similar [133] (Table 14.6). Unfortunately, this has not been considered when the risk of fluorosis by toothpaste ingestion is discussed; and as most publications overestimate the effect of toothpaste alone or the relative contribution of F⁻ toothpaste to total daily F⁻ ingestion by young children, this has had implications on the recommendations of toothpaste use by children [66].

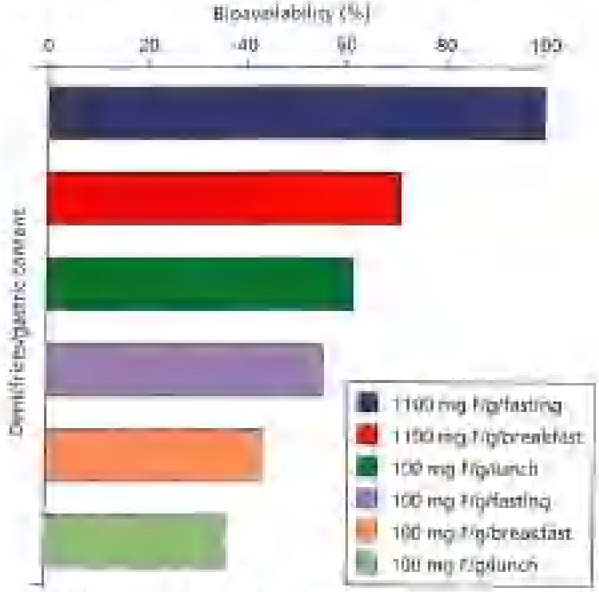


Figure 14.22 Bioavailability of F⁻ ingested from toothpastes, depending on the content of the stomach. From [42].

Table 14.6 Estimated dose of F⁻ (mg F/kg body weight per day) to which a sample of Brazilian children were subjected during toothbrushing with MFP/CaCO$_3$ or NaF/silica formulations, based on total or soluble F⁻ concentrations in toothpastes (mean ± SD).

Toothpaste formulations	Dose based on F⁻ concentration determined in toothpaste	
	Total F⁻	Soluble F⁻
MFP/CaCO$_3$[a] (n = 80 children)	0.074 ± 0.007	0.039 ± 0.005
NaF/silica (n = 79 children)	0.039 ± 0.003	0.039 ± 0.005
All (n = 159 children)	0.057 ± 0.004	0.039 ± 0.003

From [133].

[a] MFP/CaCO$_3$ toothpastes formulated with a higher total F⁻ concentration (1500 ppm F⁻) but with similar soluble F⁻ concentration (1000–1100 ppm F⁻) when compared with NaF/silica toothpastes (1000–1100 ppm F⁻).

Tables 14.4 and 14.7 show that the amount of toothpaste children use is fairly consistent between the ages of 2 and 7. This has important consequences for fluorosis risk. Young children not only swallow more toothpaste and are often not supervised when brushing, but they also are at greater risk of fluorosis as their body weight is lower than older children. Therefore, we must be particularly cautious when using F⁻ toothpaste in the youngest children and ensure that small (pea-sized or in Brazil rice sized) amounts are used and they are encouraged to spit out the waste toothpaste slurry as efficiently as possible [14, 13].

Although the quantity of F⁻ swallowed from toothpaste is not as high as often anticipated, F⁻ in toothpaste will add to an increase in overall F⁻ consumption and hence increase the risk of developing more fluorosis in populations living in areas with F⁻ in the drinking water or using other forms

Table 14.2 Estimated median weights of children [94] and fluoride intake according to age estimated from twice daily use of a 1000 ppm F toothpaste [88].

Age	Median weight of child (kg)	Toothpaste use per day (g)	Toothpaste ingested (%)	(mg F⁻/kg for 1000 ppm F⁻ toothpaste)
2	11.9	1.16	48	0.047
3	14.3	1.16	48	0.039
4	16.3	1.12	47	0.029
5	18.3	1.00	34	0.019
6	20.6	1.32	25	0.013

Source: [78].

of systemic F^-, such as tablets or salt. In regions with fluoridated drinking water there are a number of studies reporting a relationship between F^- ingestion from toothpaste and milder forms of dental fluorosis [120, 134, 137–139, 149, 180]. In countries, like the USA and Brazil, where water fluoridation is widespread and the use of F^- toothpaste is common, the most prevalent degree of dental fluorosis found is claimed to be 'mild' and not of 'public health concern' [31, 53, 123, 140, 141]. Whether a degree of dental fluorosis is of 'public health concern' is very culturally dependent. If living in an area with widespread milder forms of fluorosis, this is often considered 'normal'.

Where is fluoride found in nature?

F^- is a trace element widely present in the environment. F^- gets into the hydrosphere by leaching from soils and minerals into ground waters. Volcanic eruptions and dust storms in areas rich in volcanic rocks add to the F^- in the atmosphere.

Owing to the small radius of the fluorine atom, it is the most electronegative and reactive element and is rarely found in its elemental state. It is most commonly found in combination in the ionic F^- and the electrovalent or covalent form. Most of the ionic fluorides are soluble in water, although some, such as CaF_2, are only slightly soluble. Further information is available from the detailed textbook chapters by Smith and Ekstrand [158] and Clemser [84].

Water is by far the most common natural source of F^-, but even in areas with levels of F^- in the drinking water less than 0.5–0.7 mg/L, the importation of commercially prepared beverages and other foods from areas where water supplies contain higher levels can add substantially to the amount of F^- ingested. Some fruit-flavored, carbonated soft drinks and mineral water may also contain significant (0.7–0.9 mg/L) amounts of F^- [38, 152]. Fish is a particularly good source of F^-, as are tea leaves, although they differ on F^- bioavailability. A cup of tea [56] or iced tea [89] may have a F^- concentration of 0.5–4 mg/L. An assessment of the total exposure of a given population to F^- requires not only a thorough knowledge of the F^- concentrations of foods and beverages and an understanding of the open markets of a modern society, but also a careful assessment of potential F^- ingestion from dental products.

Fluoride absorption, distribution, and elimination in the body

F^- ingestion is particularly important in infants as dental fluorosis can only occur when teeth are developing. F^- is poorly transported from plasma to breast milk, even when the mother or animal has a high intake of F^-, and human and other mammalian milks contain very low concentrations of F^- [159]. In contrast, commercially prepared formula milks may have a highly variable F^- content, and if they are prepared with fluoridated water, children may potentially ingest considerable amounts of F^- from this source [78, 185].

It is outside the scope of this textbook to deal in detail with F^- metabolism in humans, but any dentist should be expected to have a thorough knowledge about the pharmacokinetics of F^- and are referred to authoritative texts (see Ekstrand [60] and Whitford [179] for reviews). Following ingestion, soluble F^- is rapidly absorbed into the blood plasma, predominantly in the stomach. The stomach contents are important in determining the rate of absorption. Milk, calcium-rich breakfasts, and even lunch may reduce the degree of absorption from about 90% to about 60%. The time of F^- ingestion in relation to meals is critical with respect to how much of the F^- will become bioavailable [42, 64]. Also, when toothpastes are ingested by children, the amount of F^- that is absorbed depends on toothpaste formulation because in those containing calcium in the abrasive only part of the F^- is bioavailable [150].

F^- not absorbed in gastrointestinal tract is excreted by feces, which usually accounts for less than 10% of the amount ingested each day by diet [63]. F^- is distributed all over the body by plasma, predominantly as ionic F^-. Plasma F^- concentrations vary considerably over the day depending on the intake of F^-. With increasing age, plasma F^- levels gradually increase because there is a direct relationship between the amounts of F^- accumulating in bone, which, as time passes by, is gradually released from the bone as part of bone remodeling [135]. There is no homeostatic mechanism to maintain the F^- concentration in any body compartment, and blood F^- levels are largely dependent upon daily intake. This has important implications for the oral environment, as will be described further in this chapter.

F^- is distributed from the plasma to all tissues and organs in body. Naturally, the degree of blood flow through the different types of tissues determines how rapidly distribution occurs. Of particular interest is that the kidney in general has a higher concentration of F^- than the corresponding concentration in plasma (high ratio tissue/plasma). In contrast, the central nervous system, like adipose tissue only contains about 20% of the concentration of that of plasma [160].

As previously stressed, F⁻ is a highly reactive agent and it reacts rapidly with mineralizing tissues. Over time the F⁻ gradually becomes incorporated into the crystal lattice structure in the form of fluorhydroxyapatite. It is during the growth phase of the skeleton, during active mineralization, that the highest proportion of an ingested F⁻ dose will be deposited. Thus, retention of F⁻ in infants may be as high as 90%, whereas in adults only about 50% of the F⁻ may be retained in the bone.

F⁻ in the bone is not irreversibly bound to the crystals. Bone in humans constantly undergoes remodeling and F⁻ is thus mobilized slowly from the skeleton. Therefore, when studying cross-sectional samples, F⁻ concentrations in plasma and urine will not only be determined by the immediate past intake of F⁻ but also by earlier F⁻ exposure and the degree of accumulation of F⁻ in bone. Moreover, with age the mobilization rate from bone and how efficient the kidneys are at excreting F⁻ will strongly influence such data [62]. Thus, bone might be considered a F⁻ reservoir that maintains F⁻ concentrations in the body fluids between the periods that F⁻ is not being ingested.

F⁻ absorbed and not incorporated in bone is eliminated mainly by urine during the excretion. If the pH of urine is low, F⁻ is reabsorbed in renal tubules, returning to the blood [179]. This mechanism may be important regarding the chronic effect of F⁻ because the duration of high plasma F⁻ concentration is prolonged.

Fluoride concentrations in teeth

Concentrations of F⁻ in all mineralized tissues will vary depending on the actual F⁻ intake and the length of time during which such an intake has taken place. The F⁻ concentration in bulk enamel is fairly constant but increases steeply at the surface within the outer 100 μm. Recently, this has been suggested to be a result of the fluctuating pH changes in the surface of enamel caused by the ameloblasts during the long-lasting phase of enamel maturation, which in permanent teeth may last for several years before eruption [96]. The F⁻ concentration of dentin is generally slightly higher than that of bulk enamel and usually increases as we go deeper into the tooth (Fig. 14.23). As dentin formation continues slowly throughout life, F⁻ steadily accumulates at the dentin–pulpal interface.

It can be seen in Fig. 14.23 that the overall shape of the F⁻ profile from the surface of the enamel to the enamel–dentin junction is a characteristic 'hockey stick' shape. The relative concentrations of F⁻ in the different layers of enamel reflect the F⁻ exposure during tooth development. Hence, the higher the dose of F⁻ occurring during development, the higher the concentration of F⁻ is to be found in enamel. The effect of different levels of F⁻ exposure can be seen in Fig. 14.24. Clearly, teeth with the more severe forms of fluorosis (TF scores 7 + 8 + 9) have significantly higher levels of F⁻ in the enamel than those with less severe forms, and this difference is maintained even deeper in the enamel. The concentration of F⁻ at the outermost surface of the enamel is not only an indicator of F⁻ exposure during the developmental period of the tooth but also highly dependent upon post-eruptive changes (see Fig. 14.25).

Once the enamel is fully formed and mineralized, the F⁻ content in human enamel can only be permanently altered as a result of chemical traumas to the tooth (dental caries and erosions) or through mechanical abrasion. Unless chemical interactions take place with substantial fluctuations in pH over a prolonged period of time it is in fact not easy to significantly change the F⁻ content in the surface enamel even after several topical F⁻ treatments. However, the F⁻ concentration in the surface layers increases whenever de- and remineralization processes are ongoing [40, 146, 178]. This means that, in cervical regions, where dental plaque accumulates, F⁻ concentrations will gradually increase over time. It is also the reason why the surface zone covering a subsurface carious lesion contains significantly higher amounts of F⁻ than the surrounding normal enamel (Fig. 14.26).

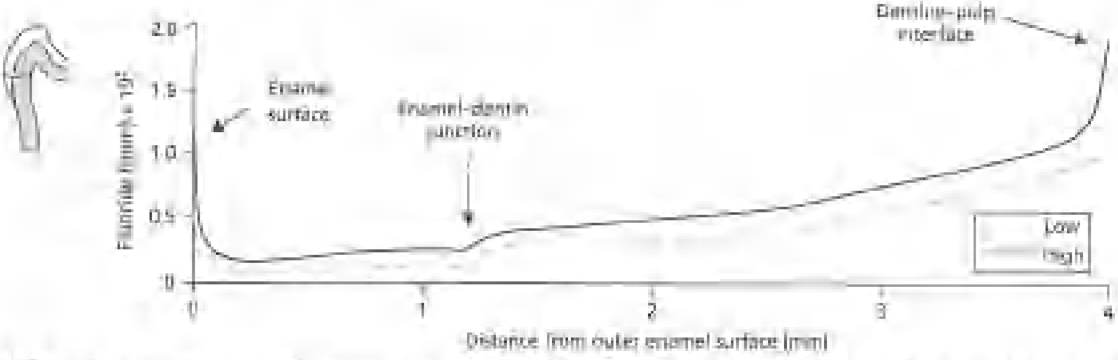


Figure 14.23 Schematic representation of the F⁻ concentration in enamel and dentin from the outer surface of the enamel to the dentin–pulp interface for subjects with a low and higher F⁻ intake.

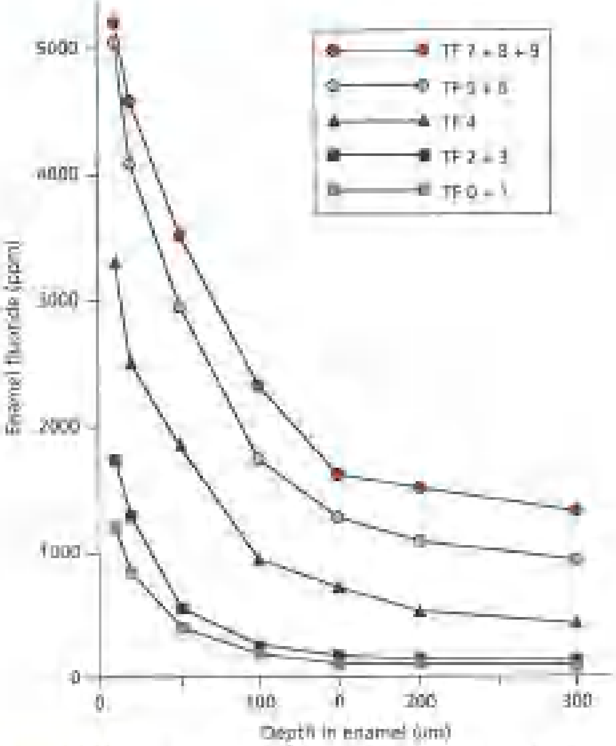


Figure 14.24 Enamel F^- concentrations in the outer 300 µm of the enamel in erupted teeth with different degrees of fluorosis. See Fig. 14.16 for explanation of the TF index [146].

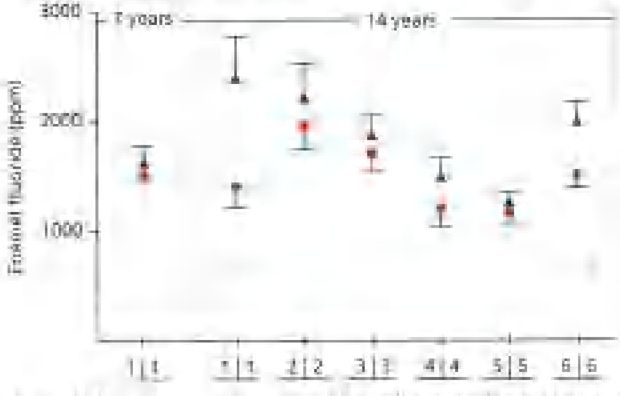


Figure 14.25 F^- concentration measured in surface enamel *in vivo* in upper central incisors at the age of about 7 years (shortly after eruption). The concentration is the same in central and cervical enamel. However, after 7 years in the oral environment it is apparent that F^- in the cervical enamel (where plaque accumulates) increases, whereas it remains unchanged or gradually drops in central parts that have been exposed to attrition/toothbrushing [144].

The difference in F^- content of enamel formed in low F^- areas (<0.2 ppm F^- in the water supply) and an area with about 1 ppm of F^- is so small that it cannot explain differences in caries experience in populations living in low and higher F^- areas. Also, even in the enamel surface, where F^- concentration is 'maximum,' it represents only a substitution of 5–10% of hydroxyl by F^- ions and it is necessary to have 60% of substitution to form a mineral that is more acid resistant. Moreover, there is no association between the F^- concentration in the surface zone of teeth and the individual's caries experience for either the primary or permanent teeth (Fig. 14.27).

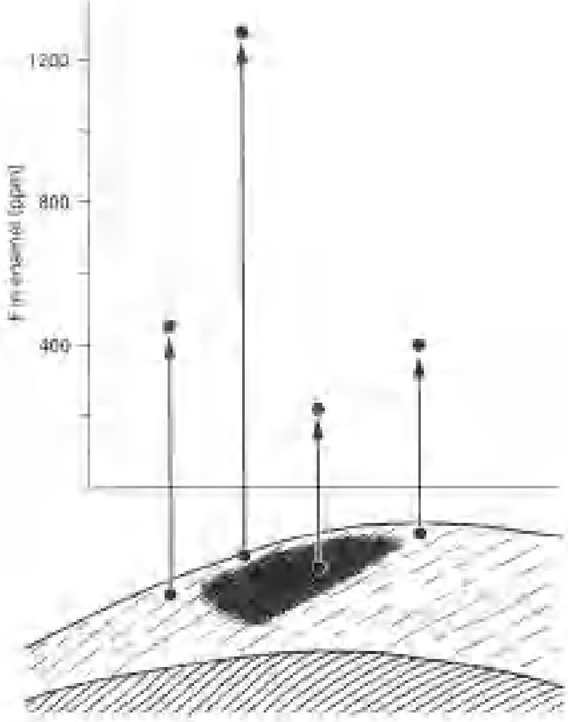


Figure 14.26 Fluoride concentrations in sound and carious enamel. The lowest concentrations are found in body of the lesion and then the sound bulk enamel. The surface enamel layer covering the lesion has picked up considerable amounts of F^- from the surrounding fluids. Modified from [178].

Pathogenesis of dental fluorosis

Until the 1970s it was generally assumed that F^- caused dental fluorosis by interfering with the process of enamel matrix formation and mineralization and that the secretory ameloblast was highly sensitive to slightly elevated plasma concentrations of F^-. However, microscopic studies of human enamel [69, 70] showed that enamel fluorosis was a hypomineralization of the enamel in an otherwise normal enamel maturation. Therefore, it was suggested that F^- predominantly affected enamel by retarding the processes of pre-eruptive enamel maturation [71]. Moreover, the studies showed that enamel pits resulted from mechanical damage to the enamel after eruption of the tooth [10, 73]. To test the hypothesis that dental fluorosis might be a result of F^- delaying otherwise normal enamel maturation, Richards and coworkers [5, 145] conducted a series of experiments in domestic pigs which clearly showed that F^- given systemically during enamel maturation only, in dosages comparable to humans, would result in subsurface hypomineralized

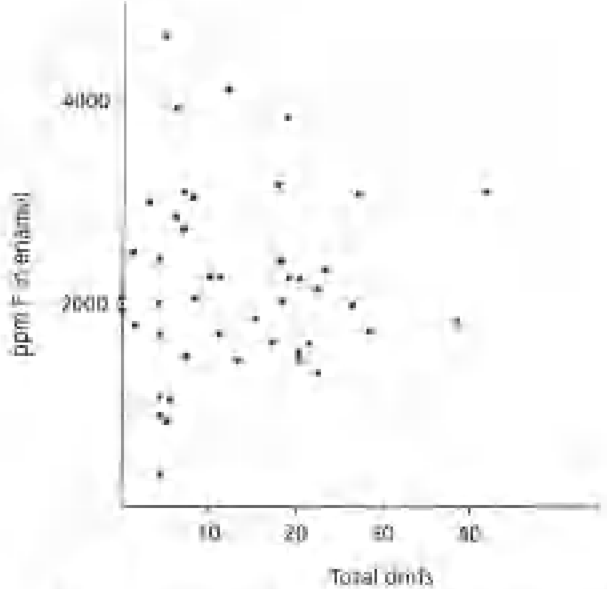


Figure 14.27 F^- concentrations in the surface enamel of deciduous canines and dental caries prevalence in the deciduous dentition. No relationship between the two is apparent [143]. Reproduced with permission of Karger Publishers.

enamel at the time of eruption. How F^- ingested in just slightly elevated concentrations over several years can influence enamel maturation at the time of pre-eruptive maturation is still unknown!

It should be understood that once the full width of enamel is laid down the enamel is far from fully mineralized. The transformation of soft, protein-rich enamel into highly mineralized, hard mature enamel is a result of growth in size of the already seeded crystals. Once a matrix is laid down, the apatite crystals are instantaneously seeded and mineral increase occurs as a result of longitudinal growth of the crystals. In fact, in rats it has been calculated that the enamel contains only about 18–20% of mineral after being fully formed (see [157] for a review). Following this the enamel matrix proteins have to be broken down and removed from the enamel while calcium and phosphates have to be simultaneously transported into the enamel and allowed to precipitate onto the growing crystal surfaces. The hydroxyl apatite crystals grow predominantly in width and thickness until the enamel contains about 96% mineral by weight. Enamel crystals grow very slowly, and pre-eruptive enamel maturation may last for several years in humans! Despite extensive studies on normal enamel maturation in experimental animals, the processes leading to a fully mineralized enamel are far from understood [96]. Therefore, it is speculative as to how F^- in small elevated dosages in plasma may interfere with the processes.

In a review, Aoba and Fejerskov [6] discussed in depth the various possibilities for how F^- ions may influence enamel mineralization during tooth development. Enamel mineralization is highly sensitive to free F^- ions promoting the hydrolysis of acidic precursors to apatite formation, such as octacalcium phosphate. This results in precipitation of fluoridated apatite crystals.

The effectiveness of fluorides in the control of dental caries: evidence from systematic reviews

Evidence from comprehensive systematic reviews on fluorides for caries prevention and control has come to occupy a key position between research and practice in the last decade. As reliable summaries of accumulated knowledge, they inform decisions, are the basis for recommendations about the appropriate use of F^--based caries preventive interventions, and are making clearer the scientific justification for future research on the subject. Cochrane reviews are systematic reviews that employ rigorous research methods and are published in full in *The Cochrane Library* (http://www.thecochranelibrary.com) following a detailed editorial process that is common to all reviews. Cochrane reviews have answered important questions regarding the effects of F^- on caries prevention. Consequently, they have become very influential as a foundation for preventive practice and policy in dentistry.

The UK National Health Service (NHS) Centre for Reviews and Dissemination's (CRD's) review of the effects of water fluoridation was the first systematic review undertaken on the subject. This systematic review was set up by the University of York and is colloquially known as the York review. It was conducted as an open process and to the highest standards [118]. This review has shown that research carried out over the past half century has been of a much lower methodological quality than had previously been reported. This review pointed out that the evidence of a benefit of a reduction in dental caries should be considered together with the evidence of an increased prevalence of dental fluorosis, and that there would continue to be a need for high-quality studies providing more definite current evidence on the effects, both positive and negative, of water fluoridation. The findings of this review published in 2000, which have been interpreted in quite different ways on both sides of the fluoridation debate, reinforced the importance of systematic reviews of the large body of experimental evidence on the effects of all the main forms of F^- treatments used for caries prevention/control.

The series of Cochrane systematic reviews on the effectiveness and safety of F^- toothpastes, mouthrinses, gels, and varnishes published throughout the last decade are considered the most comprehensive and most detailed on the subject to date [109–115, 176, 180]. They bring together, in a consistent manner, the available evidence on the effects of the main modalities of topically applied F^- interventions currently used for the prevention/control of dental caries.

and examine systematically the main factors that can influence their effectiveness. These reviews have clearly confirmed the relative effectiveness of F^- toothpastes, mouthrinses, gels, and varnishes, and showed that some additional caries reduction can be expected when another topically applied F^- treatment is combined with F^- toothpaste.

Moreover, since the York review on the effects of water fluoridation was published there has been no other high-quality systematic review that would alter its findings, which has been chosen to form the evidence base on the effects of water fluoridation on dental caries in subsequent overviews and guidelines on the topic, such as the Australian National Health and Medical Research Council review (NHMRC, 2007).

The evidence available from the above-mentioned CRD and Cochrane F^- reviews, on the effectiveness and safety of water fluoridation and topically-applied F^- treatments – toothpastes, mouthrinses, gels, and varnishes – are the focus of this section. The evidence available from several subsequent Cochrane reviews on the effectiveness of other F^- treatment modalities for preventing caries – slow-release F^- devices, milk fluoridation, and F^- supplements/tablets [18, 172, 182] – are also presented here, together with the latest evidence from systematic reviews on the caries-preventive effect of salt fluoridation [128, 181].

However, the section highlights first the importance of systematic reviews, especially Cochrane reviews, in informing decisions in health care, with a brief history of the evaluation of the effectiveness of fluorides in such reviews, and it concludes by considering relevant implications for research and practice.

Systematic reviews as objective summaries of the best evidence from research in informing decisions in health care, and the importance of Cochrane reviews

Decisions about the appropriate provision of preventive or therapeutic strategies should be informed by knowledge of the effects of the interventions, and require that this knowledge is quantitative. The formal synthesis of research evidence can help increase access to this knowledge base by ordering and summarizing the evidence available and by increasing the precision of estimates of effect. Systematic reviews locate, appraise, and synthesize the evidence from relevant and valid studies in order to provide informative empirical answers to research questions. Unlike other types of reviews that do not adhere to an explicit method, and tend to be based on only a selection of the literature and thereby may be open to substantial bias and chance errors, systematic reviews aim to avoid these pitfalls by presenting an objective and comprehensive scientific summary of the available evidence.

In addition, by including a quantitative synthesis of the results of individual experimental studies, a meta-analysis in a systematic review, this can provide valuable insights concerning the *effectiveness* of health-care interventions. This is achieved through the epidemiological exploration and evaluation of the included studies, especially when these are randomized controlled trials (RCTs), considered the most reliable type of study design for assembling comparison groups on which to base causal inferences about the effects of care [100]. *Effectiveness* can be defined as the extent to which a specific intervention, when used under ordinary circumstances, does what it is intended to do – clinical trials that assess effectiveness are sometimes called pragmatic trials. *Efficacy*, on the other hand, is the extent to which an intervention produces a beneficial result under ideal conditions – clinical trials that assess efficacy are sometimes called explanatory trials and are restricted to participants who fully cooperate. Systematic reviews using meta-analysis of multiple well-designed RCTs are therefore often the most robust type of research evidence to guide decisions and research about effectiveness (Table 14.8). This is because, in most circumstances, the effect of an intervention will not be very large. So a large amount of randomized evidence pooled together is needed to detect or refute reliably such moderate but potentially worthwhile effects [37].

The Cochrane Collaboration (http://www.cochrane.org/), an international nonprofit organization established in the early 1990s, challenged those working in health care to put policy and practice on a footing of strong, critically appraised and objectively synthesized evidence. The Collaboration makes reliable information about the effects of health-care interventions readily available worldwide in the form of Cochrane reviews, which are largely funded through government sources [30, 36]. Cochrane reviews, which concentrate mainly, but not exclusively, on synthesizing the evidence from randomized studies, have been shown to be of higher methodological quality on average, than other systematic reviews [85, 93, 94, 97]. The degree of certainty any Cochrane review provides, however, depends on the quality of the evidence that has been included in the review, where the level of quality of evidence will not only depend on the risk of bias and the directness of the evidence, but also on the consistency and precision of the findings [152].

Table 14.8 Hierarchy of evidence about effectiveness (for therapeutic interventions)

Level	Research evidence type
I	Systematic reviews of multiple RCTs, at least one RCT
II	Quasi-experimental studies, controlled trials without randomization
III	Observational analytic studies (cohort, case–control studies)
IV	Descriptive studies, other observational studies without control groups (cross-sectional, ecological studies, case series)
V	Expert opinion, consensus

Systematic reviews on the effectiveness of fluorides, with a special focus on the Cochrane fluoride reviews

Since the mid 1960s, the various F^- interventions – in the form of toothpastes, mouthrinses, gels, and varnishes mainly – have been subjected to intensive clinical testing in RCTs, the least biased evidence type from primary research into effectiveness. However, less conclusive study designs have been used to assess the effectiveness of F^- in drinking water and F^- added to salt.

Yet, it is only relatively recently that this evidence started to be summarized more objectively in rigorous systematic reviews, taking such differences in study question and design systematically into account. It is even more recently that decisions and recommendations for the appropriate use of F^- for caries control are being based on the results of such reviews. This is despite the fact that reviews employing meta-analysis of controlled trials summarizing the evidence on fluorides for caries prevention had started to appear as early as in the mid 1980s in dentistry [35, 162], coinciding with the growth in their availability in the field of medicine.

Nevertheless, the general picture in the early1990s was that the effectiveness of fluorides in caries prevention had been extensively summarized in traditional narrative reviews based on selected published literature, and effectiveness estimates had been reported in broad ranges with no general agreement on the causes of differences in reported effectiveness. However, by the end of the 1990s various reviews focusing mainly on the evaluation of specific F^- active agents within specific delivery systems had used the quantitative meta-analytical approach to synthesize study results [13, 90, 93, 161, 164, 175].

Furthermore, the systematic reviews published since 2000 have compiled evidence synthesized from hundreds of reports of RCTs, as well as nonrandomized evidence (from other types of studies), on the effects of fluorides in various forms [4, 12, 18, 27, 32, 87, 109–115, 118, 142, 163, 165, 172–174, 176, 180–182]. The large number of systematic reviews of trials published between 2002 and 2004 in particular are associated with the publication of the first Cochrane reviews [109–115] and the reviews from the Swedish Council of Technology Assessment in Health Care reviews [142, 173, 174], all of which assess the effectiveness of F^- toothpastes, mouthrinses, gels, and varnishes.

Recommendations systematically developed for the appropriate use of F^- in different settings/countries in practice guidelines are based largely on the results of the series of Cochrane F^- reviews for preventing caries in children and adolescents [109–115, 176, 180] and on the UK NHS CRD systematic review on water fluoridation [118]. They form the basis of the international evidence base used in numerous guidance documents worldwide [3, 20, 66, 128, 154].

Thus, the main features and findings of the York review on water fluoridation are presented next, followed by those of the Cochrane F^- reviews, mainly in terms of the relative and combined caries-preventive effectiveness of the various F^- modalities, and their safety, in an attempt to account for any assessment of beneficial and undesirable (adverse) effects.

Before presenting the evidence from each systematic review, however, an explanation would appear important in order to facilitate the interpretation of the results from systematic reviews of caries trials.

Measuring treatment effect in systematic reviews of caries trials

When estimating effectiveness in caries trials of fluorides, the primary outcome measure is usually caries increment in treatment and control groups, where a typical measure is increment in decayed, missing, and filled surfaces (DMFS). There are several variations of this measure (e.g., DMFS, DFS, DS, DMFT, DFT), however, and also different levels at which dental caries is defined/diagnosed, different methods of detecting dental caries, and so on (see also Chapter 4).

It is important to realize that when combining the results of caries trials of F^- effectiveness in a meta-analysis in most systematic reviews the chosen measure of treatment effect is the prevented fraction (PF). This is the difference in mean caries increments between the 'treatment' and 'control' groups divided by the mean increment in the control group:

$$PF = \frac{m_c - m_t}{m_c}$$

It can be expressed as a percentage of the mean increment in the control group – the so-called percentage reductions in caries increment, which is the usual measure of effect in trials of caries preventive interventions. For an outcome such as caries increment (where discrete counts are considered to approximate to a continuous scale and are treated as continuous data), the PF is generally considered a more appropriate measure of effect to be used in the meta-analysis than is the mean difference or the standardized mean difference. This is because the PF allows combination of different ways of measuring caries increment in the included trials, and a meaningful investigation of heterogeneity between trials. It is also simple to interpret.

Systematic review of evidence on the effects of water fluoridation

The effects of water fluoridation were investigated in a systematic review by the University of York. The full report is available via the CRD Fluoridation Review website (http://www.york.ac.uk/inst/crd/fluorid.htm). There have been several examples of misrepresentation of the research evidence from the systematic review, and a Cochrane review to update and publish it in *The Cochrane Library* has been registered recently (OHG, personal communication).

The York review on water fluoridation addressed five main questions:

1. What are the effects of fluoridation of drinking water supplies on the incidence of caries, and what is the effect of termination of water fluoridation on caries levels?
2. If water fluoridation is shown to have beneficial effects, what is the effect over and above that offered by the use of alternative F^- interventions and strategies?
3. Does water fluoridation result in a reduction of caries across social groups and between geographical locations, bringing equity?
4. Does water fluoridation have negative effects?
5. Are there differences in the effects of natural and artificial water fluoridation?

A comprehensive search to identify the body of evidence available on the efficacy and safety of water fluoridation was carried out and studies in any language were sought. Studies included in the review were classified into levels/hierarchy of evidence based on study design and adjustment for confounding and for measurement bias. Evidence rated below a level of moderate quality/moderate risk of bias was not considered in the evaluation of efficacy. In the assessment of safety, all levels of evidence were considered.

The main findings from the York review were:

1. Water fluoridation reduces caries incidence by an average of 15% (ranging from −5.0% to +64%) as measured by the mean difference in the proportion of children caries free, and by an average of 2.25 (ranging from 0.5 to 4.4) as measured by the mean change in dmft/DMFT, and caries prevalence increases following withdrawal of water fluoridation.
2. Water fluoridation has a caries preventive effect over and above F^- toothpaste.
3. Water fluoridation may reduce inequalities between social groups, by reducing the differences in caries severity (as measured by dmft/DMFT) between social classes among 5- and 12-year-old children.
4. Water fluoridation probably causes more dental fluorosis than previously thought – the pooled estimate of fluorosis prevalence at a water F^- concentration of 1 ppm was 48% (95% confidence interval (CI): 40–57%) and for fluorosis of aesthetic concern 12.5% (95% CI: 7.0–21.5%); and may or may not cause other harms, such as cancer, bone defects, and so on (no clear associations have been shown).
5. There may or may not be differences in the effects of natural and artificial water fluoridation.

Table 14.9 shows the main results of the review (for the outcomes of dental caries and fluorosis).

These findings, however, are based on moderate- to poor-quality evidence. There were 214 studies included; none was of evidence level A (high quality, bias unlikely). The study designs used included 102 cross-sectional studies, 47 ecological studies, 45 controlled before–after studies, seven case–control studies, and 13 cohort studies.

Systematic review of evidence on the effects of topically applied fluoride modalities (toothpastes, mouthrinses, gels, varnishes)

The series of Cochrane reviews on the effects of self-applied F^- toothpastes and mouthrinses, and professionally applied F^- gels and varnishes, used alone or in conjunction with

Table 14.9 York review on water fluoridation [118]. Summary of main results (for dental caries and fluorosis)

Study ID, year of publication	Aim	Number and types of studies included, by main outcome	Main findings
UK NHS CRD review, 2000	To assess the positive and negative effects of population-wide drinking water fluoridation strategies to prevent caries	*Evaluation of efficacy (positive effects – caries prevention)* Moderate quality evidence: 23 before-and-after studies 2 prospective cohort studies 1 retrospective cohort study *Evaluation of safety (adverse effects – fluorosis)* Low quality evidence: 4 before-and-after studies 1 case–control 83 cross-sectional studies	*Evaluation of efficacy (positive effects – caries prevention)* median diff in percentage caries free (range) 14.6% (−5.0% to +64%) median diff in dmft/DMFT (range) 2.25 (0.5–4.4) *Evaluation of safety (adverse effects – fluorosis)* Pooled estimate of prevalence at 1.0 ppm F^- Any fluorosis = 48% (95% CI 40–57%) Fluorosis of aesthetic concern (TF ≥3, or Dean's mild or higher, or TSIF ≥2) = 12.5% (95% CI 7.0–21.5%) Proportion of the population with any fluorosis (pooled) at 0.1 ppm F^- = 15% (95% CI 10–22%) at 4 ppm F^- = 72% (95% CI 67–80%)

are another, have been published from 2002 to 2010 [109–115,176,180], and are available in *The Cochrane Library* (http://www.thecochranelibrary.com). Cochrane reviews are updated as new evidence emerges and in response to feedback, and *The Cochrane Library* should be consulted for the most recent version of the reviews.

The Cochrane reviews addressed five major questions:

1. What is the efficacy of F^- toothpastes, mouthrinses, gels, and varnishes in preventing dental caries in children and adolescents?
2. Is the efficacy of each of these F^- modalities, and of them in general, influenced by background exposure to other F^- sources, initial level of caries, F^- concentration and frequency of application, use under supervision, and the form (modality) used?
3. Are there differences in the efficacy of the various F^- modalities either used singly (one compared with another), or in combination with each other (primarily F^- toothpaste plus another F^- modality compared with F^- toothpaste alone)?
4. Are there differences in the efficacy of F^- toothpastes of different F^- concentrations?
5. What is the risk of developing dental fluorosis in young children with the use of F^- applied topically?

Thorough searches were performed of published and unpublished evidence, from RCTs mainly, with no language restrictions. The studies included were collated and critiqued using similar methodology and measures of effect for caries. The Cochrane reviews on topically applied fluorides involved meta-analyses of all relevant evidence comparing a F^- treatment against non-F^- controls, against each other, and against a combination of F^- treatments. They investigated their comparative effectiveness, as well as the dependence of the caries-preventive effect of fluorides on prognostic features through meta-regression analysis, and by direct and indirect comparisons in a network meta-analysis. The reviews also investigated the relative effectiveness of F^- toothpastes of different concentrations, and the relationship between the use of topical fluorides in young children and the risk of developing fluorosis, where nonrandomized evidence was considered.

The main findings from the Cochrane reviews on fluorides applied topically are as follows.

1. There is unequivocal evidence from the first five Cochrane reviews [109–113] that topically applied F^- in the form of toothpaste, mouthrinse, gel, and varnish reduce the incidence of caries. Research involving more than 65 000 children and adolescents in over 130 trials shows a clear reduction in caries increment in both the permanent dentition (for all forms of topically applied F^- treatments examined) and the deciduous dentition (for F^- gels and varnishes).

   The average D(M)FS prevented fractions in the four individual Cochrane reviews ranged from 24% (95% CI: 21–28%) for F^- toothpaste, through 26% (95% CI: 23–30%) for mouthrinses and 28% (95% CI: 19–37%) for gels, to 46% (95% CI: 30–63%) for F^- varnishes. For the primary dentition, the average d(e/m)fs prevented fraction was 33% (95% CI: 19–48%) for F^- varnishes, based on three trials only. Pooled estimates of D(M)FS and d(m/e)fs prevented fractions were calculated in the summary review, which compiled all four reviews together [113] combining all the data from the four individual reviews for D(M)FS estimates, and the varnish and gel data for the effect in primary teeth – d(m/e)fs prevented fractions.

   However, conclusions on treatment effects were made on a clearer basis in the placebo-controlled trials, as caries reductions were overestimated in no-treatment control trials, which were not double blind, and likely to be of lower methodological quality. Table 14.10 shows the results for both types of comparisons together and for placebo comparisons only from each of the four individual reviews on F^- gel, varnish, mouthrinse, and toothpaste, alongside the results from the summary review compiling all four reviews together.
2. The Cochrane reviews also show that use of topically applied F^- treatments can reduce dental caries irrespective of exposure to water fluoridation – estimates of topical F^- treatment effect were similar between trials conducted in fluoridated and nonfluoridated areas. It is also shown that supervising a child's use of self-applied F^- (toothpaste or mouthrinse) leads to greater benefits. A significant influence of initial level of caries (baseline risk of the study population) and of frequency, concentration, and intensity of F^- application was also

Table 14.10 Cochrane reviews of topically applied F^- treatments (TFTs), D(M)FS/d(m)fs pooled estimates of effect measured as prevented fractions (PFs).

F^- type[a]	PF	95% CI (%)	TFT type[c]	PF	95% CI (%)
Permanent tooth surfaces					
Varnish (7)	46%	30–63	Varnish (3)	60%	09–72
Gel (24)	28%	19–37	Gel (13)	21%	14–28
Rinse (34)	26%	23–30	Rinse (30)	26%	22–29
Toothpaste (70)[b]	24%	21–28	Toothpaste (70)	24%	21–28
All 4 TFTs (133)	26%	24–29	All 4 TFTs (116)	24%	22–27
Primary tooth surfaces					
Varnish (3)	33% PF	19–48	Varnish (1)	20% PF	2–38
Gel (2)[b]	26% PF	−11–63	Gel (2)	26% PF	−11–63
Varnish and gel (5)	33% PF	22–44	Varnish and gel (3)	27% PF	8–46

[a] Number of placebo/no treatment comparisons.
[b] Number of placebo comparisons.
[c] Placebo comparisons only.

indicated in the reviews. Although the magnitude of the effect for initial level of caries was small (1% increase in the PF per unit increase in mean baseline caries, $p = 0.004$), this implies that, as the caries levels decline in a population, the percentage caries reductions (PFs) will decrease with the use of F⁻ treatments. The relatively larger number of studies reporting relevant data made these analyses more reliable in the Cochrane toothpaste review [111], which included 70 placebo-controlled trials in the meta-analysis, and in the summary review [113], which included 133 trials from the four individual reviews (Table 14.11).

3. For the influence of F⁻ modality, no significant differences in treatment effects between F⁻ gel, mouthrinse, and toothpaste were shown in the summary review [113], although significantly lower D(M)FS prevented fractions for these in comparison with F⁻ varnish was suggested (DMFS PFs were on average 14% (95% CI: 2–26%) higher in F⁻ varnish trials). However, in these adjusted indirect comparisons of all four F⁻ modalities, *it is difficult to rule out the possibility of an overestimation of the size of the differential effect in favor of F⁻ varnish since relatively few varnish trials were included and few among these were placebo controlled*.

   In fact, the Cochrane review assessing direct comparisons between F⁻ toothpastes, mouthrinses, gels, and varnishes [114] is consistent with *no evidence of a differential effect between F⁻ treatment modalities*. The review showed that F⁻ toothpaste can protect against dental caries as much as F⁻ mouthrinse or gels (but relevant comparisons of F⁻ toothpastes with varnishes were lacking) – the pooled DMFS PF for the nine trials combined in this comparison was 1% (95% CI: −13% to +14%). The results from this and the other direct comparisons of one F⁻ modality versus another are summarized in Table 14.12. Taking these results on the relative effectiveness of the four F⁻ modalities into account, and those of a further investigation employing a simultaneous analysis of both types of comparisons (direct and indirect, in a network meta-analysis) with the available data from the reviews, *no clear evidence was found that any modality is more effective than any other* [151].

   The results from the Cochrane review on the combined use of different F⁻ modalities with toothpaste against toothpaste used alone [115] are also summarized in Table 14.13. Evidence from nine trials showed that

Table 14.12 Cochrane reviews of topically-applied F⁻ treatments: Comparative effect on caries increment from direct comparisons between F⁻ treatments (used against each other and against in combination) – D(M)FS pooled estimates measured as prevented fractions (PFs).

F⁻ modalities in the comparisons (no. of studies)	PF (%)	95%CI (%)
Varnish versus gel (1)	14	−12 to +40
Varnish versus mouthrinse (4)	10	−12 to +32
Gel versus mouthrinse (1)	−14	−40 to +12
Toothpaste versus gel (3)	0	−21 to +21
Toothpaste versus mouthrinse (6)	0	−18 to +19
Toothpaste versus any F⁻ [a] (9)	1	−13 to +14
Toothpaste + varnish versus toothpaste alone (1)	48	17–64
Toothpaste + gel versus toothpaste alone (3)	14	−9 to +38
Toothpaste + mouthrinse versus toothpaste alone (5)	7	0–13
Toothpaste + any F⁻ versus toothpaste alone (9)	10	2–17

[a] Three gel trials and six mouthrinse trials; no varnish trial.

Table 14.11 Cochrane reviews of topically applied F⁻ treatments. Factors potentially influencing effectiveness; results from random effects meta-regression analyses of D(M)FS prevented fractions (PFs).

Characteristic/factor (no. of studies) [a]	Estimate (95% CI)	Characteristic/factor (no. of studies) [b]	Estimate (95% CI)	Interpretation
Mean initial caries (67)	0.7% (0.37–1.3%)	Mean initial caries (126)	0.7% (0.2–1.2%)	Increase in PF per unit increase in mean initial level of caries
Background fluoridation (58)	3.2% (−4% to +11%)	Background fluorides (116)	2.9% (−3.3% to +9.1%)	Higher PF in presence of water fluoridation
F⁻ content (69)	8.3% (1–16%)	F⁻ content (68)	−0.3% (−1.4% to +0.9%)	Increase in PF per 1000 ppm F⁻
Frequency of toothbrushing (70)	14% (6–22%)	Frequency of application (131)	3% (0.4–5.7%)	Increase in PF moving from once to twice a day for toothpaste/per 100 extra a year for any F
Use under supervision (70)	−11% (−18% to −4%)			Lower PF with unsupervised toothbrushing
		Use under supervision (111)	11% (3.7–17%)	Higher PF with self-applied supervised use

[a] Analysis in the Cochrane F⁻ toothpaste review [111].

[b] Analysis in the Cochrane F⁻ review including all four F⁻ treatment modalities [113].

the simultaneous use of a topical F^- treatment with F^- toothpaste results in an enhanced caries reduction compared with the use of toothpaste alone, although the additional effect in the order of 10% (95% CI: 2–17%) on average may not be substantial.

4. The Cochrane review looking specifically at the relative effectiveness of different levels of F^- in toothpastes [176], based on a network meta-analysis, confirmed that the relative caries-preventive effects of F^- toothpastes *increased with higher F^- concentrations*. Pooled results from randomized trials with D(M)FS scores in the mixed or permanent dentition showed the caries-preventive effect of F^- toothpaste was 23% for 1000/1055/1100/1250 ppm F^-, 30% for 1450/1500 ppm F^-, and 36% for 2400/2500/2800 ppm F^-. The benefits of increasing F^- concentration were only apparent from concentrations of 1000 ppm F^- and above – for 440/500/550 ppm F^- and below there was no significant effect shown compared with placebo, reflecting the small number of trials for these comparisons (Table 14.14). The studies on the deciduous dentition were equivocal.
5. As regards adverse effects with the use of topically applied fluorides, the evidence found in the Cochrane review addressing one aspect in particular, the risk of fluorosis in young children [180], focused mainly on F^- toothpaste and on the outcome of mild fluorosis. Based on the results of observational studies mainly (1 cohort, 6 case-control, 16 cross-sectional surveys), there is weak evidence that starting the use of F^- toothpaste in children under 12 months of age may be associated with an increased risk of fluorosis, and the evidence of an increased fluorosis risk between the age of 12 and 24 months is equivocal. However, *the use of higher concentration F^- toothpastes (>1000 ppm F^-), when evaluated in RCTs (two), was found to be associated with an increase in fluorosis*. No significant association between frequency of toothbrushing or the amount of F^- toothpaste used and fluorosis was shown.

Table 14.13 Comparative effect on caries increment from direct comparisons of toothpastes of different F^- concentrations. D(M)FS pooled estimates measured as PFs (placebo comparisons only) – Cochrane review.

F^- concentration (ppm) (no. of trials)	Direct comparison meta-analysis PF [95% CI]	Network meta-analysis PF [95% CI]
Placebo versus		
250 (3)	8.90 [−1.62, 19.42]	9.14 [−3.62, 21.96]
440/500/550 (2)	7.91 [−6.11, 21.94]	15.35 [−1.89, 32.53]
1000/1055/1100/1250 (54)	22.20 [18.68, 25.72]	22.99 [19.34, 26.58]
1450/1500 (4)	22.07 [15.26, 28.88]	29.29 [21.24, 37.46]
1700/2000/2200 (0)		33.7 [16.52, 50.77]
2400/2500/2800 (4)	36.55 [17.46, 55.64]	35.52 [27.23, 43.82]

Table 14.14 Cochrane reviews on the effects of fluoridated milk, slow-release F^- devices, and F^- supplements.

Study ID, year of publication	Focus	No. of studies included, types of studies, main outcome	Main findings
Young *et al.*, 2005 [182]	To determine the effectiveness of community-delivered fluoridated milk for preventing caries	Two trials, involving 353 children, with an intervention or follow-up period of at least 3 years. Outcome measure: changes in caries increment (DMFS/T-dmfs/t)	For permanent teeth, reduction in DMFT (78.4%, *P* <0.05) shown in one trial after 3 years. For primary teeth, reduction in the dmft (31.3%, *P*=0.05) shown after 3 years, also in one trial
Bonner *et al.*, 2006 [18]	To evaluate the effectiveness of slow-release F^- devices on preventing, arresting, or reversing the progression of caries	One trial involving 174 children Outcome measures: changes in caries increment (DMFS/dmfs), progression of lesions through enamel and dentine	Although 132 children included at the 2 year completion point, examination and statistical analysis performed only on 63 children who had retained the beads Mean difference in caries increment – lower in the intervention group, −0.72 DMFT, 95% CI −1.23 to −0.21 −1.52 DMFS, 95% CI −2.68 to −0.36
Tubert-Jeannin *et al.*, 2011 [172]	To evaluate the efficacy of F^- supplements for preventing dental caries in children	Eleven studies involving 7196 children Outcome measure: changes in caries increment (DMFS/dmfs)	*F^- supplements vs no F^- supplements* (five trials) DMFS PF 24% (95% CI, 16–33%) Unclear effect on deciduous teeth (two trials) *F^- Supplements vs topical fluorides* (five trials) No differential effect on permanent or deciduous teeth Limited information on the adverse effects/fluorosis (one trial)

Systematic review of evidence on the effects of fluoride supplements (tablets, drops, lozenges), slow-release fluoride devices, fluoridated milk, and salt fluoridation

The Cochrane review on F^- supplements [172] included data from five trials on children aged 5–12 years. It showed that the use of F^- supplements was associated with a 24% (95% CI: 16–33%) reduction in D(M)FS, but the effect on primary teeth was unclear, as data from two trials provided discrepant results. When the F^- supplements were compared with the use of topically applied fluorides (toothpastes, varnishes, rinses) or with the use of other preventive measures (xylitol lozenges), there was no differential effect on permanent or deciduous teeth. There was limited information from one trial on adverse effects (fluorosis) associated with the use of F^- supplements.

The Cochrane review on slow release F^- devices [18] showed that there is weak and insufficient evidence from one trial only, involving 174 children, of a caries inhibiting effect of slow-release F^- glass beads. The trial results are based on a population selected on the basis of bead retention, which excluded 52% of available participants, whose beads had become dislodged.

The Cochrane review on fluoridated milk [182] included data from two trials involving 353 children, and provided some evidence that fluoridated milk was beneficial to school children. For both permanent and primary teeth, after 3 years there was a significant reduction in DMFT in one trial, but not in the other.

The main features/results of these Cochrane reviews are shown in Table 14.14. Owing to the general lack of randomized evidence addressing the questions posed in the reviews, a common conclusion from all of them is that more research, and research of better methodological quality, is needed.

What about the effects of salt fluoridation? According to two recent systematic reviews [128, 181], fluoridated salt was beneficial to children, especially their permanent dentition. However, *the studies examining the effects of salt fluoridation in preventing dental caries are of lower levels in the hierarchy of evidence about effectiveness, and data are of poor methodological quality in general.*

The Australian study [128] showed that three before-and-after cross-sectional studies suggest that salt fluoridation reduces caries in populations of children aged from 6–15 years, and that one comparative cross-sectional study provides evidence of a significantly increased risk of 'any fluorosis' associated with salt fluoridation. However, there were no data relating to the risk of 'fluorosis of aesthetic concern' and to other potential health risks. The South African study [181] pooled together caries data from nine included studies for different age cohorts in meta-analyses; no RCTs were identified, and *the quality of the evidence was variable and poor, with estimates of effectiveness based mainly on data from studies without a concurrent control group.*

A summary of the main evidence from systematic reviews: relevant implications for practice and research

The evidence on the beneficial effects of F^- toothpastes, mouthrinses, gels, and varnish is consistent and strong, based on a sizeable body of evidence mainly from RCTs. However, research conducted on the effects of water fluoridation, milk fluoridation, F^- supplements, and salt fluoridation is still insufficient and/or of lower methodological quality.

Regarding the effects of the two most widely used and recommended forms of F^- application – fluoridated toothpaste and water fluoridation – it can be concluded that the caries-preventive benefits of regular toothbrushing with F^- toothpastes are firmly established, but scientific controversy on the effects of water fluoridation are likely to continue until higher quality studies are conducted and more definitive evidence is produced.

The main conclusions from the Cochrane reviews on the effectiveness of topically applied fluorides for caries control are:

- There is a clear reduction in caries increment in both the permanent (for all forms of topically applied fluorides examined) and the primary dentition (for F^- gels and varnishes) with topically applied F^- treatments.
- These F^- interventions can reduce dental caries irrespective of water fluoridation or other sources of F^- exposure. It is also shown that the caries-preventive effect of topically applied F^- increases when there are higher initial levels of caries (D(M)FS) and when higher F^- concentrations and/or frequency of application are used, and that supervising a child's use of self-applied F^- (toothpaste or mouthrinse) leads to greater benefits.
- F^- toothpaste, the most readily available form of F^-, which is commonly linked to the decline in caries prevalence in many developed countries, can protect children and adolescents against dental caries as much as other topically applied F^- intervention, strengthening the major role of F^- toothpaste as an effective and acceptable public health approach for the prevention of dental caries.
- In addition, the evidence shows that children using another form of topically applied F^- therapy with F^- toothpaste will experience additional reductions in dental caries, compared with children using F^- toothpaste only, although the size of the caries-preventive effect may not be substantial.
- Furthermore, when higher F^- concentration is used in the formulation, the caries-preventive effect of F^- toothpaste increases (dose–response from 1000 ppm F^-), but the effectiveness of low F^- concentration is unclear, since benefit is only significant for F^- concentrations of 1000 ppm and above. In this regard, the current F^- levels of toothpaste products that are marketed worldwide generally fall within an effective range, between 1000 and 1500 ppm F^-.
- As for the dental adverse effect of enamel fluorosis, there is weak, unreliable evidence that starting the use of F^-

toothpaste in children under 12 months of age may be associated with an increased risk of fluorosis, and the use of higher concentration F^- toothpaste (>1000 ppm F^-), when evaluated in RCTs, was also found to be associated with an increase in fluorosis.

- The general lack of information across the Cochrane F^- reviews on relevant outcomes other than caries increment also makes it more important that further experimental research includes assessments of potential benefits, as well as harms and costs.

In this regard, it should also be noted that all Cochrane F^- reviews are now being updated, and as evidence from new trials is being incorporated into the existing reviews, the precision of the estimates of effects are likely to increase, although no major changes in conclusions are likely to occur. It is expected, however, that the reporting of relevant outcomes in new trials might be generally improved through initiatives such as the CONSORT for randomized trials, and the PRISMA for systematic reviews [131, 132], as these reporting guides become more widely adopted by dental journals. This would improve the future identification and quantification of effects, and recommendations for the appropriate use of fluorides.

Rational use of fluorides in caries control in different parts of the world: recommendations

Any recommendations for the appropriate use of fluorides based on the systematic reviews findings should be made bearing in mind that such (Cochrane) reviews are not intended to provide recommendations for practice in any particular clinical context, even though all Cochrane reviews include an authors' Conclusions section, which are rich sources of information for anyone making decisions and recommendations about appropriate health care and future research. The evidence from the reviews, therefore, is usually the foundation of evidence-based guidelines, which are systematically developed statements/recommendations specifically developed to assist practitioners' and patients' decisions in specific clinical and public health circumstances.

- Dental caries is not a result of F^- deficiency – but frequently available F^- in the oral environment can effectively slow down the rate of caries lesion progression at any age.
- It is essential to appreciate that dental caries is ubiquitous and lesions form and progress lifelong. F^- should be available at slightly elevated levels in the oral environment every day and fluoridated toothpaste is so far the only agent that significantly can slow down the rate of lesion progression irrespective of age.
- To obtain a maximal caries control it is mandatory also to perform daily oral hygiene with F^- toothpaste and to restrict the intake of dietary carbohydrates.
- Therefore, in children until the age of about 12 years parents have to supervise their children in appropriate toothbrushing with F^- toothpaste to obtain maximum caries control.

Today, individuals in many parts of the world are consuming F^- from multiple sources. When combinations of F^- therapy are used, often unintentionally, we are inevitably having some individuals ingesting so much F^- that the prevalence and severity of fluorosis on a population basis will be increasing. The use of F^- has to be based on a sound scientific understanding, and clearly the outdated maxim 'if a little is good then more is better' has to be avoided at all costs.

- Dietary F^- supplements therefore, should not generally be used. Other sources of systemic F^-, other than water, such as salt or milk, are not to be generally recommended either, not least because the studies examining the effects of salt fluoridation in particular are of lower levels in the hierarchy of evidence about effectiveness, and data are of poor methodological quality in general.
- The primary mode of action of F^- is topical. The methods we need to employ to maximize the caries control and minimize the risk of dental fluorosis are clearly delineated. We need to encourage methods that ensure that elevated F^- levels are sustained in the oral cavity and children swallow as little as possible of the F^-, so that the risk of fluorosis, particularly the cosmetically annoying forms, is minimized. From a practical point of view, we can be sure that upon eruption of the first permanent molars (6 years) the enamel maturation of the anterior teeth is near to completion and, therefore, from a cosmetic point of view, ingestion of F^- will have impact only on premolars and on second molars. Efforts to minimize F^- ingestion are therefore particularly important in preschool children under the age of 6 years.
- The most common combination of F^- methods is the use of F^- dentifrices in populations with fluoridated drinking water. Any additional benefit to F^- toothpastes used in combination with other topical methods, such as mouthrinses, gels, and varnishes, is not substantial, and only modest caries reductions might be anticipated.
- The combination of methods is primarily recommended for patients with insufficient oral hygiene and suffering from hyposalivation.
- In orthodontic treatment, special focus on proper oral hygiene using fluoridated toothpaste is mandatory, possibly combined with regular mouth rinsing or topical paint with high-concentration vehicles.

There is no single method of delivering F^- that is appropriate for all, and consideration of the risks/benefits and cost-effectiveness of any program must be examined in detail at national, local, and individual levels. At a national level we must consider variations in occurrence of caries within the population (see Chapter 4), existing exposure to F^-, the infrastructure available, economic development, the availability of personnel, oral hygiene habits, and dietary behavior.

- A fundamental decision to be made by politicians and health-care workers is the distribution of the costs of any program between the individual and the state. The important message is 'make it simple and cheap'.
- Avoid many different concentrations in toothpastes. To minimize small children ingesting too much, reduce the size of toothpaste used rather than the concentration.
- In the elderly with exposed root surfaces at risk, it may be recommended to finish brushing at night by not rinsing with water and with a finger apply a little toothpaste in approximal spaces. This creates a long-lasting F^- reservoir, as salivation during sleep is very limited.
- In populations where the caries prevalence and severity is high (see Chapter 22) and evenly distributed throughout the population there can be little argument that water fluoridation provides the most cost-effective and efficient method of F^- delivery. However, for reasons already discussed, water fluoridation has been difficult to implement as the infrastructure and/or the political will required in most countries may not be available. Moreover, in many societies there has been a widespread opposition towards this approach, which may be seen as a 'mass medication'. It should be realized, however, that in countries with a high standard of living and where caries prevalence and incidence were amongst the highest in the world – the Scandinavian countries – about 90% caries reductions have occurred during the last two to four decades (see Chapter 1) without water fluoridation. This has been achieved by combining the use of F^- in different ways with good oral hygiene practices, including widespread use of F^- toothpastes.
- F^- toothpaste has been by far the most successful F^- delivery system to be developed. Its efficacy and efficiency are well documented. The majority of a population can use it and methods of application can be tailored to suit the individual. Toothbrushing is the cultural norm in many societies but we must remember that it is probably the cosmetic rather than the therapeutic benefits that have ensured such widespread penetration into the market place.
- It is important that the dental profession realizes that F^- in toothpaste is a highly potent *therapeutic* agent when used to control ongoing, active disease. Ensuring a supply of cheap and effective F^- toothpaste, and ensuring that it is used effectively, should be the key element in all caries control programs. In low-economy countries the cost of toothpaste constitutes a major burden for the population and great efforts should be made to minimize widespread use of fermentable carbohydrates while introducing health-promoting habits, including good oral hygiene.
- Other F^- delivery systems, such as mouthrinses and gels, should be seen as adjuncts to toothpaste usage, not an alternative, and predominantly should be used for high-risk caries individuals and groups. For rational caries control in populations with high or low caries prevalence and severity, please see Chapters 22–24.

Background literature

Fejerskov O, Ekstrand J, Burt BA. *Fluoride in dentistry*. 2nd ed. Copenhagen: Munksgaard, 1996.

Murray JJ, Rugg-Gunn AJ, Jenkins GN. *Fluorides in caries prevention*. 3rd ed. Oxford: Wright 1991.

Whitford GM. *The metabolism and toxicity of fluoride*. 2nd rev. ed. Monographs in oral science, Vol. 16. Basel: Karger, 1996.

References

1. Aasenden R, Peebles TC. Effects of fluoride supplementation from birth on human primary and permanent teeth. *Arch Oral Biol* 1974; 19: 321–6.
2. Ainsworth NJ. Mottled teeth. *Br Dent J* 1933; 55: 233–50.
3. American Dental Association, Council on Scientific Affairs (ADA-CSA). Professionally applied topical fluoride: evidence-based clinical recommendations. *J Am Dent Assoc* 2006; 137: 1151–9.
4. Ammari AB, Bloch-Zupan A, Ashley PF. Systematic review of studies comparing the anti-caries efficacy of children's toothpaste containing 600 ppm of fluoride or less with high fluoride toothpastes of 1,000 ppm or above. *Caries Res* 2003; 37: 85–92.
5. Andersen L, Richards A, Care AD, Andersen HM, Kragstrup J, Fejerskov O. Parathyroid glands, calcium, and vitamin D in experimental fluorosis in pigs. *Calcif Tissue Int* 1986; 38: 222–6.
6. Aoba T, Fejerskov O. Dental fluorosis: chemistry and biology. *Crit Rev Oral Biol Med* 2002; 13: 155–70.
7. Arnold FA, Dean HT, Knutson JW. Effect of fluoridated public water supplies on dental caries incidence. Results of the seventh year of study at Grand Rapids and Muskegon, Mich. *Public Health Rep* 1953; 68: 141–8.
8. Arnold FA, Likins RC, Russell AL, Scott DB. Fifteenth year of the Grand Rapids fluoridation study. In: McClure FJ, ed. *Fluoride drinking waters*. Bethesda, MD: National Institute of Dental Research, 1962: 253–6.
9. Backer-Dirks O. The relationship between the fluoridation of water and dental caries experience. *Int Dent J* 1967; 17: 582–605.
10. Baelum V, Manji F, Fejerskov O. Posteruptive tooth age and severity of dental fluorosis in Kenya. *Scand J Dent Res* 1986; 94: 405–10.
11. Barnhart WE, Hiller LK, Leonard GJ, Michaels SE. Dentifrice usage and ingestion among four age groups. *J Dent Res* 1974; 53: 1317–22.
12. Bartizek RD, Gerlach RW, Faller RV, Jacobs SA, Bollmer BW, Biesbrock AR. Reduction in dental caries with four concentrations of sodium fluoride in a dentifrice: a meta-analysis evaluation. *J Clin Dent* 2001; 12: 57–62.
13. Beiswanger BB, Stookey GK. The comparative clinical cariostatic efficacy of sodium fluoride and sodium monofluorophosphate dentifrices: a review of trials. *J Dent Child* 1989; 56: 337–47.
14. Bentley EM, Ellwood RP, [illegible] Davies RM. Factors influencing the amount of fluoride toothpaste applied by the mothers of young children. *Br Dent J* 1997; 183: 412–14.
15. Bentley EM, Ellwood RP, Davies RM. Fluoride ingestion from toothpaste by young children. *Br Dent J* 1999; 186: 460–2.
16. Bergman C, Gray-Scott D, Chen JJ, Meacham S. What is next for the Dietary Reference Intakes for bone metabolism related nutrients beyond calcium: phosphorus, magnesium, vitamin D, and fluoride? *Crit Rev Food Sci Nutr* 2009; 49: 136–44.
17. Black GV, McKay FS (1916). Mottled teeth: An endemic developmental imperfection of the teeth heretofore unknown in the literature of dentistry. *Dental Cosmos* 1916; 58: 129–56.
18. Bonner BC, Clarkson JE, Dobbyn L, Khanna S. Slow-release fluoride devices for the control of dental decay. *Cochrane Database Syst Rev* 2006; (4): CD005101.
19. Bratthall D, Hänsel Petersson G, Sundberg H. Reasons for the caries decline: what do the experts believe? *Eur J Oral Sci* 1996; 104: 416–22.
20. British Association for the Study of Community Dentistry (BASCD). *Delivering better oral health: an evidence-based toolkit for prevention*, 3rd ed. Department of Health, 2014. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/367563/DBOHv32014OCTMainDocument_3.pdf (accessed November 12, 2014).

21. Bruun C, Thylstrup A. Dentifrice usage among Danish children. *J Dent Res* 1988; **67**: 1114–17.
22. Bruun C, Thylstrup A, [illegible] Loosely bound fluoride extracted from natural caries lesions after topical application of APF in vitro. *Caries Res* 1983; **17**: 458–61.
23. Bruun C, Lambrou D, Larsen MJ, Fejerskov O, Thylstrup A. Fluoride in mixed human saliva after different topical fluoride treatments and possible relation to caries inhibition. *Community Dent Oral Epidemiol* 1982; **10**: 124–9.
24. Bruun C, Givskov H, Thylstrup A. Whole saliva fluoride after toothbrushing with NaF and MFP dentifrices with different concentrations. *Caries Res* 1984; **18**: 282–8.
25. Burt BA, Marthaler TM. Fluoride tablets, salt fluoridation, and milk fluoridation. In: Fejerskov O, Ekstrand J, Burt BA, eds. *Fluoride in dentistry*. Copenhagen: Munksgaard, 1996: 291–310.
26. Butler WJ, Segreto V, Collins E. Prevalence of dental mottling in school-aged lifetime residents of 16 Texas communities. *Am J Public Health* 1985; **75**: 1408–12.
27. Carvalho DM, Salazar M, Oliveira BH, Coutinho ES. Fluoride varnishes and decrease in caries incidence in preschool children: a systematic review. *Rev Bras Epidemiol* 2010; **13**: 139–49.
28. Cawson RA, Stocker IP. The early history of fluorides as anti-caries agents. *Br Dent J* 1984; **157**: 403–4.
29. Cenci MS, Tenuta LM, Pereira-Cenci T, Del Bel Cury AA, ten Cate JM, Cury JA. Effect of microleakage and fluoride on enamel–dentine demineralization around restorations. *Caries Res* 2008; **42**: 369–79.
30. Chalmers I, Haynes B. Reporting, updating, and correcting systematic reviews of the effects of health care. *BMJ* 1994; **309**: 862–5.
31. Chankanka O, Levy SM, Warren JJ, Chalmers JM. A literature review of aesthetic perceptions of dental fluorosis and relationships with psychosocial aspects/oral health-related quality of life. *Community Dent Oral Epidemiol* 2010; **38**: 97–109.
32. Chaves SC, Vieira-da-Silva LM. Anticaries effectiveness of fluoride toothpaste: a meta-analysis. *Rev Saude Publica* 2002; **36**: 598–606.
33. Chesters RK, Huntington E, Burchell CK, Stephen KW. Effect of oral care habits on caries in adolescents. *Caries Res* 1992; **26**: 299–304.
34. Churchill HV. Occurrence of fluorides in some waters of the United States. *Ind Eng Chem* 1931; **23**: 996–8.
35. Clark DC, Hanley JA, Stamm JW, Weinstein PL. An empirically based system to estimate the effectiveness of caries-preventive agents. A comparison of the effectiveness estimates of APF gels and solutions, and fluoride varnishes. *Caries Res* 1985; **19**: 83–95.
36. Clarke M. The Cochrane Collaboration. *Eval Health Prof* 2002; **25**: 8–11.
37. Clarke MJ, Stewart LA. Obtaining data from randomised controlled trials: how much do we need for reliable and informative meta-analyses? *BMJ* 1994; **309**(6960): 1007–10.
38. Clovis J, Hargreaves JA. Fluoride intake from beverage consumption. *Community Dent Oral Epidemiol* 1988; **16**: 11–15.
39. Cury JA. Fluoride therapy. In: Baratieri LN, eds. *Advanced operative dentistry*, 2nd ed. São Paulo: Quintessence, 2005: 43–67.
40. Cury JA, Rebelo MA, Del Bel Cury AA, Derbyshire MT, Tabchoury CP. Biochemical composition and cariogenicity of dental plaque formed in the presence of sucrose or glucose and fructose. *Caries Res* 2000; **34**: 491–7.
41. Cury JA, Tenuta LMA, Ribeiro CCC, Paes Leme AF. The importance of fluoride dentifrices to the current dental caries prevalence in Brazil. *Braz Dent J* 2004; **15**: 167–74.
42. Cury JA, Del Fiol FS, Tenuta LM, Rosalen PL. Low-fluoride dentifrice and gastrointestinal fluoride absorption after meals. *J Dent Res* 2005; **84**: 1133–7.
43. Dean HT. Classification of mottled enamel diagnosis. *J Am Dent Assoc* 1934; **21**: 1421–6.
44. Dean HT. Endemic fluorosis and its relationship to dental caries. *Public Health Rep* 1938; **53**: 1443–52.
45. Dean HT. Chronic endemic dental fluorosis (mottled enamel). In: Gordon SM, ed. *Dental science and dental art*. Philadelphia, PA: Lea and Febiger, 1938: 387–414.
46. Dean HT. The investigation of physiological effects by the epidemiological method. In: Moulton FR, ed. *Fluorine and dental health*. AAAS Publication No. 19. American Association for the Advancement of Science, 1942: 23–31.
47. Dean HT, Elvove E. Some epidemiological aspects of chronic endemic fluorosis. *Am J Public Health* 1936; **26**: 567–75.
48. Dean HT, McKay FS. Production of mottled enamel halted by a change in common water supply. *Am J Public Health* 1939; **29**: 590–6.
49. Dean HT, Jay P, Arnold FA, Elvove E. Domestic water and dental caries, including certain epidemiological aspects of oral *L. acidophilus*. *Public Health Rep* 1939; **54**: 862–88.
50. Dean HT, Jay P, Arnold FA, Elvove E. Domestic water and dental caries II. A study of 2832 white children aged 12–14 years of eight suburban Chicago communities, including *Lactobacillus acidophilus* studies of 1761 children. *Public Health Rep* 1941; **56**: 761–92.
51. Dean HT, Arnold FA, Elvove E. Domestic water and dental caries V. Additional studies of the relation of fluoride domestic waters to dental caries experience in 4,425 white children aged 12–14 years of 13 cities in 4 states. *Public Health Rep* 1942; **57**: 1155–79.
52. Dean HT, Arnold FA, Jay P, Knutson JW. Studies on mass control of dental caries through fluoridation of the public water supply. *Public Health Repor* 1950; **65**: 1403–8.
53. De Menezes LMB, de Sousa Mda L, Rodrigues LK, Cury JA. Self-perception of fluorosis due to fluoride exposure to drinking water and dentifrice. *Rev Saude Publica* 2002; **36**: 752–4 (in Portuguese).
54. Documenta Geigy. *Scientific tables*, 7th ed. Basel: Ciba Geigy, 1975: 693–8.
55. Dowell TB. The use of toothpaste in infancy. *Br Dent J* 1981; **150**: 247–9.
56. Duckworth SC, Duckworth R. The ingestion of fluoride in tea. *Br Dent J* 1978; **145**: 368–70.
57. Duckworth RM, Morgan SN. Oral fluoride retention after use of fluoride dentifrices. *Caries Res* 1991; **25**: 123–9.
58. Duckworth RM, Morgan SN, Murray AM. Fluoride in saliva and plaque following use of fluoride-containing mouthwashes. *J Dent Res* 1987; **66**: 1730–4.
59. Duckworth RM, Morgan SN, Burchell CK. Fluoride in plaque following use of dentifrices containing sodium monofluorophosphate. *J Dent Res* 1989; **68**: 130–3.
60. Ekstrand J. Fluoride metabolism. In: Fejerskov O, Ekstrand J, Burt BA, eds. *Fluoride in dentistry*. Copenhagen: Munksgaard, 1996: 55–68.
61. Ekstrand J, Oliveby A. Fluoride in the oral environment. *Acta Odontol Scand* 1999; **57**: 330–3.
62. Ekstrand J, Alván G, Boréus LO, Norlin A. Pharmacokinetics of fluoride in man after single and multiple oral doses. *Eur J Clin Pharmacol* 1977; **12**: 311–17.
63. Ekstrand J, Hardell LI, Spak CJ. Fluoride balance studies on infants in a 1-ppm-water-fluoride area. *Caries Res* 1984; **18**: 87–92.
64. Ekstrand J, Spak CJ, Vogel G. Pharmacokinetics of fluoride in man and its clinical relevance [review]. *J Dent Res* 1990; **69** (Special No.): 550–5; discussion 556–7.
65. Ericsson Y, Forsman B. Fluoride retained from mouthrinses and dentifrices in preschool children. *Caries Res* 1969; **3**: 290–9.
66. European Academy of Paediatric Dentistry. Guidelines on the use of fluoride in children: an EAPD policy document. *Eur Arch Paed Dent* 2009; **10**: 129–35.
67. Evans RW, Stamm JW. An epidemiologic estimate of the critical period during which human maxillary central incisors are most susceptible to fluorosis. *J Public Health Dent* 1991; **51**: 251–9.
68. Fejerskov O. Concepts of dental caries and their consequences for understanding the disease. *Community Dent Oral Epidemiol* 1997; **25**: 5–12.
69. Fejerskov O, Johnson NW, Silverstone LM. The ultrastructure of fluorosed human dental enamel. *Scand J Dent Res* 1974; **82**: 357–72.
70. Fejerskov O, Silverstone LM, Melsen B, Møller IJ. Histological features of fluorosed human dental enamel. *Caries Res* 1975; **9**: 190–210.
71. Fejerskov O, Thylstrup A, Larsen MJ. Clinical and structural features and possible pathogenic mechanisms of dental fluorosis. *Scand J Dent Res* 1977; **85**: 510–34.
72. Fejerskov O, Thylstrup A, Larsen MJ. Rational use of fluorides in caries prevention. A concept based on possible cariostatic mechanisms. *Acta Odont Scand* 1981; **39**: 241–9.
73. Fejerskov O, Manji F, Baelum V, Møller IJ. *Dental fluorosis. A handbook for health care workers*. Copenhagen: Munksgaard, 1988.
74. Fejerskov O, Manji F, Baelum V. The nature and mechanisms of dental fluorosis in man. *J Dent Res* 1990; **69**: 692–700.

75. Fejerskov O, Larsen MJ, Richards A, Baelum V. Dental tissue effects of fluoride. *Adv Dent Res* 1994; 8: 15–31.
76. Fejerskov O, Baelum V, Richards A. Dose-response and dental fluorosis. In: Fejerskov O, Ekstrand J, Burt BA, eds. *Fluoride in dentistry*. Copenhagen: Munksgaard, 1996; 153–66.
77. Fejerskov O, Escobar G, Jøssing M, Baelum V. A functional natural dentition for all – and for life? The oral health care system needs revision. *J Oral Rehabil* 2013; 40: 707–22.
78. Fomon SJ, Ekstrand J. Fluoride intake by infants. *J Public Health Dent* 1999; 59: 229–34.
79. Galagan DJ. Climate and controlled fluoridation. *J Am Dent Assoc* 1953; 47: 159–70.
80. Galagan DJ, Lamson GG. Climate and endemic dental fluorosis. *Public Health Rep* 1953; 68: 497–508.
81. Galagan DJ, Vermillion JR. Determining optimum fluoride concentrations. *Public Health Rep* 1957; 72: 491–3.
82. Geddes DAM, McNee SG. The effect of 0.2 per cent (48 mM) NaF rinses daily on human plaque acidogenicity in situ (Stephan curve) and fluoride content. *Arch Oral Biol* 1982; 27: 765–9.
83. Glass RL, Peterson JK, Zuckerberg DA, Naylor MN. Fluoride ingestion resulting from the use of a monofluorophosphate dentifrice by children. *Br Dent J* 1975; 138: 423–6.
84. Gurman D, Tourgain. Fluorine chemistry, 1900–1945. *J Fluorine Chem* 1986; 33: 45–69.
85. Glenny AM, Esposito M, Coulthard P, Worthington HV. The assessment of systematic reviews in dentistry. *Eur J Oral Sci* 2003; 111: 85–92.
86. Granath L, Widenheim J, Birkhed D. Diagnosis of mild enamel fluorosis in permanent maxillary incisors using two scoring systems. *Community Dent Oral Epidemiol* 1985; 13: 273–6.
87. Griffin SO, Regnier E, Griffin PM, Huntley V. Effectiveness of fluoride in preventing caries in adults. *J Dent Res* 2007; 86: 410–15.
88. Hargreaves JA, Ingram GS, Wagg BJ. A gravimetric study of the ingestion of toothpaste by children. *Caries Res* 1972; 6: 237–43.
89. Hayacibara MF, Queiroz CS, Tabchoury CP, Cury JA. Fluoride and aluminum in teas and tea-based beverages. *Rev Saude Publica* 2004; 38: 100–5.
90. Helfenstein U, Steiner M. Fluoride varnishes (Duraphat): a meta-analysis. *Community Dent Oral Epidemiol* 1994; 22: 1–5.
91. Hodge HC. The concentration of fluorides in drinking water to give the point of minimum caries with maximum safety. *J Am Dent Assoc* 1950; 40: 436–9.
92. Hunt CD, Stoecker BJ. Deliberations and evaluations of the approaches, endpoints and paradigms for boron, chromium and fluoride dietary recommendations. *J Nutr* 1996; 126(9 Suppl): 2441S–51S.
93. Ijaz S, Croucher RE, Marinho VC. Systematic reviews of topical fluorides for dental caries: a review of reporting practice. *Caries Res* 2010; 44: 579–92.
94. Jadad AR, Cook DJ, Jones A, Klassen TP, Tugwell P, Moher M, Moher D. Methodology and reports of systematic reviews and meta-analyses: a comparison of Cochrane reviews with articles published in paper-based journals. *JAMA* 1998; 280: 278–80.
95. Johnson MF. Comparative efficacy of NaF and SMFP dentifrices in caries prevention: a meta-analytic overview. *Caries Res* 1993; 27: 328–36.
96. Josephsen K, Takano Y, Frische S, Praetorius J, Nielsen S, Aoba T, Fejerskov O. Ion transporters in secretory and cyclically modulating ameloblasts: a new hypothesis for cellular control of preeruptive enamel maturation. *Am J Physiol Cell Physiol* 2010; 299: 1299–307.
97. Jørgensen AW, Maric KL, Tendal B, Faurschou A, Gøtzsche PC. Industry-supported meta-analyses compared with meta-analyses with non-profit or no support: differences in methodological quality and conclusions. *BMC Med Res Methodol* 2008; 8(1): 60.
98. Kalsbeek H, Verrips GH, Backer Dirks O. Use of fluoride tablets and effect on prevalence of dental caries and dental fluorosis. *Community Dent Oral Epidemiol* 1992; 20: 241–5.
99. Kempf GA, McKay FS. Mottled enamel in a segregated population. *Public Health Rep* 1930; 45: 2923–40.
100. Kleijnen J, Gøtzsche P, Kunz RA, Oxman AD, Chalmers I. So what's so special about randomisation? In: Maynard A, Chalmers I, eds. *Non-random reflections on health services research*. London: BMJ Publishing Group, 1997; 93–106.
101. Larsen MJ, Kirkegaard E, Fejerskov O, Poulsen S. Prevalence of dental fluorosis after fluoride-gel treatments in a low-fluoride area. *J Dent Res* 1985; 64: 1076–9.
102. Larsen MJ, Richards A, Fejerskov O. Development of dental fluorosis according to age at start of fluoride administration. *Caries Res* 1985; 19: 519–27.
103. Larsen MJ, Kirkegaard E, Poulsen S. Patterns of dental fluorosis in a European country in relation to the fluoride concentration of drinking water. *J Dent Res* 1987; 66: 10–12.
104. Levy SM. A review of fluoride intake from fluoride dentifrice. *J Dent Child* 1993; 60: 115–24.
105. Levy SM, Kiritsy MC, Warren JJ. Sources of fluoride intake in children (review). *J Public Health Dent* 1995; 55(Winter): 39–52.
106. Lima YB, Cury JA. Seasonal variation of fluoride intake by children in a subtropical region. *Caries Res* 2003; 37: 335–8.
107. Larsen M, Fejerskov O, Thylstrup A. The effect of fluoride on dental plaque, tooth structure and dental caries. In: Thylstrup A, Fejerskov O, eds. *Textbook of cariology*. Copenhagen: Munksgaard, 1986; 299–329.
108. Manji F, Baelum V, Fejerskov O. Fluoride, altitude and dental fluorosis. *Caries Res* 1986; 20: 473–80.
109. Marinho VC, Higgins JP, Logan S, Sheiham A. Fluoride gels for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2002; (2): CD002280.
110. Marinho VC, Higgins JP, Logan S, Sheiham A. Fluoride varnishes for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2002; (3): CD002279.
111. Marinho VC, Higgins JP, Sheiham A, Logan S. Fluoride toothpastes for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2003; (1): CD002278.
112. Marinho VC, Higgins JP, Logan S, Sheiham A. Fluoride mouthrinses for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2003; (3): CD002284.
113. Marinho VC, Higgins JP, Logan S, Sheiham A. Topical fluoride (toothpastes, mouthrinses, gels or varnishes) for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2003; (4): CD002782.
114. Marinho VC, Higgins JP, Sheiham A, Logan S. One topical fluoride (toothpastes, or mouthrinses, or gels, or varnishes) versus another for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2004; (1): CD002780.
115. Marinho VC, Higgins JP, Sheiham A, Logan S. Combinations of topical fluoride (toothpastes, mouthrinses, gels, varnishes) versus single topical fluoride for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2004; (1): CD002781.
116. Martins CC, Paiva SM, Lima-Arsati YB, Ramos-Jorge ML, Cury JA. Prospective study of the association between fluoride intake and dental fluorosis in permanent teeth. *Caries Res* 2008; 42: 125–33.
117. McCollum EV, Simmonds N, Becker JE, Bunting RW. The effect of addition of fluoride to the diet of rats on the quality of their teeth. *J Biol Chem* 1925; 63: 553.
118. McDonagh MS, Whiting PF, Wilson PM, Sutton AJ, Chestnutt I, Cooper J, Misso K, Bradley M, Treasure E, Kleijnen J. Systematic review of water fluoridation. *Br Med J* 2000; 321: 855–9.
119. McKay FS. The relation of mottled teeth to caries. *J Am Dent Assoc* 1928; 15: 1429–37.
120. Milsom K, Mitropoulos CM. Enamel defects in 8-year-old children in fluoridated and non-fluoridated parts of Cheshire. *Caries Res* 1990; 24: 286–9.
121. Moher D, Liberati A, Tetzlaff J, Altman DG; PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *J Clin Epidemiol* 2009; 62: 1006–12.
122. Moher D, Hopewell S, Schulz KF, Montori V, Gøtzsche PC, Devereaux PJ, Elbourne D, Egger M, Altman DG; CONSORT. CONSORT 2010 explanation and elaboration: updated guidelines for reporting parallel group randomised trials. *Int J Surg* 2012; 10: 28–55.
123. Moysés SJ, Moysés ST, Allegretti AC, Argenta M, Werneck R. Dental fluorosis: epidemiological fiction? *Rev Panam Salud Publica* 2002; 12: 339–46 (in Portuguese).
124. Myers HM. Dose response relationship between water fluoride levels and the category of questionable dental fluorosis. *Community Dent Oral Epidemiol* 1983; 11: 109–12.

125. Naccache H, Simard PL, Trahan L, Demers M, Lapointe C, Brodeur JM. Variability in the ingestion of toothpaste by preschool children. *Caries Res* 1990; 24: 359–63.
126. Naccache H, Simard PL, Trahan L, Brodeur JM, Demers M, Lachapelle D, Bernard PM. Factors affecting the ingestion of fluoride dentifrice by children. *J Public Health Dent* 1992; 52: 222–6.
127. Nadanovsky P, Sheiham A. Relative contribution of dental services to the changes in caries levels of 12-year-old children in 18 industrialized countries in the 1970s and early 1980s. *Community Dent Oral Epidemiol* 1995; 23: 331–9.
128. National Health and Medical Research Council (NHMRC). *A systematic review of the efficacy and safety of fluoridation*. Australian Government, 2007. http://www.nhmrc.gov.au/guidelines/publications/eh41 (accessed October 2014).
129. Nobre dos Santos M, Cury JA. Dental plaque fluoride is lower after discontinuation of water fluoridation. *Caries Res* 1988; 22: 316–7.
130. Oliveby A, Lagerlöf F, Ekstrand J, Dawes C. Studies on fluoride concentrations in human submandibular/sublingual saliva and their relation to flow rate and plasma fluoride levels. *J Dent Res* 1989; 68: 146–9.
131. O'Brien M. *Children's dental health in the United Kingdom 1993*. London: HMSO, 1994.
132. Oliveby A, Twetman S, Ekstrand J. Diurnal fluoride concentration in whole saliva in children living in a high- and a low-fluoride area. *Caries Res* 1990; 24: 44–7.
133. Oliveira MJL, Martins CC, Paiva SM, Tenuta LMA, Cury JA. Estimated fluoride doses from toothpastes should be based on total soluble fluoride. *Int J Environ Public Health* 2013; 10: 5726–36.
134. Osuji OO, Leake JL, Chipman ML, Nikiforuk G, Locker D, Levine N. Risk factors for dental fluorosis in a fluoridated community. *J Dent Res* 1988; 67: 1488–92.
135. Parkins FM, Tinanoff N, Moutinho M, Anstey MB, Waziri MH. Relationships of human plasma fluoride and bone fluoride to age. *Calcif Tissue Res* 1974; 16: 335–8.
136. Pearce EIF, Jenkins GN. The decomposition of monofluorophosphate by enzymes in whole human saliva. *Arch Oral Biol* 1977; 22: 405–7.
137. Pendrys DG. Risk of fluorosis in a fluoridated population. Implications for the dentist and hygienist. *J Am Dent Assoc* 1995; 126: 1617–24.
138. Pendrys DG. Risk of enamel fluorosis in nonfluoridated and optimally fluoridated populations: considerations for the dental professional. *J Am Dent Assoc* 2000; 131: 746–55.
139. Pendrys DG, Katz RV. Risk of enamel fluorosis associated with fluoride supplementation, infant formula, and fluoride dentifrice use. *Am J Epidemiol* 1989; 130: 1199–208.
140. Peres KG, Latorre MdoR, Peres MA, Traebert J, Panizzi M. Impact of dental caries and dental fluorosis on 12-year-old schoolchildren's self-perception of appearance and chewing. *Cad Saude Publica* 2003; 19: 323–30 (in Portuguese).
141. Peres KG, Peres MA, Araujo CL, Menezes AM, Hallal PC. Social and dental status along the life course and oral health impacts in adolescence: a population-based birth cohort. *Health Qual Life Outcomes* 2009; 7: 95.
142. Petersson LG, Twetman S, Dahlgren H, Norlund A, Holm AK, Nordenram G, Lagerlöf F, Söder B, Källestål C, Mejàre I, Axelsson S, Lingström P. Professional fluoride varnish treatment for caries control: a systematic review of clinical trials. *Acta Odontol Scand* 2004; 62: 170–6.
143. Poulsen S, Larsen MJ. Dental caries in relation to fluoride content of enamel in the primary dentition. *Caries Res* 1975; 9: 59–65.
144. Richards A, Larsen MJ, Fejerskov O, Thylstrup A. Fluoride content of buccal surface enamel and its relation to caries in children. *Arch Oral Biol* 1977; 22: 425–8.
145. Richards A, Kragstrup J, Josephsen K, Fejerskov O. Dental fluorosis developed in post-secretory enamel. *J Dent Res* 1986; 65: 1406–9.
146. Richards A, Fejerskov O, Baelum V. Enamel fluoride in relation to severity of human dental fluorosis. *Adv Dent Res* 1989; 3: 147–53.
147. Richards A, Banting DW. Fluoride toothpastes. In: Fejerskov O, Ekstrand J, Burt BA, eds. *Fluoride in dentistry*. Copenhagen: Munksgaard, 1996: 328–46.
148. Richards LF, Westmoreland WW, Tashiro M, McKay CH, Morrison JT. Determining optimum fluoride levels for community water supplies in relation to temperature. *J Am Dent Assoc* 1967; 74: 389–97.
149. Riordan PJ. Dental fluorosis, dental caries and fluoride exposure among 7-year-olds. *Caries Res* 1993; 27: 71–7.
150. Rodrigues CR, Cury JA. Fluoride metabolism after ingestion of dentifrice. *Rev Gaucha Odontol* 1986; 34: 425–7 (in Portuguese).
151. Salanti G, Marinho V, Higgins JPT. A case study of multiple-treatments meta-analysis demonstrates that covariates should be considered. *J Clin Epidemiol* 2009; 62: 857–64.
152. Schulz EM, Epstein JS, Forrester DJ. Fluoride content of popular carbonated beverages. *J Prev Dent* 1976; 3: 27–9.
153. Schünemann HJ, Oxman AD, Higgins JPT, Vist GE, Glasziou P, Guyatt GH. Presenting results and 'Summary of findings' tables. In: Higgins JPT, Green S, eds. *Cochrane handbook for systematic reviews of interventions*, Version 5.1.0 (updated March 2011).
154. Scottish Intercollegiate Guidelines Network (SIGN). SIGN 83: *Prevention and management of dental decay in the pre-school child*. Edinburgh: Scottish Intercollegiate Guidelines Network, 2005. www.sign.ac.uk/guidelines/fulltext/83/index.html (accessed November 12, 2014).
155. Seppä L, Hausen H, Kärkkäinen S. Plaque fluoride and mutans streptococci in plaque and saliva before and after discontinuation of water fluoridation. *Eur J Oral Sci* 1996; 104(4 Pt 1): 353–8.
156. Simard PL, Lachapelle D, Trahan L, Naccache H, Demers M, Brodeur JM. The ingestion of fluoride dentifrice by young children. *ASDC J Dent Child* 1989; 56: 177–81.
157. Smith CE. Cellular and chemical events during enamel maturation. *Crit Rev Oral Biol Med* 1998; 9: 128–61.
158. Smith FA, Ekstrand J. The occurrence and the chemistry of fluoride. In: Fejerskov O, Ekstrand J, Burt BA, eds. *Fluoride in dentistry*. Copenhagen: Munksgaard, 1996: 17–26.
159. Spak CJ, Hardell LI, De Chateau P. Fluoride in human milk. *Acta Paediatr Scand* 1983; 72: 699–701.
160. Spak CJ, Ekstrand J, Eriksson S, Leksell LG. Distribution of fluoride to the central nervous system (abstract). *Caries Res* 1986; 20: 157.
161. Stamm JW. Clinical studies of neutral sodium fluoride and sodium monofluorophosphate dentifrices. In: Bowen WH, ed. *Relative efficacy of sodium fluoride and sodium monofluorophosphate as anti-caries agents in dentifrices*. London: The Royal Society of Medicine Press Limited, 1995: 43–58.
162. Stamm JW, Bohannan HM, Graves RC, Disney JA. The efficiency of caries prevention with weekly fluoride mouthrinses. *J Dent Educ* 1984; 48: 617–26.
163. Steiner M, Helfenstein U, Menghini G. Effect of 1000 ppm relative to 250 ppm fluoride toothpaste: a meta-analysis. *Am J Dent* 2004; 17: 85–8.
164. Stookey GK, DePaola PF, Featherstone JD, Fejerskov O, Möller IJ, Rotberg S, Stephen KW, Wefel JS. A critical review of the relative anticaries efficacy of sodium fluoride and sodium monofluorophosphate dentifrices. *Caries Res* 1993; 27: 337–60.
165. Strohmenger L, Brambilla E. The use of fluoride varnishes in the prevention of dental caries: a short review. *Oral Dis* 2001; 7: 71–80.
166. Taves DR. Dietary intake of fluoride ashed (total fluoride) v. unashed (inorganic fluoride) analysis of individual foods. *Br J Nutr* 1983; 49: 295–301.
167. Tenuta LM, Cury JA. Laboratory and human studies to estimate anticaries efficacy of fluoride toothpastes. *Monogr Oral Sci*. 2013; 23: 108–24.
168. Tenuta LM, Zamataro CB, Del Bel Cury AA, Tabchoury CP, Cury JA. Mechanism of fluoride dentifrice effect on enamel demineralization. *Caries Res* 2009; 43: 278–85.
169. Thylstrup A, Fejerskov O. Clinical appearance of dental fluorosis in permanent teeth in relation to histologic changes. *Community Dent Oral Epidemiol* 1978; 6: 315–28.
170. Thylstrup A, Fejerskov O. A scanning electron microscopic and microradiographic study of pits in fluorosed human enamel. *Scand J Dent Res* 1979; 87: 105–14.
171. Thylstrup A, Fejerskov O, Bruun C, Kann J. Enamel changes and dental caries in 7-year-old children given fluoride tablets from shortly after birth. *Caries Res* 1979; 13: 265–76.

172. Tubert-Jeannin S, Auclair C, Amsallem E, Tramini P, Gerbaud L, Ruffieux C, Schulte AG, Koch MJ, Rège-Walther M, Ismail A. Fluoride supplements (tablets, drops, lozenges or chewing gums) for preventing dental caries in children. *Cochrane Database Syst Rev* 2011; (12): CD007592.
173. Twetman S, Axelsson S, Dahlgren H, Holm AK, Källestål C, Lagerlöf F, Lingström P, Mejàre I, Nordenram G, Norlund A, Petersson LG, Söder B. Caries-preventive effect of fluoride toothpaste: a systematic review. *Acta Odontol Scand* 2003; **61**: 347–55.
174. Twetman S, Petersson LG, Axelsson S, Dahlgren H, Holm AK, Källestål C, Lagerlöf F, Lingström P, Mejàre I, Nordenram G, Norlund A, Söder B. Caries-preventive effect of sodium fluoride mouthrinses: a systematic review of controlled clinical trials. *Acta Odontol Scand* 2004; **62**: 223–30.
175. Van Rijkom HM, Truin GJ, van't Hof MA. A meta-analysis of clinical studies on the caries-inhibiting effect of fluoride gel treatment. *Caries Res* 1998; 32: 83–92.
176. Walsh T, Worthington HV, Glenny A-M, Appelbe P, Marinho VCC, Shi X. Fluoride toothpastes of different concentrations for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2010; (1): CD007868.
177. Warren JJ, Levy SM, Broffitt B, Cavanaugh JE, Kanellis MJ, Weber-Gasparoni K. Considerations on optimal fluoride intake using dental fluorosis and dental caries outcomes – a longitudinal study. *J Public Health Dent.* 2009; **69**: 111–15.
178. Weatherell JA, Deutsch D, Robinson C, Hallsworth AS. Assimilation of fluoride by enamel throughout the life of the tooth. *Caries Res* 1977; 11(Suppl 1): 85–115.
179. Whitford GM. *The metabolism and toxicity of fluoride*, 2nd rev. ed. Monographs in oral science, Vol. 16. Basel: Karger, 1996.
180. Wong MCM, Glenny A-M, Tsang BWK, Lo ECM, Worthington HV, Marinho VCC. Topical fluoride as a cause of dental fluorosis in children. *Cochrane Database Syst Rev* 2010; (1): CD007693.
181. Yengopal V, Chikte UM, Mickenautsch S, Oliveira LB, Bhayat A. Salt fluoridation: a meta-analysis of its efficacy for caries prevention. *SADJ* 2010; **65** (2):60–64, 66–67.
182. Yeung CA, Hitchings JL, Macfarlane TV, Threlfall AG, Tickle M, Glenny AM. Fluoridated milk for preventing dental caries. *Cochrane Database Syst Rev* 2005; (3): CD003876.
183. Zero DT, Raubertas RF, Pedersen AM, Fu J, Hayes AL, Featherstone JD. Studies of fluoride retention by oral soft tissues after the application of home-use topical fluorides. *J Dent Res* 1992; 71: 1546–52.
184. Zero DT, Raubertas RF, Fu J, Pedersen AM, Hayes AL, Featherstone JD. Fluoride concentrations in plaque, whole saliva, and ductal saliva after application of home-use topical fluorides. *J Dent Res.* 1992; 71: 1768–73.

15

The role of oral hygiene

B. Nyvad

Introduction

Motivation and instruction in oral hygiene form the basis of school-based caries preventive programs for children in many populations. Today, 80% of 11-year-old schoolchildren in Scandinavia report that they brush their teeth at least twice a day [34]. Daily toothbrushing with fluoride toothpaste is believed to be the primary reason for the caries decline observed in many populations since the 1970s [38, 39]. However, the role of oral hygiene in caries control has been questioned. Dental practitioners have seen that many patients do not develop cavities, in spite of the fact that they perform rather poor oral hygiene and consume candy and soft drinks on a regular basis [48]. Furthermore, it has been claimed that the effect of tooth cleaning is primarily an effect of fluoride in the paste rather than an effect of biofilm removal per se [35]. Other researchers have placed more emphasis on the fact that dental caries is a biofilm-mediated disease by promoting the old saying that 'a clean tooth never decays.' In a systematic review, Sutcliffe [52] proposed a more balanced view by concluding that 'there is no unequivocal evidence that good oral cleanliness reduces caries experience, nor is there sufficient evidence to condemn the value of good oral cleanliness as a caries preventive measure.'

The aim of this chapter is to present and discuss some of the literature that has evaluated the caries-preventive effect of oral hygiene in an attempt to explain why there are such diverging opinions on the usefulness of this important method in caries control.

Some theoretical considerations

It is not surprising that it is not always possible to find a strong positive association between the presence of dental biofilm and caries. According to the caries concept proposed by Fejerskov and Manji [17] (see Chapter 2), biofilms on teeth are the one and only prerequisite for caries; they are a necessary but not a sufficient cause. Because of the

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

multifactorial nature of the disease there are numerous determinants that may influence the outcome by either increasing or decreasing the rate of demineralization. Increased sugar consumption and decreased salivary secretion are typical examples of determinants that speed up the carious process because of acidification of the dental plaque (see Chapter 7). Fluoride, in contrast, owing to its stabilizing effect on the mineral balance, tends to decrease the rate of mineral loss (see Chapters 9 and 14). It is the combined effect of all the determinants, positive and negative, rather than the amount of biofilm itself, that determines whether a carious lesion develops and progresses. Therefore, there is no standard level of oral hygiene to be recommended [44]. In fact, it might be expected that, given a perfectly balanced combination of determinants, no lesion progression will occur if individuals suspend their regular tooth-cleaning habits!

To evaluate the importance of dental cleanliness per se it is necessary to take into account all the determinants that may potentially influence the association between plaque and caries. Unfortunately, studies describing the caries-controlling effect of toothbrushing often fail to use such an analytical approach. For example, most studies published after the introduction of fluoride toothpaste have not made an attempt to separate the effect of cleaning from the effect of the toothpaste itself.

The biological effect of tooth cleaning

Before describing the clinical effect of tooth cleaning it may be helpful to illustrate the extent to which tooth cleaning can influence the metabolism of the biofilm. Most people believe that every time they brush their teeth the dentition becomes perfectly free from debris. The truth is that this goal is seldom achieved in the hands of the patient. This is clearly shown in Fig. 15.1. Cleaning of an approximal surface with dental floss significantly reduces the production of organic acids after a carbohydrate challenge, but residual biofilm maintains the ability to elicit a moderate pH drop [18]. Thus, even after carefully performed plaque removal, teeth are never 'clean' from a microbiological point of view. Bacteria will often be retained in surface irregularities and in areas that are difficult to reach, such as approximal surfaces and fissures. Therefore, it is not surprising that dental cleanliness plays a crucial role in the effect of toothbrushing.

The clinical effect of tooth cleaning

When evaluating the results from clinical studies assessing the caries-preventive effect of toothbrushing, it is important to appreciate that the design of the study, as well as the method of analysis, will affect the conclusions. Depending on the design of the study, the outcome may reflect either the efficacy or the effectiveness of the preventive measure [1].

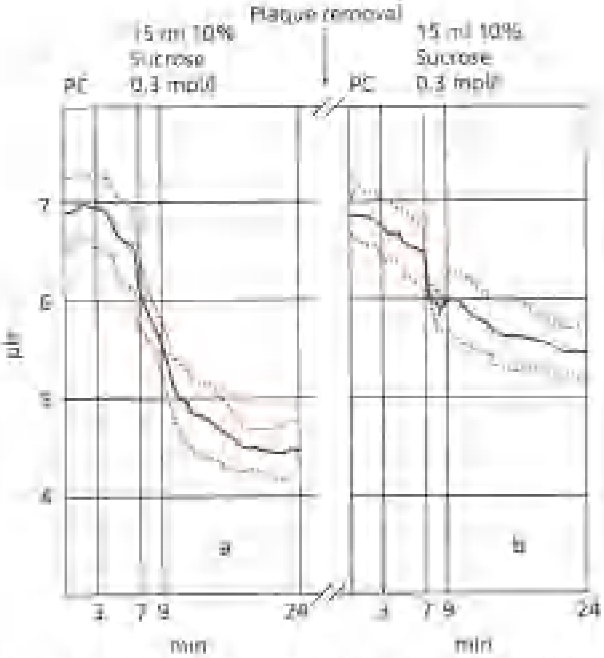


Figure 15.1 Mean pH (blue) and standard deviation (red) of approximal plaque following a 2 min rinse with 10% sucrose solution (a) before and (b) after plaque removal with dental floss ($n = 8$). PC: paraffin chewing. From [18]. Reproduced with permission of Stevens Publishing Corp.

Efficacy is used to refer to the benefits observed when a procedure is applied as it 'should' be, and with full compliance by all concerned. The term *efficacy* is usually reserved for benefits at the individual level (or the tooth/site level) – for example, as measured by a controlled clinical trial – and answers the question: 'Can the procedure work?' Effectiveness refers to the degree of realization of desirable effects observed at the population level, or among people to whom a procedure is offered. Hence, the term *effectiveness* answers the question: 'Does the procedure work?' As shall be demonstrated in the following sections, these distinctions are very useful when discussing the effects of oral hygiene. For the purpose of clarity the discussion will therefore be dealt with at the following levels: the tooth/site level, the level of the individual, and the population level.

The tooth/site level

The strongest evidence supporting an effect of oral hygiene on caries stems from experimental *in vivo* studies. In a study conducted in dental students by von der Fehr *et al.* [55], it was shown that withdrawal of oral hygiene procedures for 23 days led to the emergence of whitish, opaque, noncavitated enamel lesions along the gingival margin of the teeth (see Fig. 9.17a and b). Not surprisingly, students who performed nine daily mouthrinses with 50% sucrose solution during the test period developed more lesions than students who did not rinse. Equally important, however, was the observation that, irrespective of whether sucrose

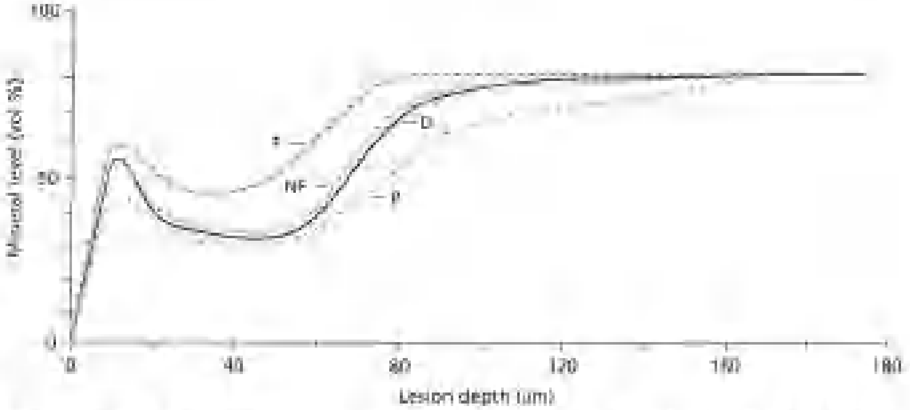


Figure 15.2 Mineral distribution curves of enamel specimens after different experimental toothbrushing regimens in situ. The mineral content is plotted versus the distance from the outer surface. P: no toothbrushing for 3 months; NF: brushing with a non-fluoride toothpaste for 3 months; F: brushing with a fluoride toothpaste for 3 months; D: artificially demineralized control specimen. From [15]. Reproduced with permission of Karger Publishers.

had been applied or not, the early manifestations of caries were reversible. Thus, after 30 days of careful oral hygiene (possibly using non-fluoride toothpaste) and daily mouthrinses with 0.2% sodium fluoride (NaF) the clinical appearance of the enamel had almost returned to pre-experimental levels. These observations have been confirmed by other studies showing that improved oral hygiene, including daily use of fluoride toothpaste, favors the arrest of active enamel and dentin caries lesions [3, 36, 43] (see Chapter 13).

More recently, modified orthodontic bands have been applied as an experimental model to study the effect of prolonged protection from mechanical forces on the buccal surfaces of premolars. When using this technique it has been demonstrated both clinically and histologically that undisturbed biofilm formation under the band leads to the development of progressive stages of white spot carious lesions within a period 4 weeks [25, 26]. After re-exposing such lesions to the natural oral environment, including normal oral hygiene with a non fluoride toothpaste, the lesions showed evidence of regression and microwear of the surface [27, 28] (for further details, see Chapter 5). Increased microwear with time supported the concept that mechanical biofilm removal was the main factor responsible for the arrest of the lesions.

The role of biofilm removal as an essential mode of caries control has also been addressed in in-situ studies. In-situ studies are experimental studies carried out under conditions that closely mimic the natural conditions in the oral cavity, for example, by inserting tooth specimens into lower partial dentures and exposing them to the oral environment for varying periods of time, while subjecting them to a well-defined experimental procedure. Before the start of the experiment the volunteers are told to comply carefully with the instructions, and often compliance is monitored and reinforced at regular intervals during the study. After the experimental period, changes in the mineral content of the tooth specimens can be measured by quantitative microradiography and compared with specimens obtained from a control group. Provided that full compliance is achieved, such studies provide information about the efficacy of a procedure.

In one in-situ study Dijkman *et al.* [15] assessed the effect of two oral hygiene regimens – twice-daily brushing with a fluoride toothpaste (1250 ppm fluoride) and twice-daily brushing with a non-fluoride toothpaste – relative to no brushing, on the mineral content of shallow enamel lesions that were developed under artificial conditions in the laboratory. After 10 weeks in situ, a distinct mineral uptake in the lesions after brushing with the fluoride toothpaste was observed. The mineral content of the lesions that were cleaned with a non-fluoride toothpaste did not change, while the control lesions that were not subjected to any treatment at all became deeper and lost considerable mineral (Fig. 15.2). The authors calculated that twice-daily brushing with fluoride toothpaste resulted in a 90% reduction in mineral loss compared with the control group that did not brush. The effect was ascribed to a combination of two factors: a cleaning effect and a fluoride effect, both of which were of the same order of magnitude. These findings suggest that there may be an additive effect of brushing the teeth with fluoride toothpaste. Therefore, individuals who either do not use a paste containing fluoride or neglect the importance of mechanical biofilm removal are unlikely to achieve maximum protection against caries.

Another in-situ study was designed to test whether a caries-preventive program consisting of careful daily brushing with a 1100 ppm fluoride toothpaste, supplemented with topical 2% NaF applications, had a controlling effect on natural actively progressing root caries lesions over a 3-month period [45]. The nonoperative treatment program applied in this study had previously been shown to arrest root caries lesions in clinical studies (see Chapter 13).

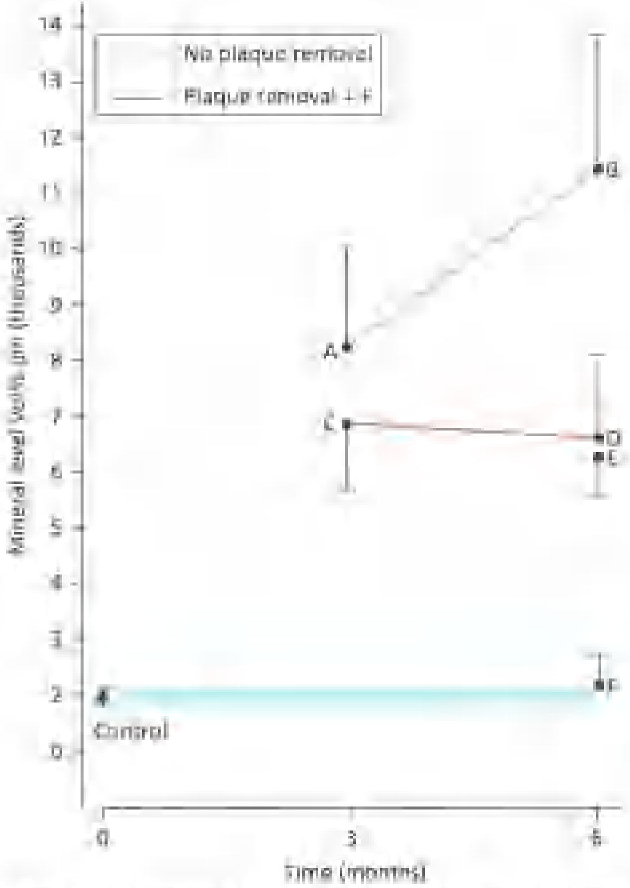


Figure 15.3 Mineral loss of root-caries specimens after different treatments in situ. The red and green lines indicate periods with and without plaque removal respectively. The solid data points (A–D) and error bars give the mean values and standard error of the mean for the amount of mineral removed in each group (*n* = 9). E and F indicate the mean amount of mineral removed from sound root surfaces after a 3-month period without and with tooth cleaning respectively. The mean mineral content value for sound control surfaces (blue horizontal line) is included for comparison (n = 5). From [45]. Reproduced with permission of Sage Publications.

Assessment of the mineral content of the root lesions after 3 months of treatment revealed that most lesions did not experience further mineral loss, whereas in control specimens (no brushing with fluoride toothpaste and no topical fluoride application) the mineral loss continued (Fig. 15.3). Importantly, the nonoperative treatment also had a pronounced inhibitory effect on lesion progression in newly exposed root surfaces. Unfortunately, the study did not include a test group that brushed with a non-fluoride toothpaste. Hence, it was not possible in this study to determine the impact of the oral hygiene procedures relative to the impact of the fluoride component.

Collectively, studies at the tooth/site level have shown that when meticulous oral hygiene and fluoride toothpaste are applied together and targeted specifically at sites with a high rate of lesion progression it is possible to control the development and progression of caries. Thus, tooth cleaning with fluoride toothpaste can be highly efficacious.

The level of the individual

Conclusions from studies analyzing the effect of tooth cleaning at the individual level are less consistent. While some clinical trials have shown that children brushing their teeth more than once a day may develop fewer new carious lesions than children who brush their teeth less frequently [13, 53], other studies have not been able to confirm such a relationship [29]. This is probably because reported toothbrushing in itself does not say anything about the quality of the oral hygiene procedures [8]. When examining the effect of toothbrushing expressed in terms of oral cleanliness, a clearer picture has been obtained. Thus, children whose dental cleanliness is consistently good may experience lower caries increments than those whose cleanliness is consistently bad [7, 42, 51, 53].

Only one clinical trial has so far allowed evaluation of the effect of tooth cleaning as an isolated variable relative to the effect of fluoride [33]. The overall aim of this study was to assess the effect of daily supervised toothbrushing in groups of 9–11-year old children over a 3-year period. Brushing at school was supervised as a means to control compliance. The design of the study was very elaborate (Table 15.1). There were two supervised brushing regimens: one with and one without a fluoride toothpaste. Three experimental groups served as controls: one group not performing supervised brushing at school, and two groups rinsing fortnightly with either distilled water or a 0.5% NaF solution. The results demonstrated that fortnightly fluoride rinses reduced dental caries increments significantly. However, daily brushing with fluoride toothpaste was more efficacious than fortnightly fluoride rinses. The effect of toothbrushing with fluoride toothpaste was most pronounced on smooth surfaces that are easy to clean and easily accessible to fluoride. Another observation from the study was that supervised toothbrushing with a non-fluoride toothpaste did not appear to have a detectable effect.

The findings of the study suggest that, in most people, toothbrushing performance (even under supervision) may be insufficient to obtain a caries-preventive effect when using a fluoride-free toothpaste. However, when toothbrushing is performed with a fluoride-containing toothpaste it can have a very significant caries-preventive effect. Moreover, the fact that supervised brushing with fluoride toothpaste had a better clinical effect than did plain rinsing with a fluoride solution supports the contention that dental cleanliness plays an important role in the outcome. This assumption is further supported by the results from clinical trials in which it was demonstrated that children performing unsupervised toothbrushing with toothpaste, with or without fluoride, developed significantly less caries with

Table 15.1 Caries increment (decayed surfaces) during the final year of a 3-year experiment of different preventive measures.

Prophylactic measure		New carious surfaces				
	n	Total	Proximal	Occlusal	Buccal	Lingual
Daily supervised toothbrushing with an NaF dentifrice	57	4.4	2.3	1.6	0.2	0.4
Daily supervised toothbrushing with a non-fluoride dentifrice	56	8.3	4.7	2.5	0.5	0.6
Fortnightly rinsing with a 0.5% NaF solution	60	6.3	3.3	2.2	0.5	0.3
Fortnightly rinsing with distilled water	71	8.4	4.8	2.3	0.8	0.5
Control	46	9.0	5.2	2.0	0.9	0.9

Adapted from [33]. Reproduced with permission of Elsevier.

better oral hygiene [7, 42]. A closer look at the data in the latter studies revealed that the caries-controlling effect was higher in the groups using the fluoride paste, again suggesting that biofilm removal and fluoride, when acting together, have an additive effect. It should also be appreciated however, that poor oral hygiene cannot be compensated for by the intensive use of fluorides. Thus, the effect of professional administration of fluorides in the form of gels, rinses, or tablets has been shown to be limited in individuals who do not practice good oral hygiene [41, 56].

To summarize, the above findings indicate that the most simple and efficacious way to control the development and progression of caries at the level of the individual is to suppress the presence of dental biofilm in conjunction with the regular use of fluoride, preferably in the form of a fluoride toothpaste. Toothbrushing can be efficacious without the additional help of fluoride, provided that brushing is supervised and the degree of cleanliness is high [19]. However, most individuals will find it difficult to achieve and maintain such a high proficiency of cleaning.

The population level

Self-performed toothbrushing is not particularly effective in controlling dental caries at the population level. Of the investigations quoted in the review by Sutcliffe [52], only about half of the cross-sectional studies showed a positive association between plaque and caries. However, multivariate analyses have shown that oral hygiene status is a strong risk indicator of caries when controlling for various other factors, such as sugar consumption and fluoride exposure [11, 40, 50, 54].

It is hardly surprising that there is no clear-cut association between oral hygiene and caries in population studies. Because of the multifactorial nature of caries, the presence of dental biofilm does not by itself indicate a high rate of lesion progression. Furthermore, cross-sectional studies have often measured the level of dental cleanliness by indices developed for periodontal purposes. However, gingival plaque is probably a poor predictor of caries on occlusal surfaces and on root surfaces. Thus, in a study of periodontal patients followed over an 8-year maintenance period, Ravald *et al.* [47] reported that only about 7% of the new lesions occurred along the gingival margin. The majority of new carious lesions developed along the cemento-enamel junction (25%) or in relation to margins of restorations (51%).

Because of the low clinical effectiveness of toothbrushing, as revealed by cross-sectional studies, some researchers believe that the primary purpose of toothbrushing is to serve as a vehicle for the application of fluoride [36]. As discussed in the previous sections, this belief is hardly justified. It is true that at the population level the effect of brushing with a fluoride toothpaste does often not exceed that obtained by water fluoridation [2] or by fortnightly fluoride rinses [24]. However, this does not mean that careful toothbrushing should not be advocated. Toothbrushing is cheap and easy to apply and, when performed properly, has the potential to control both caries and gingivitis. Toothbrushing can be implemented in all societies throughout the world, even in less-privileged populations who do not have access to modern tooth-cleaning devices [14]. Figure 15.4 illustrates how a person from rural Kenya is successful in mastering plaque control by using a chewing stick with a self-designed brush at one end and a tooth pick at the other.

Finally, it should be appreciated that biofilm removal could play a significant role in caries control by an interaction with the diet. Kleemola-Kujala and Räsänen [32] suggested that there may be a synergistic interaction between dental biofilm and sugar consumption; that is, the effect of the two factors in combination is higher than the sum of the separate effects. The authors calculated the relative risks of caries in three groups of children with increasing levels of biofilm and sugar consumption, relative to a group of children with low biofilm levels and low sugar consumption (Fig. 15.5). The data showed that at low levels of biofilm an increase in the total sugar consumption did not increase the risk of caries notably. However, the risk of caries increased significantly (up to three-fold) with increasing levels of biofilm at all levels of sugar consumption. The increase was greatest at the highest levels of sugar consumption. These findings may be taken to indicate that, when sugar consumption is high, biofilm removal can be a powerful method to control the development and progression of caries.

Figure 15.4 Demonstration of how useful the *miswaki* can be in maintaining proper oral hygiene. Look at this gentleman's clean oral cavity. He has never used anything but the *miswaki*. He cuts a thin branch of a tree and peels the bark. Then he chews the end to form a small brush which is easy to use throughout the oral cavity when used gently with small rotating movements. The other end can be cut to be used as a tooth pick approximally. From the Primary Oral Health Care Project, KEMRI, and DANIDA. Courtesy of F. Manji, V. Baelum, and O. Fejerskov.

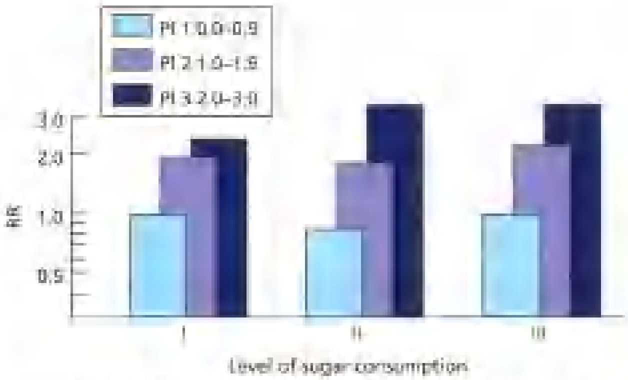


Figure 15.5 Relative risk (RR) of caries at different levels of plaque accumulation and sugar consumption in terms of unit risk for teeth with plaque index PI = 0–0.9, 1.0–1.9, and 2.0–3.0 and low (I), middle (II), and high (III) sugar exposures. Primary teeth; 5-year-olds. From [32]. Reproduced with permission of John Wiley & Sons.

The effect of professional tooth cleaning

In an attempt to overcome the difficulties encountered in obtaining improved biofilm control for some individuals, alternative strategies for nonoperative caries control have been suggested. One such strategy, commonly referred to as the Karlstad program, was developed by Axelsson and Lindhe [4]. In addition to the traditional components of a caries-preventive program (repeated oral hygiene instruction, dietary counseling, and topical fluorides), this program included a new treatment component, namely professional cleaning of the teeth at regular intervals by specially trained personnel. The idea was based on the results of the experimental *in vivo* studies described previously in this chapter, showing that when dental biofilm was allowed to accumulate on a clean tooth surface, white spot lesions developed in the enamel within a period of 2–3 weeks [55]. In the classical Karlstad program, biofilm was therefore removed professionally from all tooth surfaces of the dentition every fortnight to control the progression of caries (for details of the clinical procedure, see Chapter 17).

When the Karlstad program was carried out in children every fortnight during the school term, the number of carious lesions per year went down from about three per child to a single lesion in every 10 children (Fig. 15.6). Later studies by the Karlstad group [5], summarizing experiences with the method for more than 15 years, showed that the

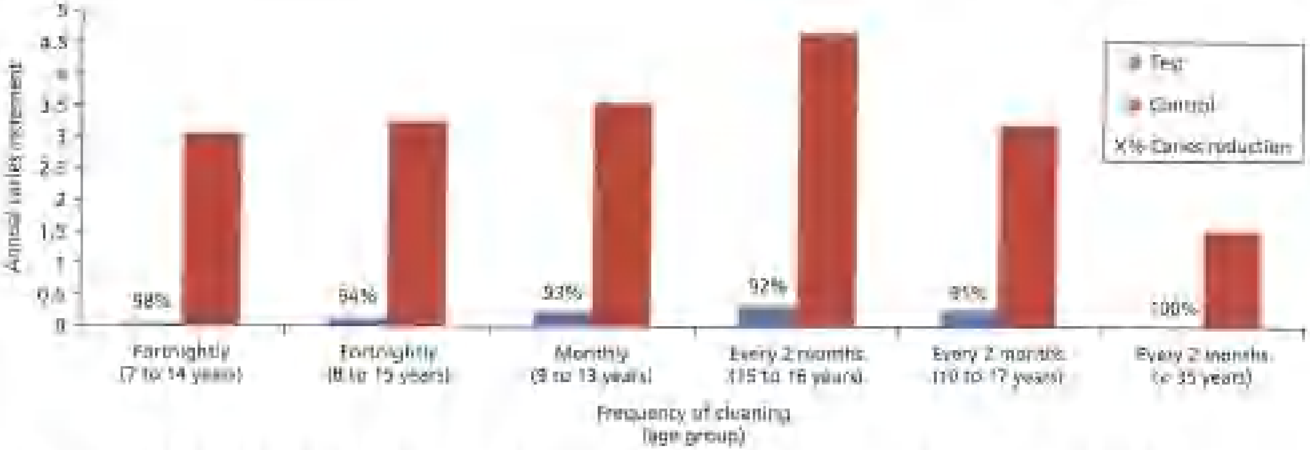


Figure 15.6 The Karlstad studies (1973–1978): annual caries increments at different professional tooth-cleaning frequencies. Adapted from [8].

caries-controlling effect was largely retained with longer intervals between the appointments (up to 3 months) in well-motivated children and adults (Fig. 15.6).

Researchers who have applied the Karlstad method in other populations have not been able to obtain quite as impressive results [6, 22, 31, 46]. However, it should be emphasized that professional tooth cleaning is particularly efficient on tooth surfaces that are difficult to clean, such as approximal surfaces [6, 22, 31] and erupting occlusal surfaces [12, 16]. Therefore, this rather costly treatment program may be justified in the management of some highly caries active patients (see Chapter 17).

The effect of dental flossing

It may come as a surprise for some dental professionals that the widely recommended use of dental floss has not been shown to have a caries-controlling effect on approximal surfaces when used as a supervised preventive measure by children at school [21, 30]. Only when flossing is performed professionally on a daily basis by trained personnel may a caries reduction be obtained [57]. A recent Cochrane review [49] has confirmed that while flossing plus toothbrushing may reduce gingivitis compared with toothbrushing alone, no studies have reported that flossing plus toothbrushing is effective for controlling dental caries. This does not necessarily mean that flossing is a poor method to control the amount of biofilm between teeth. Indeed, dental flossing, when performed properly, can be an effective means of reducing the amount of approximal bacterial deposits [10, 20, 23]. However, when self-performed flossing does often not lead to the expected effect this is probably because flossing is difficult to perform. The success of interdental cleaning is greatly dependent on the ease of use and patient motivation [9]. Therefore, implementation of a flossing program should be restricted to selected individuals who are in need of such treatment (e.g., active noncavitated lesions) and who can be expected to practice the method in the recommended way [21]. For patients who do not master the flossing technique it is helpful to remember that as toothbrushing improves there may be no advantage to follow it with flossing [23]!

Concluding remarks

This chapter provides evidence to support that tooth cleaning can be a highly efficacious method for controlling the development and progression of caries, in particular when using a fluoride toothpaste. When toothbrushing is often found to be ineffective it is probably not because of inadequacy of the method but rather because of carelessness on the part of the person who applies the method. Controlled clinical trials in children testing the effect of supervised toothbrushing at school have clearly shown that the level of oral cleanliness improves significantly during the course of the trial [33, 37]. This observation, together with the marked caries-controlling effect obtained by regular professional tooth cleaning, suggests that failure to achieve caries control by self-performed oral hygiene is primarily associated with a lack of compliance. Oral health professionals should be aware of this problem when motivating their patients in the treatment of dental caries.

In summary, the effectiveness of toothbrushing in caries control (i.e., toothbrushing as normally performed) is not very high. However, when the quality of toothbrushing is high (i.e., toothbrushing as it 'should' be) it can be a very efficacious procedure.

Tooth cleaning and fluoride may have an additive effect in caries control. Therefore, tooth cleaning should always be carried out in conjunction with the use of a fluoride toothpaste.

References

1. Abramson JH. *Survey methods in community medicine: epidemiological studies, programme evaluation, clinical trials*. 4th ed. New York: Churchill Livingstone, 1990: 47–56.
2. Ainamo J, Parviainen K. Influence of increased toothbrushing frequency on dental health in low, optimal, and high fluoride areas in Finland. *Community Dent Oral Epidemiol* 1989; 17: 296–9.
3. Årtun J, Thylstrup A. Clinical and scanning electron microscopic study of surface changes of incipient enamel caries lesions after debonding. *Scand J Dent Res* 1986; **94**: 193–210.
4. Axelsson P, Lindhe J. The effect of a preventive programme on dental plaque, gingivitis and caries in schoolchildren. Results after one and two years. *J Clin Periodontol* 1974; **1**: 126–38.
5. Axelsson P, Lindhe J, Nyström B. On the prevention of caries and periodontal disease. Results of a 15-year longitudinal study in adults. *J Clin Periodontol* 1991; **18**: 182–9.
6. Badersten A, Egelberg J, Koch G. Effect of monthly prophylaxis on caries and gingivitis in schoolchildren. *Community Dent Oral Epidemiol* 1975; **3**: 1–4.
7. Beal JF, James PMC, Bradnock G, Anderson RJ. The relationship between dental cleanliness, dental caries incidence and gingival health. *Br Dent J* 1979; **146**: 111–14.
8. Bellini HT, Arneberg P, von der Fehr FR. Oral hygiene and caries. A review. *Acta Odontol Scand* 1981; **39**: 257–65.
9. Bergenholtz A, Brithon J. Plaque removal by dental floss or toothpicks: an intra-individual comparative study. *J Clin Periodontol* 1980; **7**: 516–24.
10. Bergenholtz A, Bjorne A, Vikström B. The plaque-removing ability of some common interdental aids: an intraindividual study. *J Clin Periodontol* 1974; **1**: 160–5.
11. Bjertness E. The importance of oral hygiene on variation in dental caries in adults. *Acta Odontol Scand* 1991; **49**: 97–102.
12. Carvalho JC, Thylstrup A, Ekstrand KR. Results after 3 years of non-operative occlusal caries treatment of erupting permanent first molars. *Community Dent Oral Epidemiol* 1992; **20**: 187–92.
13. Chestnutt IG, Schäfer F, Jacobson APM, Stephen KW. The influence of toothbrushing frequency and post-brushing rinsing on caries experience in a caries clinical trial. *Community Dent Oral Epidemiol* 1998; **26**: 406–11.
14. Danielsen B, Baelum V, Manji F, Fejerskov O. Chewing sticks, toothpaste, and plaque removal. *Acta Odontol Scand* 1989; **47**: 121–5.
15. Dijkman A, Huizinga E, Ruben J, Arends J. Remineralization of human enamel in situ after 3 months: the effect of not brushing versus the effect of an F dentifrice and an F-free dentifrice. *Caries Res* 1990; **24**: 263–6.
16. Ekstrand KR, Kuzmina IN, Kuzmina E, Christiansen ME. Two and a half-year outcome of caries-preventive programs offered to groups of children in the Solntsevsky district of Moscow. *Caries Res* 2000; **34**: 8–19.
17. Fejerskov O, Manji F. Risk assessment in dental caries. In: Bader JD, ed. *Risk assessment in dentistry*. Chapel Hill, NC: University of North Carolina Dental Ecology, 1990: 215–17.
18. Firestone AR, Mühlemann HR. *In vivo* pH of plaque-covered and plaque-free interdental surfaces in humans following a sucrose rinse. *Clin Prev Dent* 1985; **7**: 24–6.
19. Fogels H, Cancro LP, Bianco J, Fischman SL. The anticaries effect of supervised toothbrushing with a nonfluoride dentifrice. *J Dent Child* 1982; **49**: 424–7.
20. Gjermo P, Flötra L. The effect of different methods of interdental cleaning. *J Periodontal Res* 1970; **5**: 230–6.
21. Granath L, Martinsson T, Matsson L, Nilsson G, Schröder U, Söderholm B. Intraindividual effect of daily supervised flossing on caries in schoolchildren. *Community Dent Oral Epidemiol* 1979; **7**: 147–50.
22. Hamp S-E, Lindhe J, Fornell J, Johansson L-Å, Karlsson R. Effect of a field program based on systematic plaque control on caries and gingivitis in schoolchildren after 3 years. *Community Dent Oral Epidemiol* 1978; **6**: 17–23.
23. Hill HC, Levi PA, Glickman I. The effects of waxed and unwaxed dental floss on interdental plaque accumulation and interdental gingival health. *J Periodontol* 1973; **44**: 411–14.
24. Heidmann J, Poulsen S, Arnbjerg D, Kirkegaard E, Laurberg L. Caries development after termination of a fluoride rinsing program. *Community Dent Oral Epidemiol* 1992; **20**: 118–21.
25. Holmen L, Thylstrup A, Øgaard B, Kragh F. A polarized light microscopic study of progressive stages of enamel caries in vivo. *Caries Res* 1985; **19**: 348–54.
26. Holmen L, Thylstrup A, Øgaard B, Kragh F. A scanning electron microscopic study of progressive stages of enamel caries in vivo. *Caries Res* 1985; **19**: 355–67.
27. Holmen L, Thylstrup A, Øgaard B, Kragh F. Surface changes during the arrest of active enamel carious lesions in vivo. *Acta Odontol Scand* 1987; **45**: 383–90.
28. Holmen L, Thylstrup A, Årtun J. Clinical and histological features observed during arrestment of active enamel carious lesions in vivo. *Caries Res* 1987; **21**: 546–54.
29. Horowitz HS, Thompson MB. Evaluation of a stannous fluoride dentifrice for use in dental public health programs. III. Supplementary findings. *J Am Dent Assoc* 1967; **74**: 979–86.
30. Horowitz AM, Suomi JD, Peterson JK, Mathews BL, Voglesong RH, Lyman BA. Effects of supervised daily dental plaque removal by children after 3 years. *Community Dent Oral Epidemiol* 1980; **8**: 171–6.
31. Kjærheim V, von der Fehr FR, Poulsen S. Two-year study on the effect of professional toothcleaning on schoolchildren in Oppegård, Norway. *Community Dent Oral Epidemiol* 1980; **8**: 401–6.
32. Kleemola-Kujala E, Räsänen L. Relationship of oral hygiene and sugar consumption to risk of caries in children. *Community Dent Oral Epidemiol* 1982; **10**: 224–33.
33. Koch G, Lindhe J. The state of the gingivae and the caries increment in schoolchildren during and after withdrawal of various prophylactic measures. In: McHugh WD, ed. *Dental plaque*. Edinburgh: Livingstone, 1970: 271–81.
34. Kuusela S, Honkala E, Kannas L, Tynjälä J, Wold B. Oral hygiene habits of 11-year-old schoolchildren in 22 European countries and Canada in 1993/94. *J Dent Res* 1997; **76**: 1602–9.
35. Lewis DW, Ismail AI. Periodic health examination, 1995 update: 2. Prevention of dental caries. *Can Med Assoc J* 1995; **152**: 836–46.
36. Lo EC, Schwarz E, Wong MC. Arresting dentine caries in Chinese preschool children. *Int J Paediatr Dent* 1998; **8**: 253–60.
37. Machiulskiene V, Richards A, Nyvad B, Baelum V. Prospective study of the effect of post-brushing rinsing behaviour on dental caries. *Caries Res* 2002; **36**: 301–7.
38. Marthaler TM. Changes in the prevalence of dental caries: how much can be attributed to changes in diet? *Caries Res* 1990; **24** (Suppl 1): 3–15.
39. Marthaler TM. Changes in dental caries 1953–2003. *Caries Res* 2004; **38**: 173–81.
40. Mascarenhas AK. Oral hygiene as a risk indicator of enamel and dentin caries. *Community Dent Oral Epidemiol* 1998; **26**: 331–9.
41. Mathiesen AT, Øgaard B, Rølla G. Oral hygiene as a variable in dental caries experience in 14-year-olds exposed to fluoride. *Caries Res* 1996; **30**: 29–33.
42. Naylor MN, Glass RL. A 3-year clinical trial of calcium carbonate dentifrice containing calcium glycerophosphate and sodium monofluorophosphate. *Caries Res* 1979; **13**: 39–46.
43. Nyvad B, Fejerskov O. Active root surface caries converted into inactive caries as a response to oral hygiene. *Scand J Dent Res* 1986; **94**: 281–4.
44. Nyvad B, Fejerskov O. Assessing the stage of caries lesion activity on the basis of clinical and microbiological examination. *Community Dent Oral Epidemiol* 1997; **25**: 69–75.
45. Nyvad B, ten Cate JM, Fejerskov O. Arrest of root surface caries in situ. *J Dent Res* 1997; **76**: 1845–53.
46. Poulsen S, Agerbæk N, Melsen B, Korts DC, Glavind L, Rölla G. The effect of professional toothcleansing on gingivitis and dental caries in children after 1 year. *Community Dent Oral Epidemiol* 1976; **4**: 195–9.
47. Ravald N, Hamp SE, Birkhed D. Long-term evaluation of root surface caries in periodontally treated patients. *J Clin Periodontol* 1986; **13**: 758–67.
48. Richardson AS, Boyd MA, Conry RF. A correlation study of diet, oral hygiene and dental caries in 457 Canadian children. *Community Dent Oral Epidemiol* 1977; **5**: 227–30.
49. Sambunjak D, Nickerson JW, Poklepovic T, Johnson TM, Imai P, Tugwell P, Worthington HV. Flossing for the management of

periodontal diseases and dental caries in adults (review). *Cochrane Database Syst Rev* 2011; (**12**): CD008829.

50. Stecksén-Blicks C, Gustafsson L. Impact of oral hygiene and use of fluorides on caries increment in children during one year. *Community Dent Oral Epidemiol* 1986; **14**: 185–9.
51. Sutcliffe P. A longitudinal clinical study of oral cleanliness and dental caries in school children. *Arch Oral Biol* 1973; **18**: 765–70.
52. Sutcliffe P. Oral cleanliness and dental caries. In: Murray JJ, ed. Prevention of oral disease. New York: Oxford University Press; 1996: 68–77.
53. Tucker GJ, Andlaw RJ, Burchell CK. The relationship between oral hygiene and dental caries incidence in 11-year-old children. *Br Dent J* 1976; **141**: 75–9.
54. Vehkalathi MM, Vrbic VL, Peric LM, Matvoz ES. Oral hygiene and root caries occurrence in Slovenian adults. *Int Dent J* 1997; **47**: 26–31.
55. Von der Fehr FR, Löe H, Theilade E. Experimental caries in man. *Caries Res* 1970; **4**: 131–48.
56. Wellock WD, Maitland A, Brudevold F. Caries increments, tooth discoloration, and state of oral hygiene in children given single annual applications of acid phosphate-fluoride and stannous fluoride. *Arch Oral Biol* 1965; **10**: 453–60.
57. Wright GZ, Feasby WH, Banting DB. The effectiveness of interdental flossing with and without fluoride dentifrice. *Pediatr Dent* 1980; **2**: 105–9.

16

Are antibacterials necessary in caries prophylaxis?

A.A. Scheie, H.V. Rukke, and F.C. Petersen

The biofilm lifestyle and the rationale for antibacterial intervention

In nature, most bacteria reside in biofilm communities. The biofilm lifestyle predominates also in humans, and is mostly beneficial to health. Biofilms, however, are also associated with the majority of diseases of bacterial origin. Dental plaque is a typical biofilm. Ecological imbalance within dental biofilms may lead to dental caries as well as periodontal disease [30]. Therefore, control of dental biofilms is fundamental to oral health. Dental biofilms, however, are not easily controlled by mechanical means. This fact has encouraged the search for agents to control caries by preventing the formation of or by disrupting biofilms on teeth, or by inhibiting acid formation or stimulating base formation by dental biofilm bacteria. The possibility of controlling dental caries by using antibacterial agents has been of long-standing interest. Researchers have searched for suitable agents ever since Miller in 1890 [34] suggested that antiseptics that destroy bacteria, or limit their number and activity, could be a way to 'counteract or limit the ravages of dental caries.'

Numerous agents, with varying modes of action, have been tested for their ability to intervene with dental biofilm formation or metabolism, assuming that dental caries development would be reduced by such agents. However, as discussed in this chapter, there are in fact few such agents with documented long-term anticaries effect. This may be due to lack of agent efficacy or lack of documentation. Lack of documentation may be related to efficacy testing in short-term studies using surrogate end-points, such as

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

Published 2015 by John Wiley & Sons, Ltd.

biofilm mass or levels of mutans streptococci to assess the potential anticaries effect. No direct relationship exists between caries development and biofilm mass or salivary and biofilm levels of mutans streptococci. One, therefore, cannot extrapolate from studies on dental biofilm inhibition or inhibition of mutans streptococci to possible anticaries properties of an agent. The only way to assess anticaries efficacy is through well-controlled longitudinal clinical studies with assessment of caries incidence or progression as end point. Such studies are laborious and, therefore, scarce.

Notably, antibacterial activity per se does not necessarily coincide with clinical efficacy. Lack of agent efficacy may be related to the fact that the oral bacteria are organized in complex biofilms. Their properties are then changed markedly from their free-floating (planktonic) condition. It is clear that biofilm bacteria are much less susceptible to antibacterial agents and to the host immune system than when they are planktonic. An agent that effectively kills planktonic cells might require 2–1000 times higher concentrations in order to kill the same type of bacteria when in a biofilm. As an example, the chlorhexidine concentration needed to kill *Streptococcus mutans* in suspension may need to be increased five times to kill them in a biofilm [24].

Antibacterial agents have generally been tested against planktonic cells, while the inherent natural biofilm tolerance to antibacterial agents was not appreciated until recently. The increased tolerance to antibacterial agents when growing in biofilm may partly explain why many oral prophylactic agents predicted to be efficacious *in vitro* only show marginal clinical effects.

There are several factors that may contribute to low antibacterial susceptibility of biofilm bacteria [3]. Formation and maintenance of a biofilm is linked to the production of an extracellular matrix. Retarded or incomplete penetration of an agent into the biofilm may be caused by electrostatic or physicochemical properties of the agent and of the biofilm matrix, or by enzymatic degradation of the agent. Reduced growth rate of the bacteria due to nutrient limitations or oxidative stress have also been considered reasons for lack of efficacy. The bacteria may also express active efflux pumps that enable bacteria to rid themselves of toxic molecules, allowing them to survive in the presence of antibacterial agents. Maybe more important is that bacteria within a biofilm are phenotypically altered by their ability to turn on and off genes. Evidence exists that bacteria are able to regulate gene expression in response to interbacterial and environmental signals. Genes are regulated according to needs. Thus, other genes may be expressed by the bacteria when in a biofilm than those expressed when they are free floating. For *S. mutans* it has been reported that approximately 12% of the genes show significant differential expression when grown as a biofilm compared with planktonic growth. The machinery involved in carbohydrate catabolism, for instance, is more active during early stages of *S. mutans* biofilm formation than in planktonic cells [53].

Unlike classical infectious diseases, which are caused by bacterial pathogens, caries is caused by the resident oral microbiota. This microbiota represents an important line of defense and protects the host against colonization by foreign bacteria. The goal, therefore, is not to eliminate the microbiota, but to prevent a shift from an ecologically favorable to an ecologically unfavorable biofilm that may lead to disease. Whether this should be achieved by chemical agents or by other means may be discussed. One view is that any reduction of dental biofilms is beneficial if accomplished safely. Since adequate self-performed mechanical control of dental biofilms is difficult and often inadequate, antibacterials may offer an adjunct. The opposing view is that such agents may disturb the ecological balance within the oral cavity, and that bacterial strains resistant to the agent or with cross- or co-resistance to clinically relevant antibiotics might emerge. It is an established fact that widespread and sometimes indiscriminate use of antibacterials has led to treatment failure of infections due to acquired resistant or multi-resistant bacteria. This has been a problem since the early 1960s and is steadily increasing.

The acquisition of resistance to antibacterials is often acquired through horizontal gene transfer of mobile genetic elements that code for resistance genes. The oral microbiota, including the early tooth colonizers *Streptococcus oralis* and *Streptococcus mitis*, may function as reservoirs of antibiotic resistance genes [19, 44]. Resistance genes from these species can be transferred and incorporated via homologous recombination in the close relative *Streptococcus pneumoniae*. *S. pneumoniae* has a high pathogenic potential and is associated with high worldwide morbidity and mortality, causing human infections such as septicemia, meningitis, and pneumonia.

Any chemical agent that affects bacterial cells may be expected to have some adverse effects against host cells, unless the target structure or metabolic pathway is unique to the bacteria. There is, however, no evidence that the common usage of chemical agents against dental biofilms has resulted in demonstrable adverse effects. On the other hand, there is lack of conclusive, controlled studies to demonstrate a health benefit from prolonged use of antibacterial agents. Thus, possible benefit must be weighed against potential disadvantages on an individual basis.

Biological activity and mode of action

An antibacterial agent is capable of destroying or inhibiting the growth of bacteria by chemical or biological means. Antibiotics, disinfectants, and biocides are antibacterial agents. Most often, they are directed against pathogenic bacteria.

The efficacy of antibacterials depends on a range of intrinsic and extrinsic factors. A general requirement for biologic activity of an agent is *bioavailability*, here defined as the delivery of the agent to the intended site of action in a biologically active form, at effective doses, and for sufficient duration. Usually, local administration is the choice for agents intended to affect oral biofilms. The clinical efficacy of an orally delivered antibacterial agent for topical use is therefore also dependent on its substantivity.

Substantivity refers to the agent's ability to bind to oral surfaces and its subsequent rate of release from its binding sites. After delivery, a substantive agent is characterized by slow release over time. An agent may be retained in the oral cavity by binding to oral surfaces, including mucosal surfaces, tooth surfaces, pellicle, and supragingival dental biofilm, according to its affinity and binding strength. The binding strength determines the equilibrium between bound and free-agent molecules and the subsequent release rate from the binding sites (Fig. 16.1). This binding and release allow for contact of varying duration between the agent and the dental biofilm, depending on agent substantivity and salivary flow rate. An agent with high substantivity will be retained in the mouth for a prolonged period (Fig. 16.2a). On the other hand, an agent without substantivity will be cleared from the oral cavity with a rate determined by the salivary clearance. This only allows a short-term effect of the agent, and bacteria might have time to metabolize and multiply between agent applications. A nonsubstantive agent, therefore, must be applied more frequently than a substantive agent in order to have similar clinical efficacy (Fig. 16.2a and b).

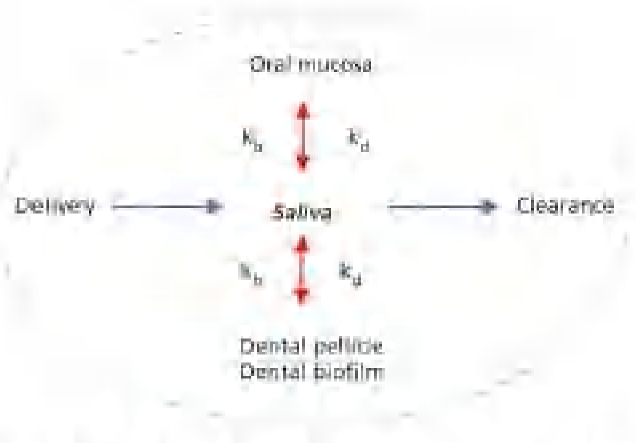


Figure 16.1 Oral delivery, binding, release, and clearance of antibacterial agents in the oral cavity. The agent binds to oral mucosa, tooth surfaces, pellicle, and dental biofilm bacteria according to its affinity K_b and released from its binding site depending on its dissociation constant K_d and salivary clearance rate. The oral mucosa represents the major reservoir for substantive agents. After [50]. Reproduced with permission of Sage Publications.

Most antibacterial prophylactic agents used today have a broad-spectrum activity aiming at reducing biofilm accumulation or activity by direct action on the bacteria. Alternative approaches designed to inhibit bacterial adhesion to the teeth without causing significant bacterial cell damage have also been proposed. Such non-antibacterial agents, however, represent a small fraction of commercially available prophylactic agents.

Antibacterial agents can reduce biofilm mass at various stages of the biofilm formation or maturation through one or more of the following mechanisms:

- inhibition of bacterial adhesion and colonization;
- inhibition of bacterial growth and metabolism;
- disruption of mature biofilms;
- detachment of biofilm bacteria;
- modification of biofilm biochemistry, ecology, or virulence (Fig. 16.3, Table 16.1).

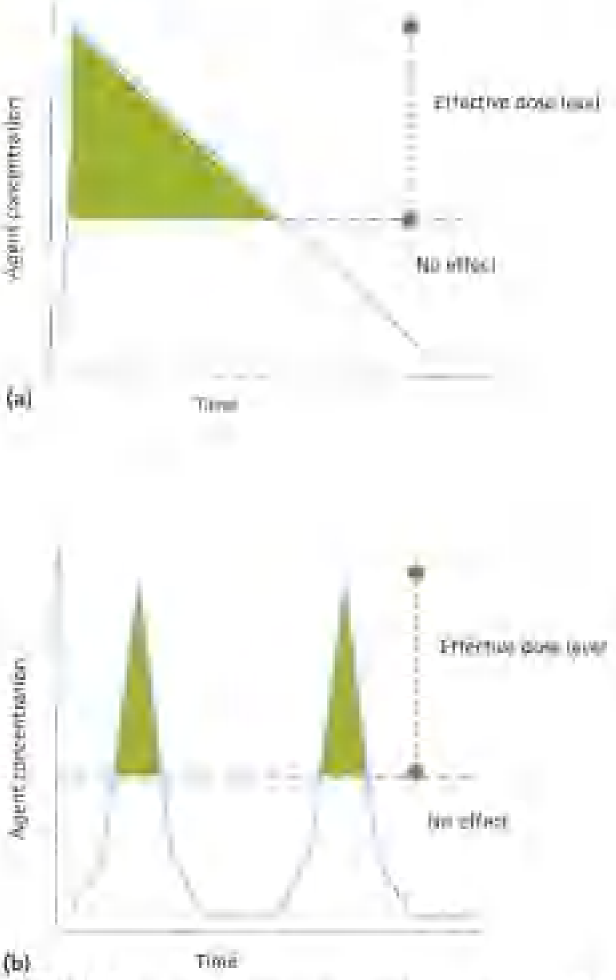


Figure 16.2 Dose curves of (a) an agent with high substantivity and (b) an agent with low substantivity. The horizontal dotted lines represent the effective dose levels. The effective dose–time area (circumscribed between the curves and the dotted lines) may be similar if the low substantivity agent is applied frequently. After [37]. Reproduced with permission of Taylor and Francis.

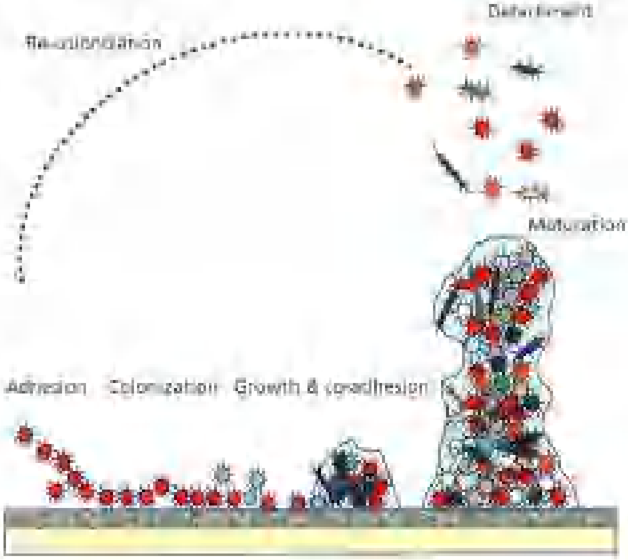


Figure 16.3 Modification of biofilm biochemistry.

Table 16.1 Stages and mechanisms of biofilm formation as targets for interference.

Mechanism and stage	Target
Inhibition of bacterial adhesion and colonization	Surface physico-chemical properties Bacterial cell surface components Cell communication
Inhibition of bacterial growth and metabolism	Transport systems Cell wall Metabolic activity Cell viability Cell communication
Disruption of biofilm maturation Detachment of biofilm bacteria	Extracellular polymers: polysaccharides, DNA Cell surface proteins Cell communication Adhesion Co-aggregation and co-adhesion Release of cell surface proteins
Modification of biofilm biochemistry and ecology Replacement	Specific bacterial niche

Inhibition of bacterial adhesion and colonization

Inhibiting bacterial adhesion to tooth surfaces will reduce accumulation of dental biofilms. *In vitro* studies have shown that agents that reduce the surface free energy will reduce bacterial adhesion to that surface. Various approaches have been explored to modify surface characteristics of teeth, pellicle, and/or bacteria. The salivary pellicle, to which the bacteria adhere through specific and nonspecific binding mechanisms, provides a complex array of binding sites. Thus, the composition of the pellicle may modulate bacterial adhesion events. One approach is to change the surface characteristics by manipulating the protein film on the enamel and thereby reducing bacterial adhesion. Several routes of surface modification have been investigated. Unfortunately, the clinical efficacy has so far been low, but future progress in material sciences may lead to novel approaches.

Specific surface proteins on the bacteria are involved in binding to pellicle components. Interbacterial communication may regulate surface protein expression. Targeting surface-associated proteins directly or through communication interference may, therefore, represent a logical strategy to control biofilm formation and activity. Expression of surface adhesins may, for instance, be impaired by subminimal inhibitory concentrations of several antibacterial agents, thus interfering with bacterial adhesion and colonization.

Immunization against dental caries has been a central research topic for many years. The aim is to inhibit adhesion or to reduce virulence, most often by use of vaccines against epitopes on mutans streptococci. The surface-bound antigen I/II and glucosyltransferases in mutans streptococci are the most studied cell surface targets for possible immunization against dental caries.

In general, immunization approaches are directed against single bacterial species. Knowing the ability of bacteria to form biofilms and to adapt and transform in such environments, a question is whether immunization will give lasting protection. The development of immunization approaches for prevention of diseases that are not deadly, such as dental caries, is also challenged by the expectation that it should have no significant side effects or health risks. No clinically applicable immunization scheme directed against dental caries is yet commercially available.

Inhibition of bacterial growth and/or metabolism

The majority of agents used to limit or inhibit dental biofilm formation are broad-spectrum antibacterial agents with bactericidal (killing) or bacteriostatic (inhibiting growth) effects. They are used according to a nonspecific plaque hypothesis, and are formulated to be used as supplements to mechanical oral cleaning.

Some antibacterial compounds bind to the bacterial membrane and thus interfere with normal membrane functions, such as transport. This disturbs the bacterial metabolism and in turn may kill the bacteria. Adsorption to bacterial membranes may also lead to alterations in the permeability, resulting in leakage of intracellular components along with denaturation and coagulation of cytoplasmic protein contents.

Present knowledge of mechanisms involved in biofilm formation indicates that it may be possible to interfere with bacterial activity on surfaces and colonization without affecting cell viability. For several bacteria, communication signals may be necessary to form structured biofilms. Compounds that interfere with signal formation or signal detection are being investigated for several bacteria.

including oral bacteria. Such signals may be involved not only in the formation of structured biofilms, but also in the ability of the cells to adapt to adverse environmental conditions. Different communication systems in *S. mutans* seem to influence, for instance, biofilm formation, antibacterial resistance, and acid tolerance. Synthetic antibacterial peptides and lytic bacteriophage-derived enzymes, that are targeted to kill specific bacteria also represent an interesting approach to prevent colonization and to control oral biofilms. Studies in these fields are, however, in an early stage. A deeper understanding of bacterial regulatory networks and signal transduction systems in complex environments will be required before the possibility of interference can be fully appreciated.

Detachment and disruption of dental biofilms

Dental biofilm formation is the result of a well-regulated series of processes, each of which may represent a potential target for biofilm control (Fig. 16.3). Adhesive biopolymers, like glucan and mutan, embed the bacteria and provide, together with other matrix components, three-dimensional stabilization of the biofilm. Frequent applications of chlorhexidine, as well as high concentrations of delmopinol, possess biofilm-dispersive activity. The dispersive activity of chlorhexidine may be attributed, at least in part, to its inhibitory effect on glucosyltransferase activity, whereas delmopinol reduces the viscosity of glucans. Since these agents have multiple mechanisms of action, it is difficult to ascertain the relative contribution of their matrix disrupting effect on biofilm. As discussed below, studies on the anticaries effects of chlorhexidine are so far inconclusive. For delmopinol, caries prophylactic effects have not been reported.

One possible reason for the lack of demonstrable anticaries efficacy by matrix-disrupting agents is that the biofilm matrix contains several types of biopolymers (including a variety of polysaccharides and DNA), and proteins. Therefore, targeting just one of these may be insufficient. Another barrier is diffusion of the disrupting agent into mature biofilms. This may explain why antibiofilm agents are in general more effective in preventing biofilm formation than in promoting disruption of mature biofilms.

Recent studies indicate that bacteria may have the ability to respond to environmental cues by activating pathways leading to detachment from biofilms. For instance, under unfavorable conditions, detachment would allow bacteria to leave the biofilm and find new sites for colonization. For several bacteria, release of surface proteins used for attachment is a regulated process. Elucidation of such mechanisms may lead to novel strategies that may prove effective in preventing caries.

Modification of dental biofilm biochemistry and ecology

Bacterial ecologic balance is considered crucial for maintenance of dental health. One way to maintain or restore such a balance could be to replace potential pathogens by harmless and beneficial bacteria through probiotics or replacement therapy. By definition, a *probiotic* is a live bacterium that, when ingested in sufficient quantity, exerts health benefits on the consumer. The term *probiotics* is often used also for replacement therapy. This latter term is more related to inhibition of colonization or displacing a pathogen by a definite effector strain, and often used to produce a more long-lasting effect on the ecology. Coupled with an understanding of how these bacteria act, genetic engineering opens the possibility of designing new probiotic strains. Such strains may be enabled to compete against and to replace known pathogens, while being nonvirulent themselves. A probiotic should preferably be able to establish as a part of the biofilm and replace or interact effectively with the given pathogen. The probiotic or replacement organism must not itself cause disease and should possess a high degree of genetic stability. With probiotics, naturally occurring harmless bacteria may exert a beneficial action by occupying colonization sites and competing with the pathogens for nutrients. They may also produce metabolites, biosurfactants, or antibacterial agents that are harmful to or that inhibit biofilm formation by the pathogen.

Probiotics are emerging as promising agents to prevent and treat various gastrointestinal disorders [10]. Probiotics have also been suggested in caries prophylaxis [23]. Lactobacilli may reduce *S. mutans* biofilm formation and inhibit *S. mutans* adherence to hydroxyapatite [21, 46]. In children given milk containing the probiotic *Lactobacillus rhamnosus* LGG over seven months [35], the probiotic milk was suggested to have a protective effect, since a tendency of low caries incidence was seen in one of the age groups. Reports on the effectiveness of applying probiotics in the prevention of dental caries, however, are limited and inconclusive. Further large-scale investigations are needed before we know whether bacteriotherapy may be effective in preventing dental caries.

Replacement strategies to reduce the pH drop in dental biofilms are also being pursued. One such approach is based on the replacement of wild type *S. mutans* by genetically engineered *S. mutans* that are defective in lactate production. To promote replacement the strains are also engineered to produce high levels of bacteriocins against wild-type *S. mutans* strains. Animal studies have shown promising results, but, as with immunization, replacement approaches have been directed against the single bacterial species *S. mutans*, disregarding a possible cariogenic role of other bacteria.

As of today, direct approaches to alter the ecology of the biofilm to become less pathogenic are restricted and have not yet led to development of agents appropriate for general clinical use. The Human Microbiome Project, which aims at identifying the complete microbiota of healthy individuals at different body sites, will increase our understanding of microbiota dynamics. Knowledge of which species are present in health and disease may in the future give us a better understanding of the ecological shifts occurring during disease development, how we may interfere, and how we may maintain a health-beneficial flora. Given the increasing problem of antibacterial resistance, approaches to promote or to restore ecological balance, for instance by use of probiotics, may become attractive future alternatives.

Vehicles for caries prophylactic agents

Caries prophylactic agents may be delivered to the oral cavity by various delivery formulations (vehicles):

- mouthrinses;
- sprays;
- dentifrices;
- gels;
- chewing gum/ lozenges;
- various sustained release formulations or devices.

The choice of vehicle depends on compatibility between the active agent and the constituents of the vehicle. For instance, the first fluoride dentifrices were ineffective owing to incompatibility between fluoride and the abrasive system of the dentifrice.

The vehicles should provide optimal bioavailability of the agent at its site of action. Delivery by dentifrices and mouthwashes, which are the most common vehicles, results in immediate high concentrations of the vehicle. The patient compliance is of vital importance. Patient compliance is probably reduced with increasing dosing frequency and with increasing length and complexity of the treatment. Therefore, the prophylaxis is most likely to succeed if the delivery vehicle does not require that the patient adopt new habits.

Recent developments in material sciences have provided novel systems for drug delivery. Active agents may be packed into micro- or nano-particles or incorporated into so-called functional films. We might in the future also see use of such new approaches in oral prophylaxis.

Mouthrinses

Mouthrinses represent the simplest vehicle formulation. Mouthrinses are usually a mixture of the active component in water and alcohol, with addition of a surfactant and flavor. Most antibacterial agents are compatible with this vehicle.

Sprays

Sprays have been evaluated for the delivery of, for instance, chlorhexidine in mouthrinse formulations. An advantage attributed to the spray is that relatively small doses are required to achieve efficacy. Good compliance may be expected with sprays because it is easy for a patient or caregiver to use. Further investigations on the use of sprays for the delivery of prophylactic agents are warranted, however.

Dentrifrices

Dentifrices fill three main functions:

- to debride teeth of stain;
- to give the cavity a feeling of freshness and cleanliness;
- to serve as a vehicle for prophylactic agents.

Dentifrices contain the following essential ingredients:

- an abrasive system to help remove stain;
- a component to carry the abrasive and the active agent;
- a surfactant to provide foam and detersive action;
- a binder for desirable rheological properties;
- flavor to make tooth brushing pleasant.

The complex formulation of dentifrices involves possibilities for component interactions. Care must therefore be taken in order to secure bioavailability of the active components. Toothbrushing with a dentifrice is a well-adopted habit. Therefore, dentifrices should be a suitable vehicle for delivery of prophylactic agents.

Gels

A gel is a thickened aqueous system, but with neither abrasive material nor foaming agents. Gels are generally compatible with relevant antibacterial agents. Gels are usually applied in pre-made or individually made appliances to provide close contact between the agent and the tooth surface.

Chewing gums and lozenges

The effect of chewing gums and lozenges depends on release of the agent during chewing, or during dissolution. The contact time is longer than with mouthrinse for instance, but increased salivation will inevitably increase the oral clearance rate of an agent. Administration of antibacterials via such vehicles may represent effective and acceptable routes, particularly in patients with low toothbrushing compliance. For individuals with reduced salivation, stimulated salivary secretion due to chewing may also be beneficial and relieve some discomfort. Increased salivation in itself may be beneficial. Further work on chewing gums and lozenges as vehicles is justified.

Sustained-release vehicles

Sustained-release vehicles, such as varnishes, may provide a long-term effect of the prophylactic agent. The agent efficacy depends on its degree and rate of release from the carrying material. Fluoride varnishes and also chlorhexidine varnishes are in use and found to be effective. The efficacy of sustained-release agents is independent of patient compliance.

Specific agents

There are three agents that have received particular interest as caries-prophylactic agents. These are chlorhexidine, which is a cationic antibacterial agent, triclosan, which is a nonionic antibacterial agent, and xylitol, which is a sugar alcohol claimed to have various effects on the oral microbiota. These agents will be described in some detail in the following. Essential oils and other less-frequently used agents such as cetylpyridinium chloride (CPC), delmopinol, hexetidine, sanguinaria extract (SE), metal ions, sodium dodecyl sulfate (SDS), and certain enzymes, will be discussed more briefly.

Cationic agents readily bind to negatively charged bacterial surfaces and, therefore, generally are more potent than anionic or nonionic agents. Likely binding sites for cations on Gram-positive bacteria are free carboxyl groups from peptidoglycans and phosphate groups from teichoic and lipoteichoic acid within the bacterial cell wall. In Gram-negative bacteria, lipopolysaccharides have high affinity for cations. Cationic agents thus can interact with both Gram-positive and Gram-negative bacteria. Cationic agents that have been used as antibiofilm agents include

- chlorhexidine;
- CPC;
- delmopinol;
- hexetidine;
- SE;
- metal ions.

Chlorhexidine (Fig. 16.4) is to date the most thoroughly studied and the most efficacious antibiofilm and antigingivitis agent. It is regularly considered a gold standard against which the efficacy of other antibiofilm agents is compared.

The antibacterial nonionic agent triclosan (Fig. 16.5) has been used as a preservative in consumer products such as deodorants, soaps, and body powder for more than 30 years. Triclosan has been added to dentifrices and mouthrinses with the object to reduce dental biofilm formation and development of gingivitis.

Xylitol is a pentitol (Fig. 16.6), which is used as a sugar substitute in, for instance, chewing gums. Like other polyols, which cannot be fermented by oral bacteria, xylitol does not lead to acid formation.

As will be discussed, evidence of cariostatic effects of these agents is inconclusive.

Chlorhexidine

Mode of action and clinical use

Chlorhexidine is a bisbiguanide with both hydrophilic and hydrophobic properties (Fig. 16.4).

The positively charged molecule may bind to negatively charged groups (i.e., to phosphate, carboxyl, or sulfate groups) on the oral mucosa, on bacteria, and in the pellicle. The bacterial membrane integrity may be disrupted by interactions with the hydrophobic portion of the molecule, causing disturbance of the membrane function. At high concentrations, chlorhexidine is bactericidal, causing leakage of low molecular weight cell constituents and precipitation of cell contents. These damages are irreversible. At lower concentrations the effect is bacteriostatic, causing interference with normal membrane functions or leakage of cell constituents [23]. The *in vitro* antibacterial effect of chlorhexidine is not outstanding, but the spectrum is broad. Gram-positive bacteria are generally more sensitive to chlorhexidine than Gram-negative bacteria are. Mutans streptococci are particularly sensitive, whereas *Streptococcus sanguinis*, for instance, exhibits great variation in susceptibility among strains [13]. The clinical antibacterial and antibiofilm effect of chlorhexidine is better than for other agents with similar or even better *in vitro* antibacterial efficacy. This superior effect has been ascribed mainly to the substantivity of chlorhexidine and to the fact that chlorhexidine retains its antibacterial effect even when adsorbed to surfaces. A single mouthrinse with 0.2% chlorhexidine exerts an immediate antibacterial effect, reducing the oral bacterial number by 80–95% [43]. Twice-daily mouthrinses inhibit dental biofilm accumulation almost completely. As a result of the direct antibacterial effect, chlorhexidine reduces the metabolic activity of the dental biofilm, thus decreasing acid challenge after carbohydrate intake. Chlorhexidine may

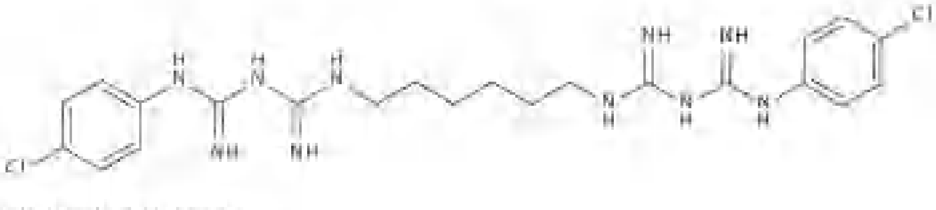


Figure 16.4 The molecular formula of chlorhexidine.

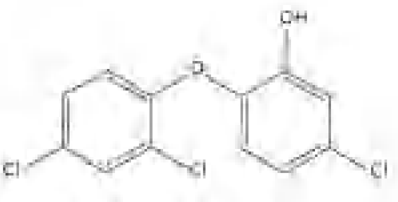


Figure 16.5 The molecular formula of triclosan.

Figure 16.6 The molecular formula of xylitol.

also inhibit the enzyme glucosyltransferase [42] that is essential for bacterial accumulation on tooth surfaces and the metabolic enzyme phosphoenolpyruvate phosphotransferase that is involved in transport and phosphorylation of glucose across the membrane [31].

Despite the widespread clinical use of chlorhexidine, reports on untoward effects are few. General and systemic effects are rare, and degradation of the chlorhexidine molecule to form potentially dangerous metabolites seems unlikely. Concern has been raised, however, that the residual activity of chlorhexidine after application may promote resistance in the resident microbiota [22].

Local adverse effects include:

- discoloration of teeth, tongue, restorations and dentures;
- soreness and desquamation of the oral mucosa;
- taste disturbances.

Local adverse effects are frequently reported, and the product itself has a bitter taste. Reducing the concentration of chlorhexidine reduces the local adverse effects. The prescribed dosage for chlorhexidine mouthrinses is usually either 10 mL of a 0.2% solution or 15 mL of a 0.12% solution with twice-daily rinses. Similar doses are obtained, and the efficacy is comparable. Similar doses may also be obtained by chlorhexidine-containing chewing gums (20 mg per piece). For long-term use, chlorhexidine should be dosed individually.

Caries-prophylactic effect

One would expect that the inhibitory effects on dental biofilm formation and metabolic activity would affect caries development. However, general use of chlorhexidine as an anticaries agent is controversial. No or very low cariostatic effect has been found in human studies where the chlorhexidine treatment is carried out as part of the individual's home care with either mouthrinses or toothbrushing. On the other hand, professional application of chlorhexidine combined with a rigorous prophylactic regimen including oral hygiene instruction, dietary advice, professional dental prophylaxis, and topical application of fluoride varnish reduced caries lesion development in children during a 3-year study period [56]. The idea was to inhibit caries lesion development by reducing the acidogenic potential of the microbiota. The number of new caries lesions in the untreated control group was 9.6 versus 4.2 for the chlorhexidine-treated group. It is worth noting, however, that a similar prophylactic regimen, but without chlorhexidine treatment, may give similar caries reduction [25].

Professional application of a chlorhexidine gel was shown to perform better than two different fluoride varnishes in a 2-year study in children [26], and better than a placebo gel when applied to approximal sites [17]. Quarterly application to approximal sites in 13–14-year-old children of either a 0.1% fluoride varnish or a 1% chlorhexidine varnish had a similar caries prophylactic effect during a 3-year study period [38]. In another study, varnishes containing either 40% chlorhexidine or fluoride (Duraphat®) applied every 3 months during 1 year were evaluated for ability to inhibit progression of already existing root caries lesions. Both fluoride and chlorhexidine decreased lesion progression compared with control [41]. In a review of chlorhexidine intervention studies performed between 1995 and 2003, chlorhexidine varnish seemed to have an inhibitory effect on fissure caries development in children with low exposure to fluoride. In elderly and in fluoride-exposed caries-active children and adolescents, evidence for an anticaries effect of chlorhexidine was inconclusive [49]. More recently, two studies that examined the caries inhibitory effect of 40% chlorhexidine varnish in Chinese children reported somewhat contradictory results. In one study, the effect was reported as questionable and only transient [55], whereas 37.3% caries reduction was found in the other study [11]. There is, therefore, lack of conclusive evidence-based data supporting the clinical use of chlorhexidine in caries prevention.

Intensive prophylaxis with chlorhexidine and fluoride in combination may be indicated in individuals with high caries activity and incidence due to for instance hyposalivation after irradiation treatment of the head and neck regions [24].

Triclosan

Mode of action and clinical use

Triclosan is a nonionic antibacterial agent with hydrophilic and hydrophobic properties (Fig. 16.5). Triclosan has a broad antibacterial spectrum, with activity against both Gram-positive and Gram-negative bacteria and fungi. Oral bacteria such as mutans streptococci, *S. sanguinis*, and *Streptococcus salivarius* are susceptible to low concentrations of triclosan *in vitro*. At low concentrations, the effect is bacteriostatic. Until recently, triclosan was thought to function as an unspecific biocide. Recent data, however, show that triclosan inhibits lipid synthesis specifically [32]. This leads to defective cell membrane synthesis.

Owing to its poor aqueous solubility, triclosan is solubilized in the flavor/surfactant phase of the triclosan formulation. In commercial products, triclosan is solubilized in one or more detergents, such as SDS, sodium lauroyl sarcosinate, or in propylene glycol or polyethylene glycol. Thus, when testing the antibacterial effect of triclosan, one must consider possible additive or synergistic effects with these constituents.

The substantivity in the oral cavity of triclosan itself is relatively low. Thus, to be efficacious, a copolymer, polyvinylmethyl-ether maleic acid (commercially known as Gantrez), or zinc citrate is added to the formulations. Without these retention mediators, triclosan toothpastes have no apparent effect on dental biofilm biomass [52].

Extensive studies have been performed to prove the efficacy of triclosan-containing products. Despite the demonstration in several short- and long-term studies that triclosan prevents dental biofilm formation and gingivitis, its effect must be considered as modest. A meta-analysis of 16 clinical studies of the long-term effect of daily unsupervised triclosan use have shown reductions in dental biofilm mass by 15% and gingivitis by 12% [9]. As to the effect on periodontitis development, the effect on the general population is not significant. Triclosan may possibly slow down progression in predisposed individuals (i.e., in individuals who have already increased dental pocket depth) [6]. Notably, this effect appears to be of moderate magnitude (between 10 and 20% compared with placebo) and independent of triclosan's antibacterial properties [5]. Data on a possible cariostatic effect of triclosan are scarce. It has been shown that triclosan neither enhances nor interferes with fluoride-enhanced remineralization and that triclosan-containing toothpastes are 'at least as good as' fluoride-containing dentifrices without antibacterial additives.

Concerns have recently been raised that the widespread use of triclosan-containing products may lead to development of antibacterial resistance [54]. In high concentrations, triclosan causes disruption of the bacterial cells by targeting multiple nonspecific targets. However, triclosan-containing products like dentifrices leave residues that will dilute to sublethal concentration. At sublethal concentrations triclosan inhibits the enzyme enoyl-acyl carrier protein reductase involved in fatty acid metabolism, giving it a specific target in a similar manner as clinically relevant antibiotics. It has been shown that triclosan use selects triclosan-resistant bacteria. Of particular public health concern is that widespread use of triclosan, in addition to selecting for triclosan resistance, may promote development of concomitant resistance to other clinically important antibacterials through cross- or co-resistance mechanisms. Since most bacteria are capable of acquiring genes from other strains or species, resistance may spread further among inhabitants of the human microbiota [19, 44]. The use of triclosan, therefore, should be restricted to purposes where there is a well-documented effect. The meager documentation of triclosan's anticaries effect hardly justifies its use in caries prophylaxis for the general population.

Xylitol

Xylitol is a sugar alcohol with five carbon atoms, a pentitol (Fig. 16.6).

Xylitol is non-acidogenic and thus does not promote dental caries. Potential effects of xylitol have been extensively studied, particularly in Finland. Interpretation of early results was that xylitol possesses anticaries or even caries-therapeutic properties. It has also been suggested that xylitol exerts effects on bacterial growth and metabolism, on salivary factors, and on de- and remineralization processes. Reduced dental biofilm formation has been reported; a decrease in the number of salivary mutans streptococci and less gingivitis has also been observed. Each factor alone or in combination could theoretically contribute to a cariostatic effect.

Caries prophylactic regimens including xylitol chewing gum have been suggested for high caries risk children and also for mothers with high salivary levels of mutans streptococci. There is however still a controversy over the caries inhibitory effect of xylitol, the optimal dose, and the mechanism of action. A recent randomized, controlled study concluded that daily use of xylitol lozenges did not result in statistically significant reduction in caries increment in adults at high caries risk during a 33-month study period [1].

A specific xylitol-induced change in salivary factors has not been confirmed in either short- or long-term studies. Nor has xylitol been shown specifically to interfere with enamel demineralization or to increase remineralization. *In vivo* studies have indicated remineralization to occur also with other sugar alcohols, such as sorbitol. In fact, even sucrose-sweetened gum chewed regularly after meals may enhance remineralization, thus pointing to the impact of increased salivation. Unfortunately, in many clinical studies, caries incidence in subjects chewing xylitol gum has been compared with nonchewing control subjects [37]. It is therefore difficult to discriminate between a true xylitol effect and the impact of increased salivation through chewing of a sweetened gum. Thus, the claim of remineralization being a xylitol-specific effect has not yet been confirmed. On the contrary, it may be concluded that any caries preventive effect of chewing sugar-free gums sweetened by xylitol or other sweeteners is related to the chewing process, and not to the sweetener itself [29].

Several studies indicate that the levels of mutans streptococci in saliva and in dental biofilm may be reduced after consumption of xylitol, and the view that a specific effect of xylitol on *S. mutans* is a cornerstone of xylitol's anticaries mechanism has been broadly supported.

Xylitol seems to be unique among sugar alcohols in its *in vitro* inhibitory effect on glycolysis, particularly in mutans streptococci. The inhibitory effect has been related to uptake of xylitol via a constitutive transport system specific for fructose and subsequent intracellular accumulation of xylitol-5-phosphate, as part of an energy, phosphoenolpyruvate, and adenosine triphosphate-consuming futile xylitol cycle. Concomitant intracellular accumulation of glucose-6-phosphate to confirm an antimetabolic effect of xylitol *in vivo* has, however, not been demonstrated.

Reduced adhesiveness through impaired polysaccharide formation has also been suggested as one of the inhibitory mechanisms of xylitol on mutans streptococci and an explanation for cariostatic effects of xylitol. It is worth noting that long-term xylitol consumption leads to selection of mutans streptococci, which are resistant to or unaffected by xylitol. Speculation has been that xylitol-resistant strains might be less virulent than xylitol-sensitive strains. According to Trahan *et al.*, selection in xylitol consumers of natural mutants with diminished virulence might be one of the mechanisms of the inhibitory action of xylitol [48]. There are, however, no clinical data to support such a contention.

Attempts have been made to incorporate xylitol as an active ingredient in dental hygiene products, and at present xylitol-containing dentifrices are available on the market. One of three longitudinal xylitol dentifrice studies consent to a caries-reducing effect of xylitol [43], whereas the two other studies failed to find an additive effect of xylitol when added to fluoride-containing dentifrices [8, 38].

Xylitol is an interesting alternative sweetening agent, and could be the sweetening agent of choice when sucrose is to be substituted, as in chewing gums for instance. Chewing in itself increases salivation, and therefore is beneficial. However, data to confirm caries prophylactic effects of xylitol or superiority claims of xylitol over other polyols are lacking. Well-designed randomized clinical studies with proper control are needed to demonstrate a role of xylitol in caries prophylaxis.

Other agents proposed for caries prophylaxis, but without documented anticaries effects

Cetylpyridinium chloride

CPC, benzalconium chloride, and benzethonium chloride are quaternary ammonium compounds. CPC has been widely used in mouthrinses, mainly because of its antibacterial property.

The CPC molecule possesses both hydrophilic and hydrophobic groups, thus allowing ionic and hydrophobic interactions. It is assumed that interaction with bacteria occurs via cationic binding in much the same way as for chlorhexidine.

The antibacterial activity of CPC is equal to or better than chlorhexidine, whereas its biofilm inhibitory property is inferior. This difference in antibiofilm efficacy may be related to the fact that CPC loses part of its antibacterial activity upon adsorption to surfaces. Notably, the substantive properties are also different. Initial retention of CPC is higher than for chlorhexidine, but CPC is cleared from the oral cavity more rapidly [2]. It has been suggested to incorporate CPC into dental materials, for instance in orthodontic adhesives with the aim to control caries lesion formation around orthodontic brackets. Although CPC retains its antibacterial properties, the clinical effect remains to be assessed. There are no data on CPC's ability to prevent dental caries in humans.

Delmopinol

Delmopinol is a potent surfactant with low molecular weight and is predominantly cationic at pH below 7. It has low antibacterial activity and is believed to act primarily by interfering with the physicochemical properties of oral surfaces. Bacterial resistance or major shifts in the bacterial composition of dental biofilm have not been observed in clinical experiments with delmopinol. Delmopinol reduces dental biofilm formation probably by reducing bacterial adhesion to the tooth surface. Its inhibitory effect on dental biofilm is less than or comparable to chlorhexidine. The effect on dental caries in humans has not yet been assessed.

Hexetidine

Hexetidine is a synthetic hexahydropyrimidine, which has antibacterial and antifungal activity *in vitro* and *in vivo*. It is active against Gram-positive and Gram-negative bacteria, including oral bacteria such as mutans streptococci, *Streptococcus sobrinus*, and *S. sanguinis*. The *in vitro* antibacterial activity of hexetidine is reported to be inferior to or essentially similar to that of chlorhexidine or CPC. Hexetidine-containing mouthrinses are commercially available, yet at clinical acceptable concentrations it exerts only a very slight inhibitory effect on dental biofilms. Increasing the concentration of hexetidine from 0.10% to 0.14% increases the antibiofilm efficacy to approach that of 0.2% chlorhexidine. However, the frequency of desquamative lesions increases correspondingly. The exact mechanism for the antibiofilm activity is not clear. Hexetidine has been claimed to inhibit glycolysis, but clinical data do not support this assumption. The antibacterial effect of hexetidine is reduced in the presence of saliva. Enhanced antibiofilm effects of hexetidine are observed in combination with divalent metal ions; for instance, Zn^{2+} [46] or Cu^{2+} [18]. This is probably related to increased intracellular uptake of the metal ions. The agent has not been evaluated for ability to prevent dental caries in humans.

Essential oils

Essential oils are extracts from plant material in a solvent, often alcohol. Essential oils have been used as antiseptics for over 100 years, and are widely used in pharmaceutical, food, agriculture, and cosmetic products, owing to their low toxicity and their antibacterial effect [4]. The exact pharmacodynamics of most essential oils is currently not fully known, but it is thought that some compounds act by interfering with normal cell membrane function, causing leakage of cellular components, disruption of the proton motive force, and denaturation of proteins. There is, however, most likely not a single mechanism of action of essential oils, considering that this is a heterogeneous group of compounds.

The most well-known oral product containing essential oils is Listerine. This product was already tested for its antiseptic properties by W.D. Miller in the 1880s [34]. It contains a mixture of menthol and methyl salicylate and two phenol-related essential oils, thymol and eucalyptol, in a solution of over 20% alcohol. A new mixture without alcohol was recently launched on the market. There is, however, little documentation of the efficacy of this product.

Essential oils have a broad antibacterial spectrum, being bactericidal against both Gram-positive and Gram-negative bacteria. Use of alcohol-containing essential oils as oral antiseptics has in some studies shown reduction in both the supragingival biofilm and in total recoverable streptococci in saliva and interproximal sites after rinsing [15]. The efficacy has in some studies been evaluated as at least as good as flossing and brushing alone [47]. Others have not found a reduction in salivary *S. mutans* or lactobacillus levels. Compared with chlorhexidine, the biofilm inhibitory effect of essential oils is inferior [39].

Sanguinaria extracts

SE is a herbal preparation. It is obtained from the bloodroot plant *Sanguinaria canadensis*. SE has been used in homeopathic preparations and in folklore medicine for treatment of topical infections and as expectorants. It is antibacterial against Gram-positive and Gram-negative bacteria including oral bacteria. The exact mode of action is not clear, but SE seems to exert a bactericidal effect by interfering with essential steps in the synthesis of the bacterial cell wall [51]. SE, reportedly, suppresses the activity of several enzymes, possibly through oxidation of SH-groups. The antibacterial activity is thought to be associated with the lipophilic property of the molecules. More important may be that SE is capable of binding metal ions. The marketed preparations of SE contain quite high concentrations of $ZnCl_2$. As will be discussed later, zinc ions have antibacterial activity. It may be speculated, therefore, that potential effects of SE are related to the Zn^{2+} content.

SE has substantive properties, but clinical data on the efficacy of mouthrinses with SE are not conclusive. In some studies, antibiofilm as well as antigingivitis, and antiglycolytic effects were reported. In others, little or no effect was found. *In vitro* studies have indicated that adherence of oral bacteria to hydroxyapatite may be inhibited, and SE may increase saliva-mediated aggregation. Both factors may contribute to inhibition of dental biofilm formation *in vivo*, but clinical effects on caries have not been assessed.

Metal ions

Metal ions have antibacterial effects depending on the ion concentration, as well as on the chemistry of the ion. Their bacteriostatic effects have been recognized for a long time. Miller proposed the use of metal ions to treat rampant caries as early as 1890 [34], and Hanke reported in 1940 that mouthrinses containing certain metal ions have antibiofilm potential [20]. The antibacterial efficacy is proportional to the concentration of free metal ions, which is the predominant bioactive form [7]. Hydrolysis of the metal ions and binding of metal ions to other components reduce the metal ion activity. The formulation of the vehicle is therefore crucial.

Metal ions of interest are Cu^{2+}, Sn^{2+}, and Zn^{2+}. Cu^{2+} and Sn^{2+} are more potent than Zn^{2+}, but these are only moderately efficacious compared with chlorhexidine. Because of the ability of Zn^{2+} to combine with odoriferous sulfur-containing compounds, zinc salts have a long history in oral hygiene products. Zn^{2+} is also an anticalculus agent. Concerns were raised as to a possible interference of Zn^{2+} with the cariostatic effect of fluoride, but this seems not a problem.

Metal ions interact with both Gram-positive and Gram-negative bacteria. The antibacterial effect is unspecific. Metal ions form metal–salt bridges with anionic groups of enzymes. This in turn may influence substrate interactions due to altered charge or conformational changes of the enzyme. Metal ions have an antiglycolytic effect, as shown both *in vitro* in pure cultures of bacteria and as reduced acid formation *in vivo*. Divalent metal ions probably inhibit glycolysis in dental biofilm by oxidative inactivation of SH groups of glycolytic enzymes.

Numerous studies have confirmed the clinical antibiofilm effect of metal ions, both alone and in combination with other agents. The antibiofilm effect relates partly to the antibacterial activity and partly to displacement of Ca^{2+} from pellicle and bacterial surfaces. Binding of metal ions to bacteria alters their surface charge and adherence ability [36].

Cu^{2+}, Sn^{2+}, and Zn^{2+} have shown cariostatic effects in rats. SnF_2 has been used as a prophylactic agent in humans for many years owing both to a potential cariostatic effect and to its antibiofilm properties.

Metal ions are substantive agents. Both salivary and dental biofilm levels of Cu^{2+}, Sn^{2+}, and Zn^{2+} are elevated for several hours after a mouthrinse. The ions bind to the same oral receptors as chlorhexidine.

Adverse effects related to metal ions are unpleasant metallic taste, tendency to induce a feeling of dryness in the oral cavity, and a yellowish to brownish dental stain. Metal sulfides, which are formed between the metal ions and sulfhydryl groups of pellicle proteins probably, cause it. Zn^{2+} ions have the least tendency to stain, because zinc sulfide is yellowish to greyish-white in color. The staining tendency is generally lower for metal ions than for chlorhexidine [illegible].

Sodium dodecyl sulfate

SDS is an anionic agent. The molecule has a hydrophilic sulfate group and a hydrophobic carbon chain. It is the most frequently used detergent in commercial dentifrices.

SDS has antibacterial activity against a range of bacteria *in vitro*, including mutans streptococci, *S. sobrinus*, and *Actinomyces viscosus*. Adsorption of SDS to the bacterial surface may interfere with cell wall integrity, with subsequent leakage of cellular components. At low concentrations SDS is reported to inhibit specific bacterial enzymes, such as glucosyltransferase from *S. sobrinus* and *S. mutans*, enzymes of the phosphoenolpyruvate phosphotransferase transport in *S. sobrinus*, and lactate dehydrogenase and glucose 6-phosphate dehydrogenase in *Escherichia coli*. These effects may be related to the strong affinity of SDS for proteins and its denaturing property.

Dental biofilm inhibitory properties of SDS have been shown in humans. This may relate, mainly, to the antibacterial effect, but competition with negatively charged bacteria and pellicle proteins for binding sites, with subsequent inhibition of bacterial adsorption to the tooth surface, may also contribute to the inhibitory effect. SDS apparently has some degree of substantivity, which may be explained by its high affinity for calcium. SDS in combination with Zn^{2+} shows increased antibiofilm and antibacterial properties. There are no data to support a cariostatic effect of SDS.

Enzymes

Whole saliva contains two peroxidase enzymes that oxidize thiocyanate (SCN^-) to hypothiocyanite ($OSCN^-$) in the presence of hydrogen peroxide. Hypothiocyanite is antibacterial and inhibits some streptococci and lactobacilli *in vitro* [28]. The activity of the salivary peroxidase system depends on available hydrogen peroxide. Hydrogen peroxide is produced by various bacteria as a metabolic end-product, but in limiting amounts for maximum activity of the salivary peroxidase. The enzyme amyloglucosidase provides glucose from which glucose oxidase produces hydrogen peroxide. Addition of these enzymes to oral products is suggested to ensure sufficient hydrogen peroxide to control proliferation of bacteria through enhanced peroxidase activity.

Mouthrinses containing the enzymes have been tested for ability to reduce dental biofilm, gingivitis, and dental caries, but the effect is not impressive. Dentifrices containing these enzymes show slightly improved antibiofilm and antigingivitis effects compared with nonenzyme dentifrices, but whether this marginal effect is of clinical relevance may be questioned.

Risk of antibacterial resistance development?

An antibacterial kills the susceptible strains, but allows bacteria carrying antibacterial-resistant factors to survive and multiply. Antibacterial resistance refers to the characteristic of a genus, species, or strain of bacteria enabling it to avoid being killed or inhibited by a defined concentration of an antibacterial agent. Bacterial resistance may be a natural property of the organism, intrinsic resistance, or may be acquired, so-called acquired resistance. Antibacterial agents exert selective pressure on the microbiota. Thus, with all use of antibacterial agents, there is an inherent risk of selecting for resistant or unsusceptible genera, species, or strains. Agents with several targets are considered less likely to induce resistance. Presence of subinhibitory agent concentrations will increase the risk of resistance development. *In vitro* studies demonstrate that some antibacterials used at sublethal concentrations trigger the emergence of antibiotic resistance and/or select bacteria resistant to clinically relevant antibiotics. The possibility of genetic linkage between genes for antiseptic resistance and those for antibiotic resistance has been described [16]. Despite this mechanistic evidence from *in vitro* data, epidemiological data indicating public health relevance are lacking.

The antibacterial agent concentrations for use in oral prophylaxis are generally higher than concentrations needed for bacteriostatic or bactericidal effects. Agents with substantive properties, however, will eventually expose bacteria to subinhibitory concentrations. This carries an inherent risk of inducing antibacterial resistance.

Studies focusing on possible adverse effects of subinhibitory concentrations of such agents, however, are limited, and there are considerable gaps in our current knowledge about the effect of residual concentrations of antibacterials. The possibility of selection and emergence of antibacterial-resistant bacteria is, nevertheless, a significant risk that should carefully be weighed against potential benefits. The finding that resistance to triclosan may result also in resistance to commonly used antibiotics underlines the importance of prudence and the need for further research to establish a possible correlation between exposure to antibacterial consumer products and development of antibiotic resistance.

Intrinsic resistance

In intrinsically resistant bacteria, the target molecule may be lacking or the agent cannot get to the target due, for instance, to diffusion restriction by electrostatic or physico-chemical properties or presence of extracellular polysaccharides. Gram-positive bacteria, characterized by a single cell membrane that is enveloped by a thick peptidoglycan layer, are generally more susceptible to antibacterials than are Gram-negatives. In Gram-negatives, the complex cell wall composed of an inner and an outer cell membrane creates a more effective barrier. Short exposure of oral bacteria to antibacterials such as chlorhexidine shows, for instance, that the Gram-positive oral streptococci are more susceptible to killing than are the Gram-negative *Fusobacterium nucleatum* and *Porphyromonas gingivalis* [12]. Bacteria may also be equipped with enzymes that can lead to biocide degradation or with efflux pumps that promote the export of internalized biocides.

The arrangement of bacteria in biofilm is a general mechanism promoting intrinsic or phenotypic resistance. Growth rates are usually slow in biofilms, contributing to reduced susceptibility. Also, bacteria in biofilms are embedded in a polymer matrix that may create a barrier against the penetration of certain agents. The expression profile of bacterial genes in biofilms is in addition often altered, with the potential to affect susceptibility levels. Finally, persister cells that represent a small fraction of the bacterial population in biofilms may enter a protected, dormant state that renders them insensitive to antibacterials [3].

Acquired resistance

Acquired resistance is the result of mutation and/or acquisition of mobile genetic elements through conjugation, transduction, or transformation. The resistance mechanisms may be exerted in different ways. It may depend on altered composition of the outer cell wall, such as the fatty acid and protein composition of the outer membranes. Mutations in the FabI enzyme involved in fatty acid synthesis, is linked to triclosan resistance in *E. coli*. Resistance may also depend on expression of antibacterial degrading enzymes or on efflux pumps. Efflux pumps enable bacteria to rid themselves of toxic molecules, allowing them to survive even in the presence of an antibacterial agent. The pumps may act on a range of chemically dissimilar compounds, giving rise to cross-resistance. This has been observed in staphylococci that carry plasmids with genes for multidrug efflux pumps. In this case, reduced levels of susceptibility to cationic agents such as chlorhexidine and quaternary ammonium compounds, concomitant with resistance to clinically relevant antibiotics, has been reported.

Transfer of resistance genes from one bacterium to another via vertical gene transfer increases the antibacterial-resistant population, while new resistant species or strains may evolve through horizontal gene transfer. Biofilm, where bacteria are in close proximity, may be an optimal environment for horizontal gene transfer.

Concluding remarks and future approaches

The oral microbiota consists of millions of bacteria of hundreds of various species that are organized in biofilms. Oral biofilm bacteria show differences in antibacterial susceptibility determined by genetic background and by their mode of growth, as well as membrane structure and permeability.

The agents suggested for caries control most often act on a broad spectrum of targets, and are used according to the nonspecific plaque hypothesis. Differences in susceptibility levels driven by intrinsic or acquired mechanisms pose a risk of bacterial selection upon exposure to antibacterial agents. Selection that favors growth of pathogens or resistant bacteria may result in unwanted effects on the microbiota. Of concern is also the fact that the antibacterials used often have multiple targets that may overlap with the more specific antibiotic targets. This poses a risk of cross resistance emergence, with the consequent reduction in the clinical efficacy of antibiotics.

Therefore, antibacterial prophylactic agents should not be instituted routinely. Such agents should be used restrictively and only if conventional prophylactic methods are likely to be ineffective. This may be the case for individuals with high caries activity and incidence due, for instance, to physical or mental handicaps, impaired dexterity due to high age, hyposalivation due to systemic diseases or medication, or similar conditions. These individuals may benefit from intermittent or chronic use of antibacterial prophylactic agents. Certain conditions, such as intra-oral fixation or splinting, treatment with orthodontic appliances, insertion of prosthetic restorations or implants, or pre- and post-surgical treatment, where mechanical cleaning is particularly difficult may justify use of antibacterial agents for periods of varying length. In all cases, expected benefit should be weighed against potential adverse effects, and the choice of agent, treatment length, mode of application, and dose should be made on an individual basis.

As discussed in this chapter, the ideal antibacterial agent for dental biofilm control is not yet available, and documentation for caries prophylactic effects in humans of available agents is sparse. The main reasons lie in the multifaceted nature of the caries disease and the fact that bacteria causing the disease are organized in complex biofilms, a fact that in the past often has been neglected. Most *in vitro* studies so far have been on the single species level. Studies with multispecies biofilm models are increasing and are giving us insight into the complex interplay between bacterial species living in biofilm. These *in vitro* models supplemented with increasing knowledge of the human oral microbiome may in the future give us novel tools to modify biofilm ecology. Biofilms are likely to represent a natural scenario for bacterial communication, and the ability to communicate has been shown in both oral streptococci and periodontal pathogens. The communication may regulate pathogenic traits like biofilm formation and expression of virulence factors. For most oral biofilm bacteria, however, the presence and function of communication pathways remain to be clarified.

We might in the future see new developments in caries prevention based on the progress presently being made in understanding the special features of biofilm bacteria and their communication systems. Developments in material science may lead to novel vehicles for delivery of targeted agents. Definite targets remain to be defined, and future research is needed to establish a correlation between exposure to oral antibacterial prophylactic agents and the development of antibacterial/antibiotic resistance.

Background literature

Busscher HJ, Evans LV. *Oral biofilms and plaque control*. Harwood Academic Publishers, 1998.

Gjermo P. Chlorhexidine and related compounds. *J Dent Res* 1989; **68** (Spec Iss): 1602–8.

Pader M. *Oral hygiene products and practice*. New York: Marcel Dekker, 1988.

Scheie AA. Modes of action of currently known chemical antiplaque agents other than chlorhexidine. *J Dent Res* 1989; **68** (Spec Iss): 1609–16.

Scheie AA, Fejerskov OB. Xylitol in caries prevention: what is the evidence for clinical efficacy? *Oral Dis* 1998; 4: 268–78.

Scheie AA, Petersen FC. The biofilm concept: consequences for future prophylaxis of oral diseases? *Crit Rev Oral Biol Med* 2004; 15: 4–12.

References

1. Bader JD, Vollmer WM, Shugars DA, Gilbert GH, Amaechi BT, Brown JP, Laws RL, Funkhouser KA, Makhija SK, Ritter AV, Leo MC. Results from the Xylitol for Adult Caries Trial (X-ACT). *J Am Dent Assoc* 2013; 144: 21–30.

2. Bonesvoll P, Gjermo P. A comparison between chlorhexidine and some quaternary ammonium compounds with regard to retention, salivary concentration and plaque-inhibiting effect in the human mouth after mouth rinses. *Arch Oral Biol* 1978; 23: 289–94.
3. Bridier A, Briandet R, Thomas V, Dubois-Brissonnet F. Resistance of bacterial biofilms to disinfectants: a review. *Biofouling* 2011; 27: 1017–32.
4. Burt S. Essential oils: their antibacterial properties and potential applications in foods – a review. *Int J Food Microbiol* 2004; 94: 223–53.
5. Cullinan MP, Hamlet SM, Westerman B, Palmer JE, Faddy MJ, Seymour GJ. Acquisition and loss of *Porphyromonas gingivalis*, *Actinobacillus actinomycetemcomitans* and *Prevotella intermedia* over a 5-year period: effect of a triclosan/copolymer dentifrice. *J Clin Periodontol* 2003; 30: 532–41.
6. Cullinan MP, Westerman B, Hamlet SM, Palmer JE, Faddy MJ, Seymour GJ. The effect of a triclosan-containing dentifrice on the progression of periodontal disease in an adult population. *J Clin Periodontol* 2003; 30: 414–19.
7. Cummins D, Watson GK. Computer model relating chemistry to biologic activity of metal anti-plaque agents. *J Dent Res* 1989; 68: 1702–5.
8. Cutress T, Howell PT, Finidori C, Abdullah F. Caries preventive effect of high fluoride and xylitol containing dentifrices. *ASDC J Dent Child* 1992; 59: 313–18.
9. Davies RM, Ellwood RP, Davies GM. The effectiveness of a toothpaste containing triclosan and polyvinyl-methyl ether maleic acid copolymer in improving plaque control and gingival health: a systematic review. *J Clin Periodontol* 2004; 31: 1029–33.
10. Doron S, Gorbach SL. Probiotics: their role in the treatment and prevention of disease. *Expert Rev Anti Infect Ther* 2006; 4: 261–75.
11. Du MQ, Tai BJ, Jiang H, Lo EC, Fan MW, Bian Z. A two-year randomized clinical trial of chlorhexidine varnish on dental caries in Chinese preschool children. *J Dent Res* 2006; 85: 557–9.
12. Eick S, Goltz S, Nietzsche S, Jentsch H, Pfister W. Efficacy of chlorhexidine digluconate-containing formulations and other mouthrinses against periodontopathogenic microorganisms. *Quintessence Int* 2011; 42: 687–700.
13. Emilson CG. Susceptibility of various microorganisms to chlorhexidine. *Scand J Dent Res* 1977; 85: 255–65.
14. Filoche SK, Soma K, Sissons CH. Antimicrobial effects of essential oils in combination with chlorhexidine digluconate. *Oral Microbiol Immunol* 2005; 20: 221–5.
15. Fine DH, Markowitz K, Furgang D, Goldsmith D, Ricci-Nittel D, Charles CH, Peng P, Lynch MC. Effect of rinsing with an essential oil-containing mouthrinse on subgingival periodontopathogens. *J Periodontol* 2007; 78: 1935–42.
16. Fraise AP. Susceptibility of antibiotic-resistant cocci to biocides. *Symp Ser Soc Appl Microbiol* 2002; (31): 158S–62S.
17. Gisselsson H, Birkhed D, Björn AL. Effect of professional flossing with chlorhexidine gel on approximal caries in 12- to 15-year-old schoolchildren. *Caries Res* 1988; 22: 187–92.
18. Grytten J, Tollefsen T, Afseth J. The effect of a combination of copper and hexetidine on plaque formation and the amount of copper retained by dental plaque bacteria. *Acta Odontol Scand* 1987; 45: 429–33.
19. Hakenbeck R, König A, Kern I, van der Linden M, Keck W, Billot-Klein D, Legrand R, Schoot B, Gutmann L. Acquisition of five high-Mr penicillin-binding protein variants during transfer of high-level beta-lactam resistance from *Streptococcus mitis* to *Streptococcus pneumoniae*. *J Bacteriol* 1998; 180: 1831–40.
20. Hanke MT. Studies on the local factors in dental caries. I. Destruction of plaques and retardation of bacterial growth in the oral cavity. *J Am Dent Assoc* 1940; 27: 1379–93.
21. Haukioja A, Loimaranta V, Tenovuo J. Probiotic bacteria affect the composition of salivary pellicle and streptococcal adhesion in vitro. *Oral Microbiol Immunol* 2008; 23: 336–43.
22. Horner C, Mawer D, Wilcox M. Reduced susceptibility to chlorhexidine in staphylococci: is it increasing and does it matter? *J Antimicrob Chemother* 2012; 67: 2547–59.
23. Hugo WB, Longworth AR. Some aspects of the mode of action of chlorhexidine. *J Pharm Pharmacol* 1964; 16: 655–62.
24. Katz S. The use of fluoride and chlorhexidine for the prevention of radiation caries. *J Am Dent Assoc* 1982; 104: 164–70.
25. Klock B, Krasse B. Effect of caries-preventive measures in children with high numbers of *S. mutans* and lactobacilli. *Scand J Dent Res* 1978; 86: 221–30.
26. Lindquist B, Edward S, Torell P, Krasse B. Effect of different caries preventive measures in children highly infected with mutans streptococci. *Scand J Dent Res* 1989; 97: 330–7.
27. Lingström P, Holm AK, Mejàre I, Twetman S, Söder B, Norlund A, Axelsson S, Lagerlöf F, Nordenram G, Petersson LG, Dahlgren H, Källestål C. Dietary factors in the prevention of dental caries: a systematic review. *Acta Odontol Scand* 2003; 61: 331–40.
28. Lumikari M, Soukka T, Nurmio S, Tenovuo J. Inhibition of the growth of *Streptococcus mutans*, *Streptococcus sobrinus* and *Lactobacillus casei* by oral peroxidase systems in human saliva. *Arch Oral Biol* 1991; 36: 155–60.
29. Machiulskiene V, Richards A, Nyvad B, Baelum V. Prospective study of the effect of post-brushing rinsing behaviour on dental caries. *Caries Res* 2002; 36: 301–7.
30. Marsh PD. Microbial ecology of dental plaque and its significance in health and disease. *Adv Dent Res* 1994; 8: 263–71.
31. Marsh PD, Keevil CW, McDermid AS, Williamson MI, Ellwood DC. Inhibition by the antimicrobial agent chlorhexidine of acid production and sugar transport in oral streptococcal bacteria. *Arch Oral Biol* 1983; 28: 233–40.
32. McMurry LM, Oethinger M, Levy SB. Triclosan targets lipid synthesis. *Nature* 1998; 394: 531–2.
33. Meurman JH. Probiotics: do they have a role in oral medicine and dentistry? *Eur J Oral Sci* 2005; 113: 188–96.
34. Miller W. *The micro-organisms of the human mouth. The local and general diseases which are caused by them*. Philadelphia: The S. S. White Dental Mfg. Co., 1890. Reprinted Basel: Karger 1973.
35. Näse L, Hatakka K, Savilahti E, Saxelin M, Pönkä A, Poussa T, Korpela R, Meurman JH. Effect of long-term consumption of a probiotic bacterium, *Lactobacillus rhamnosus* GG, in milk on dental caries and caries risk in children. *Caries Res* 2001; 35: 412–20.
36. Olsson J, Odham G. Effects of inorganic ions and surface-active organic compounds on the adherence of oral streptococci. *Scand J Dent Res* 1978; 86: 108–17.
37. Pader M. *Oral hygiene products and practice*. New York: Marcel Dekker, 1988.
38. Petersson LG, Birkhed D, Gleerup A, Johansson M, Jönsson G. Caries-preventive effect of dentifrices containing various types and concentrations of fluorides and sugar alcohols. *Caries Res* 1991; 25: 74–9.
39. Preus HR, Koldsland OC, Aass AM, Sandvik L, Hansen BF. The plaque- and gingivitis-inhibiting capacity of a commercially available essential oil product. A parallel, split-mouth, single blind, randomized, placebo-controlled clinical study. *Acta Odontol Scand* 2013; 71: 1613–19.
40. Saxer UP, Mühlemann HR. Synergistic antiplaque effects of a zinc fluoride/hexetidine containing mouthwash. A review. *SSO Schweiz Monatsschr Zahnheilkd* 1983; 93: 689–704.
41. Schaeken MJ, Keltjens HM, Van Der Hoeven JS. Effects of fluoride and chlorhexidine on the microflora of dental root surfaces and progression of root-surface caries. *J Dent Res* 1991; 70: 150–3.
42. Scheie AA, Eggen KH, Rølla G. Glucosyltransferase activity in human in vivo formed enamel pellicle and in whole saliva. *Scand J Dent Res* 1987; 95: 212–15.
43. Schiøtt CR. Effect of chlorhexidine on the microflora of the oral cavity. *J Periodontal Res* 1973; 8 (Suppl 12): 7–10.
44. Seppälä H, Haanperä M, Al-Juhaish M, Järvinen H, Jalava J, Huovinen P. Antimicrobial susceptibility patterns and macrolide resistance genes of viridans group streptococci from normal flora. *J Antimicrob Chemother* 2003; 52: 636–44.
45. Sintes JL, Escalante C, Stewart B, McCool JJ, Garcia L, Volpe AR, Triol C. Enhanced anticaries efficacy of a 0.243% sodium fluoride/10% xylitol/silica dentifrice: 3-year clinical results. *Am J Dent* 1995; 8: 231–5.
46. Söderling EM, Marttinen AM, Haukioja AL. Probiotic lactobacilli interfere with *Streptococcus mutans* biofilm formation in vitro. *Curr Microbiol* 2011; 62: 618–22.

47. Stoeken JE, Paraskevas S, van der Weijden GA. The long-term effect of a mouthrinse containing essential oils on dental plaque and gingivitis: a systematic review. *J Periodontol* 2007; **78**: 1218–28.
48. Trahan L, Bourgeau G, Breton R. Emergence of multiple xylitol-resistant (fructose PTS-) mutants from human isolates of mutans streptococci during growth on dietary sugars in the presence of xylitol. *J Dent Res* 1996; **75**: 1892–900.
49. Twetman S. Antimicrobials in future caries control? A review with special reference to chlorhexidine treatment. *Caries Res* 2004; **38**: 223–9.
50. Van der Ouderaa F, Cummins D. Delivery systems for agents in supra- and sub-gingival plaque control. *J Dent Res* 1989; **68**: 1617–24.
51. Walker C, Borden L, Zambon J, Bonta C, DeVizio W, Volpe A. The effects of a 0.3% triclosan-containing dentifrice on the microbial composition of supragingival plaque. *J Clin Periodontol* 1994; **21**: 334–41.
52. Wara-aswapati N, Krongtawakul D, Jiraviboon D, Adulyanon S, Karimbux N, Pitiphat W. The effect of a new toothpaste containing potassium nitrate and triclosan on gingival health, plaque formation and dentine hypersensitivity. *J Clin Periodontol* 2005; **32**: 53–8.
53. Welin J, Wilkins JC, Beighton D, Svensater G. Protein expression by *Streptococcus mutans* during initial stage of biofilm formation. *Appl Environ Microbiol* 2004; **70**: 3736–41.
54. Yazdankhah SP, Scheie AA, Høiby EA, Lunestad BT, Heir E, Fotland TØ, Naterstad K, Kruse H. Triclosan and antimicrobial resistance in bacteria: an overview. *Microb Drug Resist* 2006; **12**: 83–90.
55. Zhang Q, van't Hof MA, Truin GJ, Bronkhorst EM, van Palenstein Helderman WH. Caries-inhibiting effect of chlorhexidine varnish in pits and fissures. *J Dent Res* 2006; **85**: 469–72.
56. Zickert I, Emilson CG, Krasse B. Effect of caries preventive measures in children highly infected with the bacterium *Streptococcus mutans*. *Arch Oral Biol* 1982; **27**: 861–8.

17

The principles of caries control for the individual patient

B. Nyvad and E.A.M. Kidd

Introduction

Dental care neither begins nor ends with a single course of treatment, but it is ongoing. When a series of dental treatments is complete, dentist and patient must decide when it would be wise to follow up on the effect of both the nonoperative and operative treatments provided. Health authorities in some countries (e.g., UK and Denmark) recommended clinical guidelines for monitoring disease progression in patients, but none of these guidelines is based on firm scientific evidence because many of the diagnostic procedures and treatments that are used in daily practice today have not been evaluated in clinical trials. This also applies to programs aimed at controlling dental caries. Therefore, practitioners are sometimes inclined to adopt a treatment philosophy that 'what works in my hands is probably good for the patient.' In other cases the evidence exists but is not being implemented by the practitioner. Potential barriers could be that the knowledge and attitude of the practitioner, patient demands, the practice environment, and the health-care system, including funding, block the implementation of new treatment routines.

As with other dental treatment, (nonoperative) caries control procedures must be cost-effective; that is, the treatments should be given to those individuals who need them

Dental Caries: The Disease and its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

the most and who can benefit from them. This puts a firm demand on the dentist, who must have the skills to single out patients with the highest needs.

The aim of this chapter is to gather the evidence presented in many of the previous chapters to give some practical guidelines for caries control for individual patients of all ages – from cradle to grave.

How are current caries activity and risk of future caries progression assessed?

Effective management of caries requires information from two sources:

1. A visual–tactile caries examination using lesion activity assessment to give information about the current caries activity status and prognosis of existing lesions.
2. A medical and dental history highlighting potential risk factors for future caries development in an individual.

Patients should be made aware of their relative risk for developing new lesions and for progression of existing lesions. This knowledge may encourage them to become involved in their own care, to keep appropriate recall appointments, and, if they pay for their own care, help them to budget for dental bills.

How should the visual–tactile activity assessments be made?

The strongest evidence of caries activity is the presence of active carious lesions (cavitated and/or noncavitated) at the time of examination (see Chapter 11). This is because it has been shown that, where there has been no intervention, active noncavitated lesions run a higher risk of developing into a cavity than inactive lesions and sound surfaces [43]. It should be noted how many active lesions are present and where the lesions are located. Furthermore, it may be informative to consider the recent caries activity of the patient; that is, the number of new, progressing, or filled lesions observed over the past 2–3 years.

There is no consensus as to how to define a high caries activity because this is a relative judgment depending on the caries prevalence of the population. However, as a rule of thumb, in most populations a yearly increment of two or more active lesions, detected clinically and/or new lesions detected radiographically, would indicate a high rate of lesion progression. Multiple active lesions in regions of the mouth with a high salivary flow (e.g., lower incisors) always suggest a high activity status.

When estimating the activity status, due consideration should be given to the stage of development of the dentition. In children, occlusal surfaces of erupting permanent molars constitute a particular risk site. Adolescents may be more prone to caries development in approximal surfaces, especially the distal surface of second premolars and the mesial surface of second molars (see Chapter 12). In adults and the elderly, difficult-to-reach root surfaces may be the predominant risk sites, although coronal caries is also very important in this age group [15, 63].

Identifying caries risk factors

Although it may only take a short time to obtain a subjective estimate of a patient's caries activity status, identifying the relevant risk factors may take a little longer. This is time well spent, however, because the patient may be able to modify some risk factors and thus slow down disease progression.

According to Beck [3], a risk factor is defined as 'an environmental, behavioural, or biologic factor confirmed by temporal sequence, usually in longitudinal studies, which if present, directly increases the probability of a disease occurring, and if absent or removed, reduces the probability'. Important biological and environmental risk factors include salivary flow, quality of oral hygiene, some dietary aspects, and fluoride exposure, all of which are the determinants of the disease (see Chapter 5).

It is important to understand that different patients have different risk factors. Dentists must identify which of the potential risk factors play a particular role for the individual patient. A well-adjusted risk factor profile implies that the de- and remineralization processes in the dental biofilm are balanced. However, if one or more risk factors are changed in a negative direction the physiological balance in the biofilm breaks down and caries development is likely to happen [59]. Dentists, as well as patients, should be alert to possible changes in risk status because, if such disturbances are not corrected, caries control is elusive.

When identifying the risk factors it is important to use a systematic approach, much like a detective; detectives look, listen, ask questions, listen again, and collate the evidence. It is good practice to list and rank the factors thought to be responsible for the individual's caries risk status (Table 17.1). This defines what should be modified for that particular individual. It may also define factors that cannot be modified, for example, a dry mouth consequent to demolition of the salivary glands. Such a patient will always be a high caries risk.

Table 17.1 Checklist of biological and environmental caries risk factors

- Medical history
  - Current and past diseases
  - Current medications
- Dental history
  - Current activity state of caries lesions
  - Past history of caries
- Current oral hygiene practices and proficiency
- Current exposure to topical fluorides from toothpastes, rinses, or tablets
- Current dietary pattern

Medical history

A proper way to start the detective work is to take a medical history. The importance of this cannot be overemphasized.

Complaints of a dry mouth (xerostomia) and reduced salivary output (salivary hypofunction) are common conditions, particularly in older populations. Persistent salivary hypofunction is likely to result in new and recurrent dental caries (see Chapter 6), and it can be really difficult to prevent this. Table 17.2 lists causes of dry mouth (see [53] for a review).

Over 400 medications have a side effect of salivary gland hypofunction, and 80% of the most commonly prescribed medications have been reported to cause dry mouth [56]. The number of prescriptions increases as patients age, and with increased numbers of medications comes an increase in xerostomia and hyposalivation.

In addition, the systematic diseases for which these medications are taken may themselves contribute to the problem. These diseases tend to be more prevalent in older persons, whose glands are more vulnerable to the deleterious effects of the medications compared with those of younger people [18]. The problems are thus compounded in the elderly, with estimates of the prevalence of xerostomia in adult free-living and nursing-home populations ranging from 16 to 72% [64].

Sjögren's syndrome presents mainly in women during the fourth and fifth decades. It manifests in either primary or secondary forms. Primary Sjögren's syndrome is characterized by dry mouth and eyes, resulting from progressive loss of salivary and lacrimal function. Secondary Sjögren's syndrome involves one or both of these sites in the presence of another connective tissue disease, such as rheumatoid arthritis or lupus erythematosus.

Patients with HIV/AIDS frequently experience salivary hypofunction from a lymphocytic destruction of the glands that results from medications.

Diabetes can also cause changes in salivary secretions, particularly where diabetes is poorly controlled. Salivary secretion will also be inhibited in Alzheimer's disease, Parkinson's disease, strokes, cystic fibrosis, and dehydration.

All opiates reduce salivary secretion, and their misuse is associated with high levels of caries [49]. The management of opiate addiction can give rise to further oral health problems when methadone is used. Methadone itself causes a dry mouth and it can be prescribed in a sugary linctus form, although sugar-free versions are available, which are certainly preferable from a dental perspective. In addition, drug users may have a high level of sugar consumption [40] and a chaotic lifestyle that is hardly conducive to good oral hygiene or regular dental care. Alcoholics also fall into this group.

Radiation therapy, used in the treatment of head and neck cancers, causes permanent salivary gland hypofunction as a result of damage to, or loss of, salivary acinar cells and a persistent complaint of dry mouth. It is claimed there is only later recovery if the total dose to the salivary tissues is less than 25 Gy [22].

Chemotherapy sometimes causes disturbances in salivary gland function, but the long-term impact on oral health is not clear. In the short term there may be decreased flow rate and increased numbers of aciduric bacteria in saliva. In addition, there is an increased risk of oral candidiasis. Oral mucositis is a frequent, severe, and sometimes a dose-limiting complication of cancer chemotherapy and radiotherapy [24].

In some of the cases of dry mouth described above, the patient will be very aware of this unpleasant symptom. Other patients may not complain, but dentists can often detect a dry mouth during the course of a clinical examination because the mouth mirror tends to stick to the mucosal surfaces or the saliva appears frothy. If a dry mouth is suspected, the diagnosis should be verified by measuring the resting and stimulated salivary flow rates (see Chapter 6).

An emerging problem in many populations is the increasing demand for medication for attention deficit hyperactivity disorder (ADHD), in children as well as in adults. Common side effects of medication against ADHD are a dry mouth (1–10%), a phenomenon that may not be known to many dentists.

Sometimes the medical history reveals a 'hidden' sugar exposure. Many medicines are produced in a sugar syrup form and some medicated pastilles are sugar based. Asthmatics often use inhalers and many of these contain lactose in the propellant, and asthma may itself result in a dry mouth.

Table 17.2 Causes of dry mouth.

Medications	Antidepressants Antipsychotic drugs Tranquillizers Hypnotics Antihistamines Anticholinergics Antihypertensives	Diuretics Anti-Parkinsonian drugs Appetite suppressants Antinauseants Antiemetics Muscle relaxants Expectorants
Systematic diseases or conditions	Sjögren's syndrome Rheumatoid arthritis Diabetes HIV/AIDS Scleroderma Sarcoidosis Lupus Parkinson's disease Alzheimer's disease Cystic fibrosis Asthma	Strokes Dehydration Hormonal changes Pregnancy Post-menopause Neurological disease Pancreatic disturbances Liver disturbances Nutritional deficiencies Anorexia nervosa Malnutrition Drug abuse Smoking
Head and neck radiotherapy		
Chemotherapy		

The dentist should always check the constituents of a drug to identify potential side effects associated with caries.

Dental history

The patient's dental history will reveal additional important information. A history of multiple restorations that have to be frequently replaced may be an important indication of a high caries risk. There is also a well-documented association between a high past caries experience and the risk of developing root caries [15, 65]. Sometimes the dental history will reveal changes in oral health, such as no dental problems for years and then a sudden deterioration leading to multiple restorations. In a case like this it will be important to identify the relevant change. The onset of a dry mouth is a good example of a change that increases the risk of dental caries [2] (see Chapter 6).

Much of the information about caries risk emerges from asking the patient questions pertaining to the biological risk factors and listening carefully to their answers. For instance, it is always sensible to ask how often teeth are cleaned, what brushes and interdental cleaning aids are used, which toothpaste is chosen. The dentist should check that the paste contains fluoride by examining the contents listed on the tube. In some countries (e.g., Denmark) almost all toothpastes contain fluoride, while in others very little of the toothpaste is fluoridated. In other countries (e.g., UK) most toothpastes are fluoridated but some products are fluoride free. The patient may also be asked whether they use any mouthrinses and it may be illuminating to ask why these mouthrinses are used. Sometimes it is because the patient perceives that they 'freshen' the breath. Since inadequate plaque control is a major cause of halitosis, this perception may subsequently be turned to advantage.

Questions about diet are obligatory when the patient presents with active carious lesions or a history of multiple restorations that are frequently replaced. Often a few simple questions will reveal an inappropriate dietary habit, such as frequent sipping of sugared coffee or tea, sugary soft drinks, pastilles, and snacks (Fig. 17.1). In other cases it may be quite difficult to identify the nature of a caries-promoting diet, and only when using the imagination to conceive the patient's lifestyle is it possible to ask the right questions. In such cases, the simple question 'Do you have a sweet tooth?' may serve to unlock the conversation. In rare cases a verbal enquiry does not suffice to reveal a suspected misuse of sugary foods and it may be necessary to ask the patient to fill in a diet sheet for further clarification.

Caries risk assessment systems

In some countries microbiological or salivary chair-side tests are recommended as an aid to predict the risk of caries. However, dental caries cannot be predicted with certainty (Chapter 23). Neither microbiological nor salivary or dietary tests have been shown alone, or in combination with clinical parameters, to be sufficiently accurate for the assessment of future caries risk at the individual level. More recently, computer programs (e.g., Cariogram [4]) and caries risk assessment systems (e.g., CAMBRA [14]) have been developed to assist the dental practitioner in selecting individuals with a high caries risk and designing appropriate preventive protocols. It is tempting to feed relevant patient data into a computer and ask it to produce a preventive strategy. However, this may create a false impression of objectivity when in fact the program can be no better than the data that were used to produce it. Indeed, such systems have shown to have limited ability to predict [61]. The current best strategy for identifying high-risk patients, therefore, is to select individuals with active noncavitated active lesions that can be prevented from becoming cavitated by nonoperative interventions (see Chapters 11 and 13). Such targeted approaches have shown a remarkable effect by reducing the caries incidence over 4 years by 44% in a low-caries population [19].

Figure 17.1 Rapidly progressing caries in 28-year-old male who had ignored oral hygiene and who had been sipping sugared coffee regularly during the day for 5 years. The patient visited the dentist because it was difficult for him to get a new job! This is a "yellow" patient in whom all risk factors can be modified in conjunction with the operative treatment.

Identifying social and demographic risk factors

Although not directly involved in the caries process, social factors can have an overriding influence on health and disease and on what lifestyle changes patients can make. How do dentists assess these important but sensitive issues? When dentist and patient first meet they know very little about each other, but a mutual summing up will begin.

The dental professional will notice such things as age, cleanliness, demeanor, disability, nationality, speech, dress, religion, educational status, employment status, and whether the patient is alone or accompanied. Some of these assessments are fraught with difficulty, and jumping to conclusions can be very unwise. Poverty and educational status can have enormous implications, and perhaps it is a pity that patients are seen in the surgery rather than in their homes.

How is the information used to categorize patients into risk groups?

What can and what cannot be modified by the patient?

For some patients the frequency of intake of a particular drink or food may be of overriding importance to their caries risk, and modification of this factor may be essential to changing this risk. The role of the sweetened nursing bottle or dummy in early childhood caries (ECC) [51] or sipping sugared soft drinks/coffee are classical examples. In other patients the quality of the oral hygiene may need to be improved to change the risk status.

However, some factors that are highly relevant to a high caries activity cannot be modified. Some medications are only available in a sugar syrup base, although the dentist should always investigate whether there is an alternative formulation sweetened with an artificial sweetener. If an alternative seems possible, the patient's general medical practitioner should be contacted. Other medications result in hyposalivation but may be essential for the patient's well-being. Again, reference to a formulary will show whether a particular medication has an inhibitory effect on salivary secretion.

A low salivary flow from glands damaged by radiotherapy for a head and neck malignancy is another example of a caries risk factor that cannot be modified. Hyposalivation as a result of Sjögren's syndrome or other diseases is also permanent. Acknowledgment by both patient and dentist of factors that cannot be modified will be important so that other risk factors, such as plaque level and diet, can be controlled as far as possible.

Social and behavioral factors may be of overriding importance and dictate what dentist and patient can achieve. For instance, is the patient prepared to 'own the problem' and recognize his or her essential role in its solution? The answer to this question may lie in a patient's beliefs and educational background.

Sometimes the patient needs a carer to assist. Young children are incapable of removing plaque and are not in control of their own diet. Similarly, a physically and/or mentally debilitated person is dependent on a carer for both plaque control and provision of food and drink. Old age may be relevant. While some old people are free living and independent, others are living in residential care because they cannot look after themselves. These residents may be physically and/or mentally impaired and many have a major caries problem [54].

Money, or lack of it, can indirectly affect dental caries. Will the budget run to brushes, floss, artificial sweeteners, mouthwashes, or even toothpaste? Can the patient spare the time to attend the surgery? For some patients even treatment that is free at the point of delivery is expensive if they lose earnings to keep an appointment.

Categorizing caries-activity status and caries-risk status

On the basis of the clinical caries examination and the medical and dental history the patient may be allocated to one of the following caries activity and caries risk categories (Fig. 17.2).

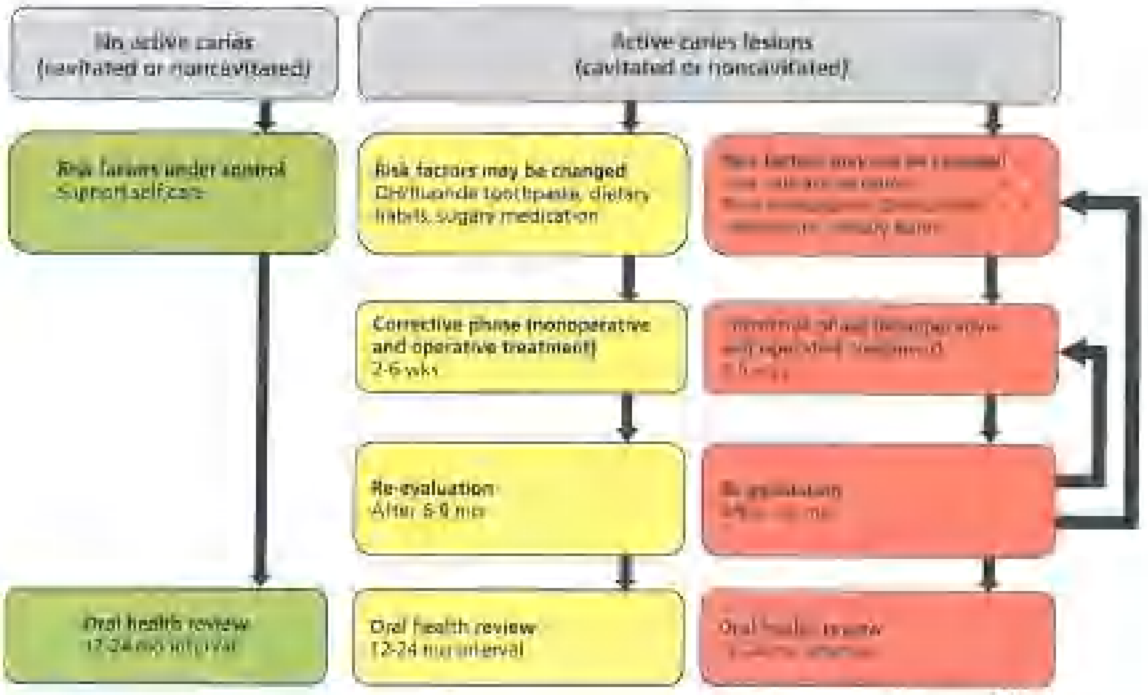


Figure 17.2 Guideline for categorizing patients into caries-activity/caries-risk status and for setting the recall interval for caries control. OH = oral hygiene.

The first step is always to decide whether the patient has active caries lesions. If the answer is yes, the next step is to decide whether risk factors can be changed.

- 🟩 *Caries inactive/caries controlled* (green). No active caries lesions and no history of recent restorations. Risk factors controlled.
- 🟨 *Caries active but all relevant risk factors can potentially be changed* (yellow). Presence of active caries lesions. Caries control may be achieved by modification of risk factors such as plaque, diet and/or use of fluoride.
- 🟥 *Caries active but some risk factors cannot be changed* (e.g., some dry mouths, some medications) *or risk factors cannot be identified* (red). Presence of active caries lesions. This patient category will always be at high risk of caries, but it may be possible to control caries by professional intervention with some risk factors.

The dentist may wish to color code this concept of activity and risk status with green, yellow, and red stickers inserted in the notes. This visual representation is potentially helpful for all concerned. The aim is to help the patient to change the risk factors, that is, to convert yellow or red to green. However, some risk factors cannot easily be changed. To give an example, a patient with a dry mouth is always a caries risk (red). Nevertheless, caries activity can still be controlled with strenuous nonoperative treatments.

It should be appreciated that balancing the risk factors is a universal goal for everyone. All too often the symptoms of caries are quickly eradicated by insertion of fillings without correcting the risk factors. While this approach might well eliminate the symptoms, it does not cure the disease!

However, patients cannot perform a proper caries control in a mouth with multiple open cavities. Therefore, uncleansable cavities should be temporarily restored to arrest caries progression (see Chapter 20) and to facilitate plaque control prior to implementing nonoperative treatments.

What nonoperative treatments are available?

This section will now describe the various nonoperative treatments relevant to caries control. Initially, a general approach to all age groups will be given. Subsequently, problems specific to children and patients with dry mouths will be covered. In many of these patients the role of the dental team is to advise, educate, and encourage behavioral change in the individual. Not too many changes should be attempted at one time. It is salutary to note here that the evidence that it is indeed possible to change behavior is lacking [26]. This, however, in no way absolves the dental professional from trying to help a patient to prevent the progression of carious lesions. We, as individual dentists, do not expect carious lesions to form and progress in our own mouths. This would pertain even if we had a dry mouth and were therefore at high risk. It is only ethical to give patients the information we have and try to 'infect' them with some of our own enthusiasm for dental care.

The arrows in the nonoperative quiver are:

- plaque control;
- use of fluoride;
- dietary modification.

The way in which each of these modalities is used will depend on the circumstances of the individual patient. Treatments with proven efficacy are highlighted here, but it is important to understand that there is no single protocol into which all patients can be fitted. In some patients, oral hygiene improvement and use of fluoride toothpaste may be the main target, while in others dietary changes and/or professional fluoride treatments are in focus. The art of caries control is exactly to deliver the nonoperative modalities in the right balance. This may not always come forward at the first appointment, but subsequent recall visits allow for finer adjustments in accord with the patient's ability and wish for change.

Plaque control

Since carious lesions form as a result of the metabolic events in the dental plaque (see Chapter 2), good plaque control must be the cornerstone of preventive and nonoperative treatment in all patients. Teeth should be brushed regularly, at least once every day [66], with a fluoride-containing toothpaste [36]. The brushing interferes with the growth and ecology of the biofilm (see Chapter 7) and the fluoride application retards lesion progression (see Chapter 14). The time of day is not crucial, but it is advisable to establish a routine for toothbrushing at specified times of the day. If time is scarce, it is better to clean the teeth carefully once a day than to perform a careless job several times a day. The quality of cleaning, rather than the frequency, seems to be of prime importance (see Chapter 15). In any case, the patient's involvement and cooperation are essential. The patient should be shown the carious lesions, both clinically and on the radiograph. The patient may need a small mirror to see the diseased sites in the mouth. Disclosing solutions will demonstrate to the patient the direct relationship of the biofilm to the specific lesion.

Toothbrushing

Oral hygiene instruction should be both general to the whole mouth and site specific for a particular lesion. The patient should be advised to clean the diseased site(s) before cleaning the whole mouth, to ensure cleaning where it is most needed. A chart of plaque deposits and active lesions can be useful. The patient now has a picture of problem areas.

Having used a disclosing solution, the patient (or, in the case of a small child, the parent) should be asked to brush. The following are worth noting.

- Can the patient remove the plaque? Is the brush reaching the salient area? Should it be angled differently? To give an example, perhaps half closing the mouth will allow access of the brush to the buccal surfaces of upper molar teeth.
- Would a different design of brush help? Perhaps the patient's brush is too big. Would an electric toothbrush help? Most modern powered toothbrushes have a small, circular head that performs oscillating, rotating, or counter-rotational movements. Some models have timers that give useful feedback to the user on the time they have spent brushing. A review of evidence [21] concluded that powered toothbrushes with an oscillating/rotating movement were more effective in removing plaque and reducing gingivitis than manual brushes. It has also been reported that powered toothbrushes may improve compliance.
- Is thorough brushing in the surgery causing gingival bleeding? How does the patient react to this? Do they think they have been rough or can they appreciate that the gums are bleeding because they are inflamed? Can the patient distinguish healthy from bleeding gums? Do they appreciate that inflammation will resolve with good plaque control?
- Encourage the patient to feel the teeth with their tongue. Plaque-free teeth have a shiny feel, whereas plaque deposits feel furry to the tongue. Does the patient like the shiny feel of clean teeth? If they do, this may be a motivating factor to brush, but if they do not, motivating the patient to clean may be difficult.

It is surprising how difficult it is for most patients to comply with recommendations. Therefore, *do not try to cover too much at one visit*. Where a recall visit shows that brushing has not improved, the operator must try to decide where the problem lies. If the patient can remove plaque but does not, the problem is motivation, not manual dexterity. Most people can remove plaque, but many do not!

Children need help with toothbrushing, and this is of particular importance as teeth erupt. Eruption of permanent teeth can take 6–30 months (longer time for second molars than for first molars), and during this time the occlusal surface will be difficult to clean because it is below the occlusal plane [13]. These erupting teeth should be brushed individually by the parent, who should stand behind the child bringing the brush in at right angles to the arch.

Elderly people who are physically and/or mentally disabled may need a carer's help to clean their mouths. This matter must be handled with tact, as the person may not wish to admit they need help and the carer may find the task physically revolting. Mechanical toothbrushes may be easier for carers to handle than conventional brushes.

Interdental cleaning

Where active approximal lesions are present, either in enamel or on the root surface, an interdental cleaning aid will be needed. In young patients, enamel lesions are best cleaned with dental floss or tape, whereas interdental brushes are preferred for cleaning larger interdental spaces and root surfaces. The operator will need to spend time showing a patient how to use these devices correctly. Many patients find this difficult, time consuming, and tedious, and they cannot easily see the results of their efforts. Dentists can help in the following ways.

- They should give site-specific advice, by showing the patient the lesion(s) on the radiograph and teaching them where these sites are in the mouth. Ideally, every interdental space should be cleaned, but if this is not practical it may be more realistic to suggest cleaning the specific interdental spaces where the lesions are.
- Careful examination of the dental floss or interdental brush after use can show the patient that they have removed plaque. This is a potential motivating factor. The patient can see and smell that they have done something useful.
- Some patients may find it easier to use a special holder for the dental floss, particularly if their manual dexterity is poor. Alternatively, interdental brushes with a small diameter may be helpful.
- Patients should be taught the relevance of any bleeding during interdental cleaning. If this persists, either cleaning is inadequate and gingival inflammation has not resolved, or a cavity is present that the floss cannot reach.

Professional tooth cleaning

In caries-active patients who for some reason do not master plaque control themselves, and/or in patients with severely decreased salivary secretion (Table 17.2; see also Chapter 6), it may be necessary to support the patient for a time with additional plaque control in the form of professional tooth cleaning. As described in Chapter 15, regular professional tooth cleaning has been shown to reduce dental caries by almost 100%. Dentists seem to forget that professional tooth cleaning is a powerful means of caries control because this treatment modality was originally developed for management of periodontal diseases. The clinical procedure is detailed in Table 17.3.

Use of fluoride

All patients should use fluoride toothpaste containing between 1000 and 1500 ppm fluoride as a basic caries-control method. For practical purposes, all individuals in the family may share the same brand of paste. However, children below the age of 7–8 years are recommended to use a smaller amount (pea size) (see also Chapter 14). Adult patients with risk factors that cannot be changed may

Table 17.3 Clinical procedure of professional tooth cleaning.

1. Disclose plaque.
2. Remove plaque with low-abrasive, fluoride-containing polishing paste (e.g. 0.1% NaF in silicon dioxide). A handpiece (rotating up to 5000 rpm) is used, with pointed brushes for fissures and a soft rubber cup for free smooth surfaces. For proximal surfaces the paste is applied with a toothpick or an interdental brush, depending on the local anatomical conditions.
3. Disclose again and check that all plaque has been removed.
4. Apply topical fluoride (2% NaF) or fluoride varnish. Make sure that the fluoride application reaches the site(s) with active caries.
5. Control visits. The interval between appointments should be short at the beginning of the program (every 2–3 weeks) but may be extended when cooperation is improved and the patient has reached a satisfactory level of plaque control.

benefit from a high-fluoride toothpaste: for example, 5000 ppm fluoride.

In caries-active patients it is essential to intensify the fluoride therapy until the situation is under control. This could be achieved through intensive self-performed use of fluoride toothpaste, fluoride-containing mouthwashes for home use, professional (operator applied) topical applications, or combinations of these methods (see Chapter 14). The choice of fluoride vehicle is not crucial as long as it is combined with improvement of the oral hygiene status (Chapters 16 and 15). The important thing is that the patient accepts the mode of treatment and complies with the advice given.

Fluoride toothpaste has much to recommend it. It is cheap and requires minimal patient cooperation and enhances patients' appreciation of their own role in maintaining oral health. A systematic review [36] concluded its use to be associated with a 24% reduction of caries in the permanent dentition of children and adolescents. Most of the evidence has been gathered in clinical trials lasting 2–3 years. Thus, the benefits accrued through a lifetime experience may be substantially greater. Elevated intraoral concentrations of fluoride may be achieved by asking the patient to refrain from rinsing the mouth vigorously with water after brushing; however, the additional effect on caries control by abstaining from rinsing after toothbrushing is dubious (see Chapter 14). Therefore, the emphasis should be on the extreme importance of dental cleanliness rather than the mechanism of clearing excess paste from the mouth. Fluoridated toothpastes may also be used therapeutically by asking the patient to apply the paste directly onto the clean active carious lesions with a finger or a brush, preferably immediately before going to bed, where decreased salivary secretion at night is an issue. This mode of application may ensure increased concentrations of fluoride for extended periods in the vicinity of the lesion.

In many countries there is a vigorous debate about the 'optimal' fluoride concentration of toothpastes to be used for caries control, and it is often argued that higher concentrations are better. It is true that there is a dose–response effect of fluoride toothpaste, hence, for every increase of 500 ppm fluoride in the toothpaste concentration above 1000 ppm (1500 ppm being the maximum concentration of fluoride allowed in over the counter toothpastes in the EEC), there will be a reduction in caries of about 6–8% [36]. However, an increase in the frequency of brushing from once to twice a day reduces caries by 14%, and supervised brushing may reduce caries by 11% compared with unsupervised brushing [34, 46]. Therefore, the best advice for the caries-active patient is not only to focus on the fluoride concentration of the paste, but rather more on the frequency of brushing and diligence of use of the paste and brush!

Fluoride mouthwashes may benefit adults with active caries who are not able to clean their teeth adequately with a fluoride toothpaste, for example, because of sensitive oral mucosa. The mouthwash (0.05 or 0.1% NaF) should be used for a full minute once or twice every day. Alternately, a 0.2% NaF solution may be used weekly. Fluoride mouthwashes are available over the counter in some countries, whereas in others they would have to be prescribed individually. It should be appreciated that the caries inhibition of fluoride mouthwashes can be as high (26%) as the daily use of fluoride toothpastes [34].

Professional applications of high concentrations of fluoride, in the form of a 2% aqueous NaF or fluoride varnish (Duraphat/Fluor Protector) should follow professional plaque removal. These products should be applied on slightly dried teeth for 2–3 min. Their principal mode of action is to deposit calcium fluoride in active carious lesions, and this is a source of fluoride that is slowly released during subsequent pH drops in the biofilm (see Chapter 14). The applications may be repeated every 1–3 months until caries activity is controlled. A systematic review [37] concluded that fluoride varnish reduced caries in the deciduous dentition by 33% and in the permanent dentition by 46% when compared with a placebo. The caries-inhibiting effect of professionally applied fluoride gel is likely to be lower (28%) [35]. Professional fluoride application is time consuming, therefore, these methods may not be cost-effective unless used in individuals with a high caries activity.

In recent years a number of alternative *fluoride-containing products* have been launched as an aid in caries prevention, such as fluoride-containing chewing gum, fluoride-containing dental materials, and fluoridated toothpicks and dental floss. However, to the best of the authors' knowledge, none of these products has been tested in well-designed,

	THURSDAY		FRIDAY		SATURDAY		SUNDAY	
	Time	*Item*	*Time*	*Item*	*Time*	*Item*	*Time*	*Item*
BEFORE BREAKFAST								
Breakfast								
MORNING								
Midday meal								
AFTERNOON								
Evening meal								
EVENING and NIGHT								

Figure 17.3 Diet analysis form.

large-scale clinical trials. Until proper documentation has been presented, therefore, it would be unwise to resort to these methods as the primary preventive strategy.

Dietary modification

No change in diet should be suggested for a caries-inactive patient, but the dentist should still make the patient aware of how a change in diet (e.g., frequent sugar attacks) may pose a problem if the oral hygiene is poor (see Chapters 8 and 15). Likewise, parents should be informed that nursing bottles and dummies may cause rampant caries (ECC) if plaque control is inadequate [51]. 'Sugar to mealtimes' or 'Saturday snacks' may be reasonable ways to proceed.

Changes in life may sometimes be accompanied by changes in diet, and where these changes are extreme they may have dental consequences. Thus, moving from home, having a baby, unemployment, divorce, retirement, and bereavement are times when a little advice on diet and caries may not be amiss.

Dietary analysis should always be carried out on patients with multiple active lesions. Sometimes a simple verbal analysis will suffice to identify a problem, while in other cases more elaborate analyses need to be performed.

There are two principal techniques for determining food intake. One, the 24 h recall system, records the dietary intake during the preceding 24 h. The other method is to obtain a 3–4-day written record, asking the patient to record food and liquid intake as it is consumed. Both methods rely on the patient's full cooperation and honesty. Furthermore, both forms of diet recording suffer from the disadvantage that the record may not be representative of the diet consumed over a much longer period, although it is this that is likely to have been responsible for the current caries and restoration status. Thus, a diet history is an unscientific tool that must be interpreted with caution.

Recording the diet

Figure 17.3 shows a suitable form for diet analysis. When this is given to the patient it should be explained that their help is needed to find the cause of their dental decay. Since this may be related to what they eat and drink, a record of this is needed, together with the time of eating. The patient should also be asked to include any medicine taken by mouth. This would allow the dentist to check whether it is sugar-syrup based or has a xerostomic effect. The patient should keep the diet sheet with them and fill it in at the time to avoid missing anything. Quantities of food consumed are not specifically requested, but it is important not to change anything just because a record is being kept.

Analysis of the dietary record

Once the patient returns the completed sheet, dentist and patient can begin to look at it together. The dentist should encourage the patient to identify the items that contain sugar; this will show whether the patient appreciates which items are potentially harmful. The effect of sugars on acid production in the biofilm should be explained in simple terms (see Chapters 7 and 8).

Then, the number of sugar attacks should be counted and this number recorded at the top of each day. Now the dentist can explain the relevance of frequency in a simple way. It would not be unreasonable to suggest that after a sugar attack the plaque may remain acidic for about 1 h; thus, nine attacks would equal 9 h of acid plaque. This is a simple explanation for someone with no knowledge of chemistry. With some patients it may be appropriate to draw and explain a Stephan curve (Chapter 8). The method of delivering the message should be tailored to the educational level and understanding of the patient. Imagine explaining the problem to a biochemist or someone with no knowledge of chemistry.

Dietary advice

On the basis of the diet sheet, dentist and patient may be able to work out some realistic strategies for reducing the frequency of intake of sugar-containing foods and drinks. It is neither necessary nor possible to cut sugar completely out of the diet, but to restrict intake mainly to mealtimes may be a realistic and attainable goal.

The following suggestions may be useful:

- Try to confine sugar to main meals; eat and enjoy it.
- Substitute a savory snack for a sweet one. A list of sugar-free drinks, snacks, and chewing gum is useful when discussing this with the patient.
- Substitute an artificial sweetener for sugar in tea and coffee.
- Water and milk are safe drinks between meals.

Age and diet

The attitude of the parents or carer is of great importance in achieving dietary change in children. The professional must be sensitive to possible feelings of guilt, anger, and even denial when dietary problems that may be responsible for caries are discussed. In addition, the influence of social and cultural pressures may be considerable. In some cultures it is not the mother who determines what the family eats and drinks, although this may be the person the professional meets.

Dietary preferences are likely to change with age. The teenage years can be a time of rebellion, and hygiene and dietary practices may change to the detriment of the dentition.

The dentist can only work with the young person, who may be fiercely resentful if a parent is involved. One of the useful things about caries is that the white spot lesion is visible. Physicians trying to persuade young people to give up smoking may envy us this tangible sign of an ecological catastrophe!

Elderly and old people often revert to a soft diet because of a dry mouth or poor dental conditions. Studies have shown that the elderly occupants of residential homes may have multiple sugar attacks [37] and it is very difficult to change this. Care staff are busy and often not dentally aware. Visitors often bring sweets as presents, and eating these may be one of the few pleasures left in life to care home residents. In addition, poor nutrition and weight loss may be a consequence of illness and require frequent snacks, food enrichment, and food supplements. These supplements are often high in sugar.

How is the individual helped to control disease progression?

The categories of caries risk that were defined in the 'Categorizing caries-activity status and caries risk status' section will now be considered individually (see Fig. 17.2). Each group will comprise a wide variety of individuals with different social backgrounds; thus, broad statements about management must still be tailored to the individual.

- 🟩 *Caries inactive/caries controlled* (green): these patients only need encouragement to sustain careful oral hygiene with the use of fluoride toothpaste.
- 🟨 *Caries active but all relevant risk factors can potentially be changed* (yellow): mechanical plaque control should be improved, and consideration given to supplementing fluoride toothpaste with chair-side fluoride applications and/or mouthwashes. Where there are multiple active lesions, the diet should also be investigated and advice given as to how it may be improved.
- 🟥 *Caries active but some risk factors cannot be changed* (red): these cases are the most challenging. There is no standard preventive treatment that will meet the needs of all patients. In each particular case the caries-controlling treatment must be designed individually, with due regard to the risk factors. All the caries control treatments – plaque control, including professional tooth cleaning, use of fluoride, dietary modification, and stimulation of salivary flow – may have a role to play. Patients with a dry mouth fall into this group and are discussed specifically on the following pages.

Caries-active patients for whom the risk factors have not or cannot be identified are frustrating because the dentist feels that he/she has missed something. The detective work should continue and the case be managed as in the red group.

When should the patient be recalled?

Setting the recall interval

Recalls should be scheduled according to individual needs and be based on assessment of the current caries activity and caries risk. Therefore, the recall interval may vary widely between patients and during the course of a treatment. Frequent automatic recalls (e.g., every 6 months) do not necessarily lead to better outcomes. Ironically enough, it has been shown that the more frequently the patient visits the dentist the more fillings they accumulate [62]. These findings have been interpreted to indicate that while frequent dental visits may help to postpone tooth loss and to maintain dental function, they may not stop the onset of further disease.

The following recommendations may be used as a guideline for setting the recall interval (Fig. 17.2).

All caries-active patients should be recalled 2–3 weeks after the first instruction to check how they master plaque control and changes in lifestyle. If the dentist does not make a special effort to follow up on these matters before engaging in operative treatments, the patient may think that nonoperative measures are not important. The atmosphere at this first control visit should be very positive, to encourage the patient to collaborate further. The patient should be shown what is good and what could be improved in the mouth, and helped with any modifications. Several control visits may be necessary before the risk factors are properly controlled.

Further recalls depend on the patient's response to the given nonoperative treatment (Fig. 17.3). A patient undergoing radiation may need to see the dentist every 2–3 weeks. A caries-active patient with a dry mouth might be seen every 2–3 months. A caries-active patient who has mastered plaque control and dietary changes, and is using fluoride toothpaste as prescribed, might be seen for a (first) recall in 6 months. A caries-inactive patient would have a longer recall interval of 1–2 years.

In younger patients, the eruption status, particularly of the first and second molars, should influence recall. The occlusal surfaces of erupting molars are prone to plaque stagnation [6] and it is probably wise to see such patients two to three times a year to check that plaque control is being maintained, in particular when there are signs of active caries (see Chapter 13). If proper plaque control cannot be achieved and active noncavitated caries lesions are present in the fissures, a sealant should be applied [71] (see Chapter 19).

Examining the mouth at recall

Clinical examination to determine current caries lesion activity and caries risk status is very important. This examination should concentrate on the presence of plaque and gingival health that reflects plaque control. The whole dentition, as well as previously detected lesions, should be carefully examined for signs of caries arrest or progression. The patient should be both told and shown what has improved and what needs further improvement.

The decision to take new radiographs should be based on current caries activity as well as the depth of previously detected lesions (see Chapters 11 and 12). In caries-active patients where outer dentin lesions have been managed successfully with nonoperative treatments, new bitewing radiographs are not required until after at least a year, whereas in caries-inactive patients the interval between bitewing examinations may be several years. In any case, it is essential to obtain comparable radiographic views if lesions are to be monitored for progression or arrest.

Assessment of compliance at recall

Patient compliance seems to improve for a short period and then tends to relapse. In a review of methods of oral hygiene instruction and problems of compliance, it was concluded that relapse occurs irrespective of the method of oral hygiene instruction [48]. This review cites several reasons why patients may fail to comply in the long term: unwillingness to perform oral self-care, poor understanding of recommendations, lack of motivation, poor dental health beliefs, unfavorable dental health values, stressful life events, and low socioeconomic status.

However, an important factor in obtaining long-term results through oral hygiene instruction is regular recall visits [45]. At these visits, compliance with advice on plaque control, diet, fluoride use, and saliva stimulation should be assessed by discussion. It is only human nature for the patient to try to please with these answers. Disclosing, recording of plaque, and a follow-up diet sheet are a little more objective than simple discussion. In some cases it may be necessary to explain to the patient what the dentist sees as the consequences of poor compliance. The dentist must be honest and the conversation should be recorded in the notes.

Recording changes in oral health behavior and caries lesion activity at recall

Since knowledge of a patient's habits is so critical to management, a record of habits should be kept. This should include toothbrushing habits, use of interdental cleaning, use of topical fluorides, and diet. A note should also be kept of any changes agreed with the patient or parent.

To maintain an overview of the nonoperative treatments given and monitor their effects on caries lesion activity it is necessary to record such variables in a sheet specifically designed for this purpose (see example in Fig. 17.4). This may be particularly useful when treatment of the patient is shared between different persons in the dental team. By doing so it will not only be easier to identify the specific points where additional focus is needed, but also to point out where the patient has already been successful in controlling lesion progression.

Resetting the recall interval

Based on the above, the interval to the next recall can be set. Where the reasons for the caries activity cannot be modified, or caries is active but the cause has not been established, recalls will be frequent. Conversely, if the clinical status is improving, the interval may be increased.

Patient: 12-year-old patient

	DATE		2012 Febr 2	2012 Febr 16	2012 Mar 10	2012 May 7				
Patient level	Instruction in biofilm removal		+	+	+	+				
	Dietary advice		+	+						
	Topical fluoride		2% NaF			2% NaF				
Tooth level	Lesion activity assessment*									
	Tooth	Surface								
	2	occl	●/+	●/+	●/−	○/+				
	15	occl	●/+	●/−	○/−	●/+				
	18	occl	●/+	○/+	○/−	○/−				
	31	occl	●/+	●/+	●/−	○/−				
	29	dist	●/+	●/+	●/+	●/−				
	20	dist	●/+	●/−	○/−	○/−				

* Surfaces with active caries are assessed for **lesion activity** and **presence of biofilm** at baseline and follow-up using the following symbols: ● active /○ inactive noncavitated caries, ■ active/□ inactive cavitated caries. Presence /absence of visible biofilm on probe. +/−

Figure 17.4 Recording sheet used to monitor caries lesion activity and maintain an overview of the nonoperative treatments given.

Caries control in children and adolescents

What is special about caries control in children and adolescents?

The cornerstones in caries control (plaque control, use of fluoride, proper diet) are the same for all ages, but up to the age of about 12 years it is the parents (or those who bring the child up) who play the most important role. When caries control strategies are planned for children it should be remembered that caries in the child is the result of decisions taken by adults. There is a relationship between the parents' behavior and beliefs and the child's dental health at 7 years of age [38]. Indeed, parents' poor dental behavior could be considered a risk indicator for caries development in their children. Thus, a logical starting point in the discussion with parents of children with overt caries lesions might be their own dental health behaviors and attitudes.

The following may be relevant:

- Parent's knowledge on the causes of caries, importance of diet, and their child's eating habits.
- Do parents supervise and help with toothbrushing?
- Is there a family crisis needing complex support from dental or other professionals?
- Is poor oral health status a symptom of abuse or neglect needing intervention by social welfare workers or others? Untreated caries is more common among physically abused/neglected children [42].

In contrast to the child, the growing adolescent comes to make their own choices and take responsibility. Early intervention to reinforce self-care for caries control is important because oral health behavior in young adults is often established in teenage years [1].

A habit of toothbrushing twice daily at the age of 12 years may predict more stable oral hygiene practices through the adolescent years compared with those who brush less [31]. A low toothbrushing frequency in teenagers may predict developing socioeconomic health differences in adulthood [38]. Dietary habits are also often established mid-teens [58]. This points to the importance of implementing training in tooth cleaning and having a conversation with the adolescent during the recall visits that includes aspects of dietary habits.

When to start caries control in children

Efforts to educate and encourage parents can start from pregnancy – it is never too early to point out they will be responsible for their infant's oral care [45]. It is common that caregivers and their children first come into contact with dental professionals when the children are about 3 years old, but this may be too late. Home visits have been shown to be highly cost-effective in caries prevention in very young children in socially deprived areas [29, 30]. Trained personnel visited infants from 8 months of age, and their families, at 3-month intervals. They provided dental health education and short video demonstrations directed towards both the child's and the mother's needs.

Risk factors for caries in young children have been reviewed by Harris *et al.* [20]. Oral hygiene and diet may interact such that good oral hygiene may balance the effect of a cariogenic diet (see Chapter 15). The role of oral hygiene was further emphasized by an epidemiological study of caries in children aged 3–4 years. Children were more likely to be caries free if teeth were brushed, twice per day, by an adult before the child was 1 year old. Indeed, the parents' perceived ability to implement regular toothbrushing was the most important predictor of whether children had caries, and this factor was also relevant to children from disadvantaged backgrounds [44]. Brushing of young children's teeth by an adult is a must. It is simply not negotiable!

Early childhood caries (ECC)

Caries in preschool children up to the age of 6 years is commonly referred to as ECC [10]. It has been proposed that very young children at the age of 12–36 months may have an 'atypical' caries pattern that differs from that of older children by primarily affecting the smooth surfaces of the maxillary primary incisors and first primary molars. This pattern, which may also be found in a more extensive and severe form involving tooth fractures and pulp involvement, was recently reclassified as severe early childhood caries (S-ECC) (Fig. 17.5) [7, 10]. Previous classifications of this condition included terms such as 'rampant caries,' 'nursing bottle caries,' 'nursing caries,' and 'baby bottle tooth decay.' In many ways the old terms seem more sensible than the new terminology because S-ECC is typically associated with caries-promoting behaviors such as frequent bottle feeding on demand (*ad libitum*) or drinks in baby bottles during sleep. Indeed, there is nothing special about S-ECC.

Figure 17.5 Caries has ruined the upper incisors in a 20-month-old child who sipped a bottle of sugar-containing liquid during the night. Note the whitish and chalky border of enamel that indicates very high caries activity.

ECC shares the same microbiological characteristics as other forms of caries [59]. When the condition appears primarily on the smooth surfaces of the upper anterior teeth this is probably due to insufficient or neglected oral hygiene in an area of the mouth with reduced salivary clearance [16], combined with regular exposure to sugared liquids.

Some studies have reported that breastfeeding for more than a year beyond the stage of tooth eruption is conducive to ECC [67]. Although prolonged breastfeeding might theoretically promote the development of ECC because of a relatively high lactose concentration in breast milk (ca. 6%) [17], it is more likely that feeding patterns (frequency and duration) play a role. To ascertain the role of breastfeeding in ECC is difficult because other factors, such as intake of other sugary foods, could bias the results. In a carefully conducted study in Southeast Asia it was shown that, in addition to supplementary sugary foods and pre-chewed rice, nocturnal breastfeeding (baby sleeping with the mother) after the age of 12 months posed a risk of developing ECC [68]. Infants without those habits who were breastfed up to 12 months did not experience ECC. Therefore, water should be the only drink offered to the child during sleep.

The prevalence of ECC differs according to the population examined, and a prevalence up to 85% has been reported for disadvantaged groups in developing countries [5, 62]. In the western world, a strong association was found between socioeconomic status, ethnicity, and prevalence of ECC [20, 55].

Achieving behavior change

It has been stated that behavior change is more likely when we 'hear' ourselves talk about the need to change rather than being told to change [69]. Behavior change is rarely a discrete, single event: the patient or parent moves gradually from being disinterested (precontemplation stage) to considering a change (contemplation stage) to deciding and preparing to make a change [74].

So how should we talk with patients or parents? The motivational interviewing (MI) technique is one way of communicating that allows the exploration of an actual problem or topic in a supportive environment [47, 69]. The technique is not based on confrontation or 'finger pointing,' but on the health professional asking open-ended questions. A condition of success is that the patient/parent talks while the professional listens. Key words in the interaction are rapport, empathy, and trust. This rapport is often established as the health professional shows a genuine interest in the child and the family.

In a recent study [70], MI was compared with traditional health education and found to have a greater effect on children's dental health than traditional health education. Children aged 6–18 months were followed for 1 year. The participants were all at high risk of developing caries (immigrants). The caries increment in the MI group was reduced by 68% compared with the control group (0.7 versus 1.9 new carious lesions). In that study the parents could choose among a menu of various caries preventive options.

Effective caries control in children

Brushing, by parents, using a small quantity of fluoride-containing toothpaste is essential and should start as soon as teeth erupt. Pine *et al.* [43] showed the benefit of twice-daily brushing in newly erupted first molar teeth compared with brushing once daily or less. This study also showed the importance of parental beliefs. If parents feel strongly that there is time to check their child's toothbrushing, the odds that their child actually brushes twice daily are about three times greater. Therefore, it is important to support the parents and convince them that their efforts make sense for the child's dental health and that they really contribute.

Eruption of the first and second molars constitutes a particular caries risk because of the difficulty of maintaining sufficient plaque control [72]. When the first permanent molar erupts at 5–7 years of age it is important to inform the parents about the new challenge of keeping the tooth healthy. In the municipality of Nexø, Denmark, a program has been developed and evaluated that emphasizes mechanical plaque control focusing particularly on erupting molars [12]. Although the study was not a randomized controlled trial, the results indicate that a dedicated program focusing on plaque control, from 8 months of age, prevents caries. The program is tailored toward the needs of each child and can be divided into three components:

- education of the parents;
- training in plaque control;
- early nonoperative intervention by the dental professional, including plaque removal, application of topical fluoride, and use of sealants.

The number of visits was individualized according to the needs of each child. The program was started in 1987 and since then the reduction in caries among 15-year-olds was greater in Nexø than in other municipalities serving as controls. Ekstrand and Christiansen [12] could not explain this improvement by variables other than the specific preventive program in Nexø.

Orthodontic treatment

Children undergoing orthodontic treatment with fixed or removable appliances have an additional risk for caries development (Fig. 17.6a and b), especially where there is frequent consumption of sugar-containing soft drinks. The daily toothbrushing with fluoride-containing toothpaste, eventually combined with use of a fluoride mouthrinse, is also the basic caries controlling measure in this group. Individual preventive programs should be tailored for each patient. Patients with active caries are at special risk, and consideration should be given to use of professional tooth cleaning with fluoride applications during visits [73]. It is also reasonable to suggest that orthodontic treatment is unwise in those where current caries status designates them as high risk.

Figure 17.6 (a) Active caries with and without cavity formation caused by frequent snacking and poor oral hygiene in combination with fixed orthodontic treatment (b). Excessive plaque formation seen at a previous visit before the appliance was removed. Courtesy of Ivar Espelid.

Patients with a dry mouth

The numerous causes of dry mouth were detailed in the 'Medical history' section. These patients are a particularly challenging group because their situation is often permanent. Thus, preventive measures may have to be intensified and continued throughout life [24], and despite these efforts it is not always possible to fully control disease progression. However, some patients with moderately decreased salivary secretion (unstimulated flow between 0.2 and 0.3 mL/min; Chapter 6) can possibly be managed by a combination of improved self-performed plaque control with fluoride toothpaste and limiting sugar intakes.

Patients with dry mouth may find some toothpastes too astringent to be comfortable to use. A mild paste should be selected, preferably one without sodium lauryl sulfate. Where caries is active and difficult to control, a high fluoride paste should be recommended (e.g., 2800–5000 ppm fluoride) and in some countries this must be prescribed by a dentist. The patient should be warned that this paste is not be used by small children for toxicological reasons.

Radiotherapy

Patients exposed to radiotherapy of the salivary glands inevitably develop ravaging dental caries (Fig. 17.7a and b) unless stringent action is taken to protect the teeth (Fig. 17.8). Salivary flow decreases rapidly with irradiation, and whether salivary flow returns has been related to the irradiation dose. Glands receiving over 26 Gy had little subsequent function and no significant recovery over time [11]. Thus, caries preventive approaches must be instituted as soon as radiotherapy is begun. Since there is a dose-response relationship between the amount of radiation delivered to the oral tissues and the damage that eventually occurs, it is sensible for the dentist to request information about the total dose of irradiation that is planned for the patient. This information will allow the dentist to set the intensity of tooth cleanings, topical fluoride treatments, frequency of recall visits, and so on.

Plaque control and fluoride

An effective approach in patients exposed to radiotherapy consists of daily, self-applied 5 min topical applications with a 1% NaF gel in individually fitted trays [9]. In addition, patients should be instructed to remove all dye-disclosed dental plaque, by toothbrushing and using dental floss/interdental brushes, every day.

Figure 17.7 (a) The patient has been irradiated in the region of the salivary glands for the treatment of a malignant tumor. Heavy plaque deposits are obvious over the lesions [27]. Reproduced with permission of Oxford University Press. (b) A typical pattern of caries attack on occlusal surfaces in a patient with a dry mouth, in this case caused by radiotherapy in the region of the salivary glands. The cusp tips and incisal edges are attacked because the dentin is often exposed by tooth wear in these areas. Plaque may stagnate in the concave areas [27]. Reproduced with permission of Oxford University Press.

Figure 17.8 Cancer patient who has mastered caries control subsequent to resection of the left mandible and radiation therapy of the head and neck. The patient received regular professional tooth cleaning and topical fluoride therapy in conjunction with meticulous self-performed oral hygiene. This is a "red" patient because some risk factors cannot be changed.

The main problem with the above treatment is compliance. Failure to comply strictly with the prescribed use of the fluoride gel invariably leads to rapid caries development. Therefore, easier to perform preventive approaches have been developed and tested. Such treatments may include twice daily mouthrinses with either fluoride (0.05% NaF) [39] or a combination of fluoride (0.05% NaF) and chlorhexidine-gluconate (0.2%) [25]. The combined rinse could potentially be more effective than rinsing with fluoride solution alone because of simultaneous suppression of the aciduric oral microflora (see also Chapter 7). However, irrespective of the type of self-performed treatment, it is important to make the patient aware that meticulous daily plaque control is crucial to the outcome. If plaque control is insufficient the patient should also receive regular professional tooth cleaning, including topical application of fluoride, as detailed earlier in this chapter.

Dietary advice for patients with dry mouth

Diet analyses and advice are always important for patients with dry mouths because these patients are very likely to change their diet. Some foods are simply so dry that they are unusable by this group. Moreover, the diet sheet will often show that the patient takes frequent sips or drinks to lubricate the mouth. Plain water or milk should be used for this.

Conservative measures to relieve the symptoms

The following measures are helpful to relieve the discomfort that accompanies a severely dry mouth:

- sipping water frequently all day long;
- restricting the intake of substances that exacerbate dryness, such as cigarettes, caffeine-containing drinks, and alcohol;
- avoiding astringent products, such as alcohol-containing or strong mint flavored mouthwashes, strongly flavored toothpastes;
- coating the lips with lip salve or Vaseline;
- humidifying the sleeping area.

Salivary stimulants

Salivary stimulants will only be helpful when there is some glandular activity conserved [8]. The following agents have been used.

- Chewing a sugar-free gum. Chewing can promote salivary flow; however, the caries-preventive effect of chewing sugar-free gum is relatively low and variable [32, 33].
- Saliva-stimulating tablets (e.g., SST Sinclair, Salivin, Dentiplus). When sucked these increase the secretion of saliva through physiological stimulation of the taste buds. The tablets contain sorbitol, xylitol, citric acid, citric acid salts, malic acid, and a phosphate buffer so that they do not damage teeth.
- Proprietary lozenges (e.g., Salivix, Provalis) containing malic acid, gum arabic, calcium lactate, sodium phosphate, lycasin and sorbitol. The manufacturers claim the lozenge stimulates salivary flow and does not demineralize enamel, despite a pH of 4.0, because of the calcium lactate buffer present.
- The systemic use of pilocarpine hydrochloride has proved successful in stimulating saliva. The drug works by reproducing the effects of widespread stimulation of the parasympathetic nervous system and can have unpleasant side effects.

Saliva substitutes

In the past, individuals with dry mouths have had to rely on frequent moistening with water. Several saliva substitutes are now available to make the patient feel more comfortable and to supply calcium, phosphate, and fluoride ions to counteract demineralization. Saliva substitutes have been produced in the form of sprays, lozenges, or mouthwashes.

Sprays or mouthwashes to give viscosity

In Europe there are currently about 30 commercially available preparations, such as Luborant, Saliva Orthana, Glandosane, Salivere, Xerostom, Salisyn, and Protiden. They all try to mimic the inorganic composition of saliva by containing calcium, phosphate, magnesium, and potassium. To provide viscosity, either carboxymethyl cellulose or pig gastric mucosa-derived mucins are added to the product.

Products containing antimicrobial proteins

Dentifrices, mouthrinses, and gels are on the market in several countries containing antimicrobial proteins such as peroxidase, lysozyme, and lactoferrins. The objective is to compensate for the lack of host-mediated protection derived from these proteins in those with normal salivary flow. Examples are the Biotene (Anglian) and BioXtra (Molar) product ranges. Clinical documentation of their efficacy is rather limited. Proteins for some products (toothpastes, mouthrinses, gels, chewing gums) are purified from cow's milk or colostrum because these milk proteins are structurally and catalytically almost identical to those in human saliva. Clinical experience of these products for severe xerostomia and cancer treatment has been positive [60].

Viscous or ropy saliva

When saliva is present but is ropy, rinsing or gargling with a mouthwash made up by mixing half a teaspoonful of baking power with 1 L of warm water will break up the mucus in the mouth and throat. This can help patients with mild mucositis due to radiotherapy.

Unfortunately, there has been no controlled study to date comparing the acceptability and effectiveness of the various saliva substitutes, so no particular one can be recommended. Indeed, none of these agents is ideal, and some patients still resort to filling a spray bottle with water to be used at frequent intervals.

Failure

A few words on failure seem appropriate. Failure to obtain proper caries control may originate in a variety of factors, including dentists' knowledge and skills in performing non-operative interventions as well as patients' motivation and diligence in complying with the recommended procedures. For obvious reasons dentists in some countries do not find nonoperative caries treatments attractive to perform because there is no fee policy (whether state funded, insurance funded, or private) that rewards such treatments. As regards the patients, it is the authors' subjective opinion that failure is usually the result of sociological rather than biological factors. In a review of the behavioral aspects of dental plaque control measures, Schou [50] states that socioeconomy and social class are strongly related to good oral hygiene behavior and a number of other health-related behaviors. People living in poor circumstances are more likely to have poor health behaviors (e.g., smoking, eating little fresh food, high intake of sweets), including poor oral hygiene. The dentist must remember that people have many problems that the dentist cannot solve. The nonoperative approach described in this chapter demands patient compliance. This is not always forthcoming, but, in the final analysis, the teeth belong to the patient!

References

1. Åstrøm AN. Stability of oral health-related behavior in a Norwegian cohort between the ages of 15 and 23 years. *Community Dent Oral Epidemiol* 2004; **32**: 354–62.
2. Bardow A, Nyvad B, Nauntofte B. Relationships between medication intake, complaints of dry mouth, salivary flow rate and composition, and the rate of tooth demineralization in situ. *Arch Oral Biol* 2001; **46**: 413–23.
3. Beck JD. Risk revisited. *Community Dent Oral Epidemiol* 1998; **26**: 220–5.
4. Bratthall D, Hänsel Petersson G. Cariogram – a multifactorial risk assessment model for a multifactorial disease. *Community Dent Oral Epidemiol* 2005; **33**: 256–64.
5. Carino KMG, Shinada K, Kawaguchi Y. Early childhood caries in northern Philippines. *Community Dent Oral Epidemiol* 2003; **31**: 81–9.
6. Carvalho JC, Ekstrand KR, Thylstrup A. Dental plaque and caries on occlusal surfaces of first permanent molars in relation to stage of eruption. *J Dent Res* 1989; **68**: 773–9.
7. DeGrauwe A, Aps JK, Martens LC. Early childhood caries (ECC): what's in a name? *Eur J Paediatr Dent* 2004; **5**: 62–70.
8. Dodds MWJ, Hsieh SC, Johnson DA. The effect of increased mastication by daily gum chewing on salivary gland output and dental plaque acidogenicity. *J Dent Res* 1991; **70**: 1474–8.
9. Dreizen S, Brown LR, Daly TE, Drane JB. Prevention of xerostomia-related dental caries in irradiated cancer patients. *J Dent Res* 1977; **56**: 99–104.
10. Drury TF, Horowitz AM, Ismail AI, Maertens MP, Rozier RG, Selwitz RH. Diagnosing and reporting early childhood caries for research purposes. *J Public Health Dent* 1999; **59**: 192–7.
11. Eisbruch A, Ten Haken RK, Kim HM, Marsh LH, Ship JA. Dose, volume and function relationships in parotid salivary glands following conformal and intensity-modulated irradiation of head and neck cancer. *Int J Radiat Oncol Biol Phys* 1999; **45**: 577–87.
12. Ekstrand KR, Christiansen ME. Outcomes of a non-operative caries treatment programme for children and adolescents. *Caries Res* 2005; **39**: 455–67.
13. Ekstrand KR, Christiansen J, Christiansen MEC. Time and duration of eruption of first and second permanent molars: a longitudinal investigation. *Community Dent Oral Epidemiol* 2003; **31**: 344–50.
14. Featherstone JD, Domejean-Orliaguet S, Jenson L, Wolff M, Young DA. Caries risk assessment in practice for age 6 through adult. *J Calif Dent Assoc* 2007; **35**: 703–13.
15. Fejerskov O, Nyvad B. Dental caries in the aging individual. In: Holm-Pedersen P, Löe H, eds. *Textbook of geriatric dentistry*. Copenhagen: Munksgaard, 1996: 338–72.
16. Fejerskov O, Nyvad B, Larsen MJ. Human experimental caries models: intra-oral environmental variability. *Adv Dent Res* 1994; **8**: 134–43.
17. Fusch G, Choi A, Rochow N, Fusch C. Quantification of lactose content in human and cow's milk using UPLC–tandem mass spectrometry. *J Chromatogr B* 2011; **879**: 3759–62.
18. Ghezzi EM, Ship JA. Aging and secretory reserve capacity of major salivary glands. *J Dent Res* 2003; **82**: 844–8.
19. Hausen H, Seppä L, Poutanen R, Niinimaa A, Lahti S, Kärkkäinen S. Noninvasive control of dental caries in children with active initial lesions. *Caries Res* 2007; **41**: 384–91.
20. Harris R, Nicoll AD, Adair PM, Pine CM. Risk factors for dental caries in young children: a systematic review of the literature. *Community Dent Health* 2004; **21**: 71–85.
21. Robinson PG, Deacon SA, Deery C, Heanue M, Walmsley AD, Worthington HV, Glenny AM, Shaw WC. Manual versus powered toothbrushing for oral health. *Cochrane Database Syst Rev* 2014; (6): CD002281.
22. Henson BS, Eisbruch A, D'Hondt E, Ship JA. Two-year longitudinal study of parotid salivary flow rates in head and neck cancer patients receiving unilateral neck parotid-sparing radiotherapy treatment. *Oral Oncol* 1999; **35**: 234–41.
23. Jensen SB, Pedersen AM, Reibel J, Nauntofte B. Xerostomia and hypofunction of the salivary glands in cancer therapy. *Support Care Cancer* 2003; **11**: 207–25.
24. Joyston-Bechal S. Prevention of dental disease following radiotherapy and chemotherapy. *Int Dent J* 1992; **42**: 47–53.
25. Katz S. The use of fluoride and chlorhexidine for the prevention of radiation caries. *J Am Dent Assoc* 1982; **104**: 164–70.
26. Kay E, Locker D. A systematic review of the effectiveness of health promotion aimed at improving oral health. *Community Dent Health* 1998; **15**: 132–44.
27. Kidd EAM. *Essentials of dental caries*. Oxford University Press, 2005.
28. Koivusilta L, Honkala S, Honkala E, Rimpelä A. Toothbrushing as part of the adolescent lifestyle predicts education level. *J Dent Res* 2003; **82**: 361–6.
29. Kowash MB, Toumba KJ, Curzon MEJ. Cost-effectiveness of a long-term dental health education program for the prevention of early childhood caries. *Eur Arch Paediatr Dent* 2006; **7**: 130–5.
30. Kowash MB, Pinfield A, Smith J, Curzon MEJ. Effectiveness on oral health of a long-term health education programme for mothers with young children. *Br Dent J* 2000; **188**: 201–5.
31. Kuusela S, Honkala E, Rimpelä A, Karvonen S, Rimpelä M. Trends in toothbrushing frequency among Finnish adolescents between 1977 and 1995. *Community Dent Health* 1996; **13**: 34–8.
32. Machiulskiene V, Nyvad B, Baelum V. Caries preventive effect of sugar-substituted chewing gum. *Community Dent Oral Epidemiol* 2001; **29**: 278–88.
33. Mäkinen KK, Bennett CA, Hujoel PP, Isokangas PJ, Isotupa KP, Pape HR Jr, Mäkinen PL. Xylitol chewing gums and caries rates: a 40-month cohort study. *J Dent Res* 1995; **74**: 1904–13.
34. Marinho VCC. Evidence-based effectiveness of topical fluorides. *Adv Dent Res* 2008; **20**: 3–7.
35. Marinho VC, Higgins JP, Sheiham A, Logan S. Fluoride gels for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2002; (2): CD002280.
36. Marinho VC, Higgins JPT, Logan S, Sheiham A. Fluoride toothpastes for preventing caries in children and adolescents. *Cochrane Database Syst Rev* 2003; (1): CD002278.
37. Marinho VC, Worthington HV, Walsh T, Clarkson JE. Fluoride varnishes for preventing dental caries in children and adolescents. *Cochrane Database Syst Rev* 2013; (7): CD002279.
38. Mattila ML, Rautava P, Ojanlatva A, Paunio P, Hyssälä L, Helenius H, Sillanpää M. Will the role of family influence dental caries among seven-year-old children? *Acta Odontol Scand* 2005; **63**: 73–84.
39. Meyerowitz C, Featherstone JDB, Billings RJ, Eisenberg AD, Fu J, Shariati M. Use of an intra-oral model to evaluate 0.05% sodium fluoride mouthrinse in radiation-induced hyposalivation. *J Dent Res* 1991; **70**: 894–8.
40. Molendijk B, Ter Horst G, Kasbergen M, Truin GJ, Mulder J. Dental health in Dutch drug addicts. *Community Dent Oral Epidemiol* 1996; **24**: 117–19.
41. Nyvad B, Machiulskiene V, Baelum V. Construct and predictive validity of clinical caries diagnostic criteria assessing lesion activity. *J Dent Res* 2003; **82**: 117–22.

42. Olivan G. Untreated dental caries is common among 6 to 12-year-old physically abused/neglected children in Spain. *Eur J Public Health* 2003; **13**: 91–2.
43. Pine CM, McGoldrick PM, Burnside G, Curnow MM, Chesters RK, Nicholson J, Huntington E. An intervention programme to establish regular toothbrushing: understanding parents' beliefs and motivating children. *Int Dent J* 2000; (Suppl): 312–23.
44. Pine CM, Adair PM, Nicoll AD, Burnside G, Petersen PE, Beighton D, Gillett A et al. International comparisons of health inequalities in childhood dental caries. *Community Dent Health* 2004; **21** (1 Suppl): 121–30.
45. Plutzer K, Spencer AJ. Efficacy of an oral health promotion intervention in the prevention of early childhood caries. *Community Dent Oral Epidemiol* 2008; **36**: 335–46.
46. Poulsen S, Richards A, Nyvad B. Om brugen af fluorider i cariesforebyggelsen. *Tandlaegebladet* 2010; **114**: 622–7 (English abstract).
47. Ramseier CA, Suvan JE, eds. *Health behavior change in the dental practice.* Ames, IA: Wiley-Blackwell, 2010.
48. Renvert S, Glavind L. Individualized instruction and compliance in oral hygiene practices: recommendations and means of delivery. In: Lang NP, Attström R, Löe H, eds. *Proceedings of the European workshop on mechanical plaque control.* Chicago, IL: Quintessence, 1998: 300–9.
49. Scheutz F. Five-year evaluation of a dental care delivery system for drug addicts in Denmark. *Community Dent Oral Epidemiol* 1984; **12**: 29–34.
50. Schou L. Behavioral aspects of dental plaque control measures: an oral health promotion perspective. In: Lang NP, Attström R, Löe H, eds. *Proceedings of the European workshop on mechanical plaque control.* Chicago, IL: Quintessence, 1998: 287–99.
51. Seow WK. Biological mechanisms of early childhood caries. *Community Dent Oral Epidemiol* 1998; **26** (Suppl 1): 8–27.
52. Sheiham A, Maizels J, Cushing A, Holmes J. Dental attendance and dental status. *Community Dent Oral Epidemiol* 1985; **13**: 304–9.
53. Ship JA. Xerostomia: aetiology, diagnosis, management and clinical implications. In: Edgar M, Dawes C, O'Mullane D, eds. *Saliva and oral health.* BDJ Books, 2004: 50–70.
54. Simons D, Kidd EAM, Beighton D. Oral health of elderly occupants in residential homes. *Lancet* 1999; **353**: 1761.
55. Skeie MS, Espelid I, Skaare AB, Gimmestad A. Caries patterns in an urban preschool population in Norway. *Eur J Paediatr Dent* 2005; **6**: 16–22.
56. Smith RG, Burtner AP. Oral side-effects of the most frequently prescribed drugs. *Spec Care Dent* 1994; **14**: 96–102.
57. Steele JG, Sheiham A, Marcenes W, Walls AWG. *National Diet and Nutrition Survey: people aged 65 years and over. Vol. 2. Report of the oral health survey.* London: The Stationery Office, 1998.
58. Sweeting H, Anderson A, West P. Socio-demographic correlates of dietary habits in mid to late adolescence. *Eur J Clin Nutr* 1994; **48**: 736–48.
59. Takahashi N, Nyvad B. The role of bacteria in the caries process: ecological perspectives. *J Dent Res* 2011; **90**: 294–303.
60. Tenovuo J. Protective functions of saliva. In: Edgar M, Dawes C, O'Mullane D, eds. *Saliva and oral health.* BDJ Books 2004; 103–18.
61. Tellez M, Gomez J, Pretty I, Ellwood R, Ismail AI. Evidence on existing caries risk assessment systems: are they predictive of future caries? *Community Dent Oral Epidemiol* 2013; **41**: 67–78.
62. Thitasomakul S, Thearmontree A, Piwat S, Chankanka O, Pithpornchaiyakul W, Teanpaisan R, Madyusoh S. A longitudinal study of early childhood caries in 9- to 18-month-old Thai infants. *Community Dent Oral Epidemiol* 2006; **34**: 429–36.
63. Thomson WM. Dental caries experience in older people over time: what can the large cohort studies tell us? *Br Dent J* 2004; **196**: 89–97.
64. Thomson WM, Chalmers JM, Spencer AJ, Ketabi M. The occurrence of xerostomia and salivary gland hypofunction in a population-based sample of older South Australians. *Spec Care Dent* 1999; **19**: 20–3.
65. Thomson WM, Broadbent JM, Foster Page LA, Poulton R. Antecedents and associations of root surface caries experience among 38-year-olds. *Caries Res* 2013; **47**: 128–34.
66. Treasure E, Kelly M, Nuttall N, Nunn J, Bradnock G, White D. Factors associated with oral health: a multivariate analysis of results from the 1998 Adult Dental Health survey. *Br Dent J* 2001; **190**: 60–8.
67. Valaitis R, Hesch R, Passarelli C, Sheehan D, Sinton J. A systematic review of the relationship between breastfeeding and early childhood caries. *Can J Public Health* 2000; **91**: 411–17.
68. Van Palenstein Helderman WH, Soe W, van't Hof MA. Risk factors of early childhood caries in a Southeast Asian population. *J Dent Res* 2006; **85**: 85–8.
69. Weinstein P. *Motivate your dental patients: a workbook.* Seattle, WA: University of Washington, 2002.
70. Weinstein P, Harrison R, Benton T. Motivating parents to prevent caries in their young children: one-year findings. *J Am Dent Assoc* 2004; **135**: 731–8.
71. Weintraub JA. Pit and fissure sealants in high-caries-risk individuals. *J Dent Educ* 2001; **65**: 1084–90.
72. Zenkner JEA, Alves LS, de Oliveira RS, Bica RH, Wagner MB, Maltz M. Influence of eruption stage and biofilm accumulation on occlusal caries in permanent molars: a generalized estimating equations logistic approach. *Caries Res* 2013; **47**: 177–82.
73. Zimmer BW, Rottwinkel Y. Assessing patient-specific decalcification risk in fixed orthodontic treatment and its impaction on prophylactic procedures. *Am J Orthod Dentofacial Orthop* 2004; **126**: 318–24.
74. Zimmerman GL, Olsen CG, Bosworth MF. A 'stages of change' approach to helping patients change behavior. *Am Fam Physician* 2000; **61**: 1409–16.

18

Caries control for frail elders

M.I. MacEntee, S.R. Bryant, H. Keller, C.T. Nguyen, and C.S. Yao

Introduction

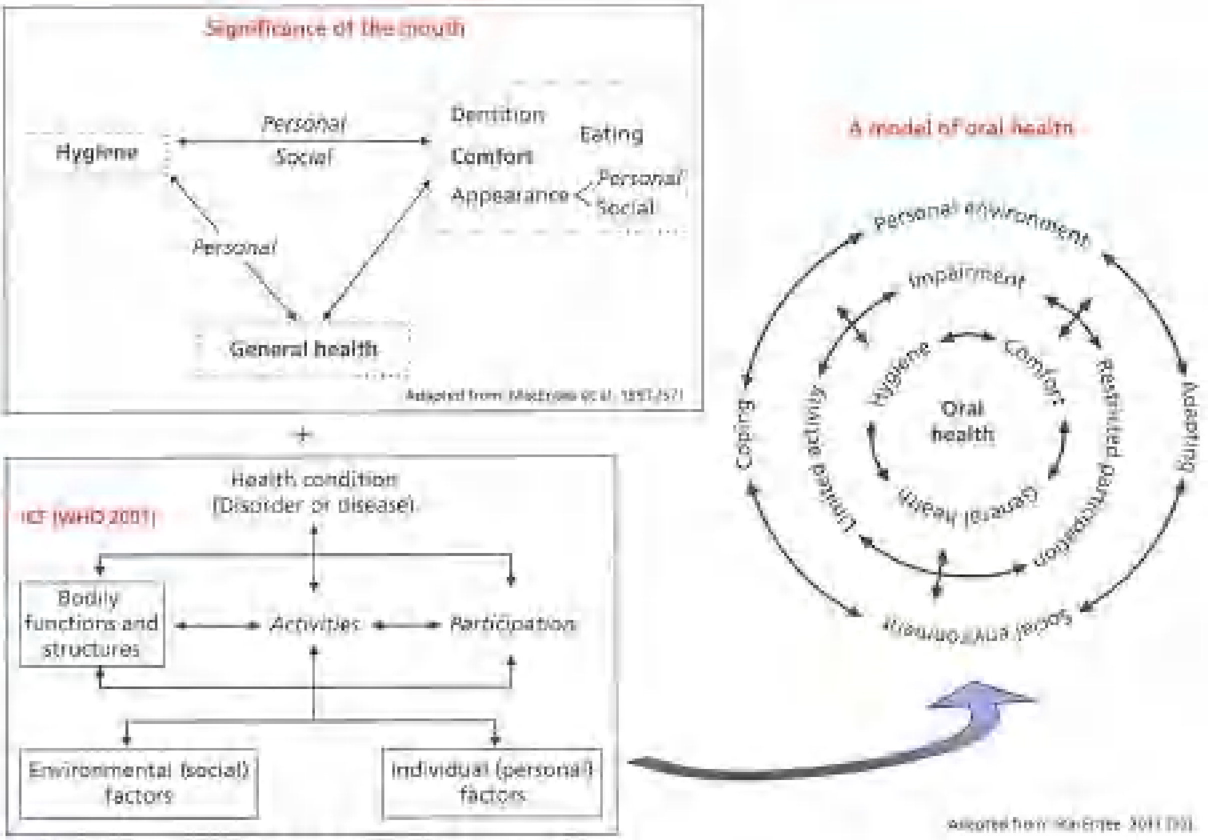
Late elder caries, like early childhood caries, is difficult to manage and the consequences are severe. It is particularly difficult and severe in people who are frail and dependent on others for care. This chapter will focus on the management of caries in people who are old, frail, and dependent on others for many of their usual daily activities.

A conceptual model of oral health

The model of oral health in Fig. 18.1 considers health and health-related functioning from the perspective of the body, the individual, and the society. It illustrates the experiences of elderly people [57], and was formed around a framework of oral health-related concerns about hygiene, general health, and comfort [53]. The inner core contains the three domains of oral health and disease – comfort, hygiene, and general health – identified by the older participants in the interviews as particularly relevant to their daily concerns. *Comfort* encompasses appearance, eating, pain, and the dentition, all of which can be disturbed by caries. *Hygiene* has both a social (e.g., smell, appearance) and a personal (e.g., feeling clean) perspective, while *general health* is entwined with and complementary to oral health. Both oral hygiene and general health have strong associations with caries [62, 73, 109].

Beyond the central core of the model are the possible consequences of oral diseases, such as caries. The middle functional layer contains the potential for structural *impairment* (e.g., tooth loss; broken or defaced teeth) to restrict or

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.



Adapted from MacEntee et al. 1997 [57]

Adapted from MacEntee 2011 [55]

Figure 18.1 A model of oral health [55, 57]. Reproduced with permission of Elsevier.

limit activities because of discomfort, pain, infection, or embarrassment. The outer environmental layer consists of interacting personal (e.g., age, sex, habits, lifestyle) and social (e.g., income, social supports, living arrangements) factors in which people live, along with their ability to *adapt* and *cope*, which is the essence of successful aging [83]. Finally, the arrows around and between the layers of the model indicate the dynamic and fluctuating relationships within and between the layers. Caries in frail elder people influences and is influenced by all of the biological, behavioral, and environmental determinants of health.

Frailty

Frailty is a physical and cognitive state that limits many activities of daily life, including oral hygiene [35, 55]. It is difficult to define precisely. One group of researchers associated frailty with three or more of the following physical conditions: shrinking or sarcopenia; weakness, slowness, low energy or endurance; and low activity level [13]. Another group [82] added a cognitive component to their definition, and in a community-based study of people aged over 65 years found that about one-third overall and about two-thirds of the 85-year-olds and older group were frail. Yet, the prevalence of frailty around the globe is elusive but can be gleaned, although imprecisely, from the size of the populations in the >85 years age group [104]. Currently, for instance, almost 5% of the Italian population are older than 85 years, with Japan at 3.9% and most western countries around 2% of their populations in this elderly stage of life (Fig. 18.2).

Most people who are frail live at home until they become severely dependent and in need of constant care and attention beyond the capacity of their families. In countries with more agricultural than industrial communities the needs of dependent people are provided by their families at home rather than by state-run facilities. However, as industrialization and urbanization expand, families are unable to provide this intensive daily care, and frail people are moved more frequently to long-term care facilities [90]. In summary, social policies, socioeconomic status, family dynamics, and cultural preferences play significant roles in determining how societies care for frail people [1, 48], and consequently there are large variations across cultures (Fig. 18.3).

The proportion of the older population with major disabilities has declined in some countries over the last few decades [107]. In the USA, for example, disability among older people declined substantially over the last quarter century owing to improved education and nutrition along with a decrease in the use of tobacco [61], and similar findings have been reported from Denmark, Finland, Italy,

Country	Number	%
Italy	2,821	4.7
Japan	4,816	3.8
Belgium	286	2.6
Germany	2,125	2.6
Canada	872	2.5
UK	1,525	2.4
Finland	125	2.3
Switzerland	189	2.3
Denmark	119	2.1
Netherlands	339	2.0
USA	6,102	2.0
New Zealand	83	1.9

Country	Number	%
Australia	430	1.5
Israel	109	1.4
Singapore	51	0.9
South Korea	174	0.9
China	7,560	0.6
Brazil	979	0.5
South Africa	165	0.4
Turkey	267	0.4
India	2,706	0.2
Saudi Arabia	41	0.1

Figure 18.2 Numbers (×1000) of people >85 years by percentage of the total population in 2013 [104]. Reproduced with permission of the US Census Bureau.

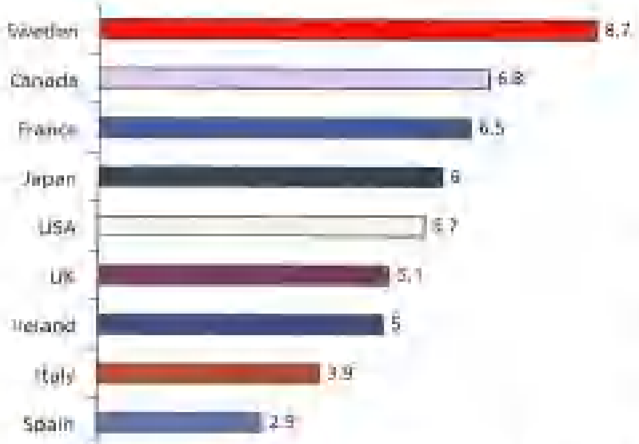


Figure 18.3 Percentage of people over 65 years of age in institutional care by country [48]. Reproduced with permission of the US Census Bureau.

and Netherlands [49]. However, despite this optimism, Germany places almost one-third of its frail population in nursing homes, and the number of nursing-home residents has increased there by 23% since 1999, and by nearly 5% between 2005 and 2007 [52]. Estimates from England indicate that from 2010 to 2030 there will be at least 100% more people over 85 years, 80% more people over 65 years with moderate to severe dementia, and a 90% increase in need of social care either at home or in a long-term care facility [42]. Yet, most people prefer to remain at home for as long as possible no matter how disabled and dependent they become, which increases the difficulty of identifying those who need special care [1].

Health problems, such as cardiovascular problems, Parkinson's disease, multiple sclerosis, and dementia, can precipitate frailty, but it is arthritic, sleeping, memory, eyesight, and hearing difficulties that typically complicate most daily activities as frailty increases in old age. Frailty can be eased and even reversed by social supports, financial resources, good health care, and other assets, or it can be exacerbated by deficits, such as physical impairments, poverty, or personal neglect [82]. There is some prospective evidence that dentistry can help to delay physical and cognitive decline by controlling disorders of the mouth, including caries, and maintaining or restoring dentitions to promote healthy diets, self-esteem, and overall quality of life [4, 47].

Physical characteristics of caries in elderly mouths

Caries on elderly teeth progresses much like it does on younger teeth, but rarely does it appear on clean teeth. However, frequently the lesions and fillings accumulated over the years leave patients with dental surfaces that are deeply scarred, structurally damaged, and a haven for plaque and bacteria that can lead to rampant caries and destruction of the entire dentition within an alarmingly short period of time (Fig. 18.4). Pigmentation of carious lesions ranges from light yellow through orange to black (see clinical pictures in Chapter 3); but it is usually the soft feel of the lesion that distinguishes it from an arrested or erosive lesion [72]. However, lesions are frequently a mix of active and arrested demineralization in which the potency of destructive activity is judged by the softness of the surface rather than by the color of the lesion.

Incidence of caries in frail adults

Caries with frailty is a potentially very destructive and mutilating disease. Exposure of cementum and dentin with advancing age and their greater solubility compared with

Figure 18.4 Rampant caries in a man consuming multiple anticholinergic medications and frequent sugar.

enamel leave the roots of teeth especially vulnerable to caries in old age, but otherwise the disease process is probably the same on coronal and radicular surfaces [25]. It is difficult to measure the prevalence of active caries in old teeth because of the confusing mix of criteria used to distinguish between active, recurrent, and inactive lesions. Consequently, the prevalence of caries in elderly populations is probably biased substantially by the scars of previous caries that are easily misdiagnosed as active lesions. Nonetheless, caries is ubiquitous in elderly mouths because of the increasing numbers of dental surfaces at risk to demineralization with advancing age [25].

A 10-year longitudinal study of 102 people aged over 65 years in Gothenburg, Sweden, found that only five of them were caries free during the decade, and the extent of caries was dramatically higher on root surfaces and among the oldest (≥85 years) group [30]. In contrast, a 2-year longitudinal study of 50 disabled residents of a long-term care facility in Vancouver, who at baseline had on average 14 teeth each, revealed that only three participants developed more than two new carious lesions during the study period [56]. There was a net incidence of 0.9 lesions per person in year 1 and 3.9 lesions in year 2. However, these mean numbers can mislead because one participant alone developed 7 lesions in year 1 and 13 in year 2, whilst another developed 19 lesions in year 1. When the analysis excluded the two outlying residents, the net incidence over the 2 years in the 48 other residents was 1.8 lesions per person. Apparently, rampant caries in elderly people, as in children, is restricted to those who are particularly vulnerable. A year-long investigation comparing elderly demented participants with others who were cognitively healthy found carious lesions – and notably large numbers of coronal lesions – in half of the group with dementia and in one-quarter of the others [15]. The investigation suggested that high increments of caries were associated with the severity of the dementia, men, poor oral hygiene, use of anticholinergic medications, and a recent history of caries.

Recognizing the risk of caries

Biological explanations dominate the risk of caries in elderly people. A Swedish study of participants receiving supportive care at home, for example, revealed that an elevated risk of caries was associated significantly with 'low saliva secretion, high plaque scores and a large number of fillings' [100]. However, caries and associated risks extend beyond biological explanations to involve also environmental and psychosocial cues and signs [3], although these characteristics have received little attention, possibly because of the large number of participants with specific characteristics required to test each variable in a multivariate model. We know very little, for instance, about the influence on caries of family composition, religion, or advertising commercials on diets, or of how dentists with different scientific and humanistic backgrounds use caries-related scripts, or of the relative benefits of different health-care systems [26].

We will now discuss specific factors that influence the risk of caries in older people who are frail.

Number of teeth

Over the last few decades there has been a huge increase in the older population with natural teeth. Today, nearly all (~80%) of the 65-year-olds and over half (53%) of 85-year-olds in the UK have natural teeth, and the majority of all age groups younger than 75 years with natural teeth have more than 21 teeth, while 85-year-olds with natural teeth have about eight teeth each [98, 111]. Similar data from the Canadian Health Measures Survey in 2007–2009 [38] indicate that most (78%) of the over 60-year-old group have on average more than 19 teeth, and that over half (58%) of them have 21 or more teeth [39]. Australian data from a 2004–2006 survey indicate similar distributions of natural teeth in the older population – nearly two-thirds (64%) of the over 75-year-old group have natural teeth, and almost half (45%) of them have at least 21 teeth [95]. Therefore, caries is a problem that will increase in the foreseeable future as more people enter old age with natural teeth [25].

Multimorbidity

The World Health Organization [112] states that:

> *Noncommunicable diseases (NCDs) are the leading global causes of death, causing more deaths than all other causes combined, and they strike hardest at the world's low- and middle-income populations. These diseases have reached epidemic proportions, yet they could be significantly reduced, with millions of lives saved and untold suffering avoided, through reduction of their risk factors, early detection and timely treatments.*

Caries is an NCD and, while rarely a cause of death, it can lead to great anxiety and distress in all age groups. Many concerns have been raised about the challenge posed by people with multiple chronic disorders (i.e., multimorbidity), which appears to be the norm for elderly people as most health-care systems are designed primarily to treat individual diseases. A survey of 314 medical practices as of March 2007 in Scotland, for example, discovered that nearly half (42%) of all patients registered had one or more chronic disorders, with the mean number of disorders at 2.6 between the ages of 65 and 84 years, and 3.6 when older than 85 years [7]. It is also thought provoking that clinical guidelines for most disorders have been created only for single diseases, and that people with multiple disorders are excluded from most clinical trials in medicine [105] and dentistry because, according to one report, their 'health might affect outcomes or ability to complete the study' [76].

Polypharmacy and dry mouth

Salivary gland hypofunction (SGH) is a physical condition of salivary glands when stimulated and unstimulated saliva is decreased and the biochemical composition of saliva changes. Xerostomia, in contrast, is the subjective or psychological response of patients to a dry mouth [41]. Sometimes the terms SGH and xerostomia are used interchangeably for a dry mouth. Either way, the thick accumulations of plaque accumulating on teeth in a dry mouth harbor bacteria and yeasts that contribute to aspiration pneumonia and premature death in people who are frail and have difficulty swallowing [62, 69, 114].

Advancing age can cause a decrease in the flow of saliva from the parotid glands, but the change is very slight compared with the adverse-effects of diseases, medications, or radiotherapy on the flow and composition of saliva [34]. A large array of medications and diseases, notably Sjögren's syndrome, cause these salivary disturbances, although the physical change in the quality or quantity of saliva might not be obvious to the patient or clinician [33, 89]. Anticholinergics, antidepressants, antihistamines, antihypertensives, anti-Parkinsonians, antipsychotics, diuretics, and tranquilizers are among the most widely used medications today, and all of them can disturb the flow and composition of saliva. Ghezzi *et al.* [34] estimate that frequent consumption of one medication from this group equates to about 14 years of change in the salivary glands due to age in a healthy person. The side effects of medications, especially on submandibular glands, are compounded further by the biochemical interactions of multiple medications [22].

Reports on the distribution of people with SGH or xerostomia in the general population are few and vary from 0.9% to 65% depending on the age and health of the populations surveyed [75]. There is little doubt, however, that a dry mouth greatly elevates the risk of caries whether from diseases such as Sjögren's syndrome, head and neck radiotherapy, or, more commonly, anticholinergic medications [78, 103]. The 2008 Canadian Survey of Experiences with Primary Health Care revealed that over one-quarter (27%) of older Canadians, and almost two-thirds (62%) of them with multiple chronic disorders, were taking five or more medications (i.e., polypharmacy) regularly, and that fewer than half had their prescriptions reviewed again by a physician or pharmacist [81]. Medications, it seems, are prescribed and dispensed with very little follow-up on adverse events, such as dry mouth.

In 1993, over three-quarters (80%) of the 131 most frequently prescribed medications in the USA were associated in the biomedical literature and in manufacturers' monographs with SGH [96]. A similar study recently in Canada found that nearly two-thirds of the most commonly prescribed medications in this country had written warnings about dry mouth in the biomedical literature or in monographs supplied by the manufacturers of the drugs. However, dry mouth as a side-effect was identified 10–30-fold more frequently in the biomedical literature than in the manufacturers' monographs supplied to physicians and pharmacists. In other words, a dry mouth is often not listed in the physicians' pharmacopeia as an adverse event associated with these medications; as a consequence, patients probably are not warned about it and could be quite confused and disturbed when it occurs without knowing the cause.

Diet

Diets are deeply entrenched in cultural behaviors, and sugar is a dominant attribute of many cultures, so it is no surprise that caries is prevalent in societies where daily consumption of sweet food and drink is frequent, and even more prevalent when oral hygiene is poor and exposure to fluoride low [97]. Sugar also has pain-reducing properties similar to opiate analgesics, and they can produce a strong attraction or addiction possibly originating within the womb from the mother's diet [20]. Consequently, it is almost impossible by prescription to change such a deeply embedded craving for sugar. The problem of sugar is compounded even more by many geriatricians and dietitians who prescribe foods high in calories, regardless of cariogenic risks, to combat malnutrition. Malnutrition among people who are frail is a widespread problem that is managed typically by prescribing frequent consumption of high-caloric sweet foods and drinks between meals and as meal replacements [66].

Changes occur in taste and smell due to age and dementia, which may precipitate or enhance a 'sweet tooth' in people who as younger adults had little attraction to sugar [67, 88, 99]. Furthermore, the metallic or salty taste accompanying Sjögren's syndrome and radiation therapy increases sensitivity to bitter and sour foods, whilst hyposalivation reduces sensitivity to sweet foods and increases a craving for sugar. The selection of food can change suddenly when a spouse dies, or when income decreases on retirement. It can also change with depression and disability, and typically the change induces or exacerbates poor oral health. Loss of multiple teeth usually disturbs chewing, reduces the stimulation of salivary glands, and favors the selection of refined carbohydrates rather than tougher meats, fruits, and vegetables [8, 84, 103]. Nonetheless, most of the differences in diet are explained more by the demographic, cultural, and behavioral characteristics of a society rather than by the teeth of its members [12, 23], and particularly when people have poor health [37].

Oral hygiene

Many administrators of residential care facilities acknowledge that their staff cannot recognize oral disorders or assist elderly residents with oral hygiene very effectively because of the conflicting priorities in the management of the facilities and the needs of the residents [58] compounded by a lack of skill in matters relating to oral health care [77, 91]. Attempts have been made to educate care aides about mouth care, but the results, although optimistic in a few situations, have been disappointing [59, 92], even in jurisdictions where regulations dictate daily oral care and ready access to dental professionals [46, 60, 110]. The situation for most people who are frail and in residential care is that they cannot get effective help with oral hygiene [91, 93]. The accumulated bacteria and yeasts in the mouth place them at high risk of caries (see Chapter 7) and other serious health hazards [2, 16, 50].

Socioeconomic status

The oral health component of the Canadian Health Measures Survey [40] found that twice as many lower income people compared with people with higher income have evidence of caries. The cause of this concentration of caries in disadvantaged communities is probably from an intermingling of many factors, such as diets of refined carbohydrates, inadequate health promotion, poor access to fluoridated toothpaste and dental services, and difficulties with oral hygiene [106]. So, as an important determinant of health generally, socioeconomics has a significant part in controlling or precipitating caries.

Prostheses

The role of dental prostheses, especially removable partial dentures, in elevating the risk of caries, and particularly root caries, seems certain [70, 79]. This was confirmed in a clinical trial involving older participants from English, Chinese, or Punjabi communities in Vancouver, British Columbia, where multiple (three or more) tooth loss occurred in one-fifth of the participants during the 5-year trial, particularly (odds ratio: 6.32) in association with use of removable dentures, and more weakly (odds ratio <1.5) in association with caries and periodontal defects at baseline [36]. Dental prostheses complicate their environment by intruding into the biological environment of teeth and allowing the biofilm to acidify when salivary buffers are weak or missing. Therefore, it is preferable to avoid dentures unless they are essential for either appearance or function, and fortunately many people can function quite comfortably with a shortened dental arch [32, 44].

Previous caries

The role is clear of past caries experience as a predictor of further caries (Fig. 18.5). Those who had it are very likely to have more, and a recent carious lesion is probably the best indicator of elevated risk to new lesions unless active steps are taken to change the multiple environmental, social, and personal factors that contribute to this risk [87].

Impact of caries in frailty

The impact of toothache from caries can be physically, psychologically, and socially debilitating [57]. Severe pain is intolerable, but the debilitating impact of pain, even when less severe, depends on the tolerance of the sufferer, and the real or perceived visibility of the underlying condition. The visibility of a carious lesion can also cause a person to become reclusive because of the stigma associated with personal neglect even if the lesion is painless [31].

Slowly progressing caries in elderly teeth stimulates reparative dentin, but it can also lead to a 'quiet' necrosis of the dental pulp and low-grade apical inflammation [6, 17]. However, pulpal inflammation is not always quiet or painless in older teeth, and this concern is particularly troubling when people with a communicative disability, such as dementia, cannot identify or explain the source or extent of their pain. This can precipitate violent and other aggressive behaviors that seem at first glance unrelated to the dental problem [14, 28]. Referred pain, phantom

Figure 18.5 Recurrent caries at the margin of a crown in a patient with a history of recurrent root caries.

dental pain, orofacial neuralgias, burning mouth syndrome, and other chronically painful disorders are always difficult to diagnose and manage, but even more so in elderly patients who are frail and have evidence of caries.

The loss of teeth may have more impact on quality of life in old age than the presence of a carious lesion that has yet to enter the pulp of an elderly tooth [18]. Carious lesions undermine tooth structure, which increases the risk of coronal fracture and tooth loss when the fracture is irreparable. Tooth loss, in turn, can precipitate a wide range of physical, psychological, and social disabilities that in many situations associated with old age remain only vaguely understood [27, 57], and managed with much uncertainty [11, 63].

The desire of patients to replace their missing teeth varies widely. Some can adapt with ease to a shortened dental arch, whereas others have a strong desire to replace any missing part of the body if at all possible to achieve a sense of psychological and functional wholeness [32, 44]. This challenge can seem insurmountable at times when patients are frail and cognitively impaired [10]. Fortunately, most people at any age can adapt and cope quite comfortably with a shortened dental arch (Fig. 18.6).

Figure 18.6 An elderly patient with a clean mouth managed successfully with a shortened dental arch and tooth restorations in the mandible, and a complete denture in the maxilla.

Management of caries in frailty

General principles of management

The patient's history and the current physical status as a whole and in the mouth will give an idea of the risk of caries. Consequently, the strategy for managing this risk should be based on the following principles: (1) prevention and control are the priorities, while surgical or operative interventions are used only if needed to improve the dental environment; (2) surgery when necessary should remove minimal tooth structure; and (3) cavity preparation and filling materials are used to preserve teeth and the general health of the patient.

Nyvad and Fejerskov [72], when planning a management strategy, recommend an assessment of carious activity rather than the physical appearance of the teeth. Active lesions can be treated differently depending upon the accessibility of the lesion to removal of microbial plaque. Deep lesions need a filling material to seal the cavity from accumulations of plaque. Shallow lesions can be kept free of plaque with a toothbrush, and occasionally enamel overhanging the periphery of a lesion can be removed to allow the toothbrush and saliva easy access to the surface of the lesion (see Chapter 19).

The strategy for controlling caries on which these principles rest depends on a 'champion' of daily oral hygiene at home or in the nursing facility [102]. The professional qualifications of the champion, whether a dentist, dental hygienist, or a specially educated assistant, are less important than the champion's ability to infiltrate the culture of the institution and communicate as a colleague with administrators and other members of staff.

Dentists alone cannot manage polypharmacy as a cause of caries without help from others on an effective interprofessional health-care team. The concept of teamwork dominates the usual approach to long-term care, and the effectiveness of teamwork is influenced strongly by the tolerance, mutual trust, and respect among the members [74]. The current role of dental personnel on interprofessional teams in long-term care facilities is improving as other team members learn about the significance of oral health in the management of frailty. Yet there remains much to be achieved before dentists and dental hygienists can reduce substantially the risk of caries in this environment [55].

Managing dementia

The challenge of managing the dental needs of frail people is especially difficult when dealing with patients who have dementia. Several strategies have been proposed to recognize that one approach does not suit all. Patients with dementia are as heterogeneous in their needs as any other group, and their treatments need preparation and organization specific to each individual need [14]'. We can suggest that mild dementia warrants no particular change in care other than the realization that the patient will need help with oral care in the future [24]. Moderate dementia needs a simplified approach to treatment with uncomplicated regimens and collaboration with other health-care providers. Finally, advanced dementia needs special approaches to reduce the patient's anxiety and stress as much as possible as the need for palliative rather than curative care increases.

Fiske *et al.* [28] provide a useful guide to planning treatment that emphasizes (1) the role of the family, (2) realism, (3) anticipation of decline, (4) prevention of disease, (5) reduction of stress, (6) effective communications, (7) the occasional need for anti-anxiety drugs, and (8) last but not least, hopeful assurances of comfort. Chalmers [14] suggested that most aggressive and other disruptive behaviors can be managed without drugs by recognizing that aggression in dementia reflects anxiety and fear. She stressed the importance of communicating with an anxious patient in a quiet environment using nonthreatening movements, touch, and other nonverbal communications supported by a clear and gentle voice offering uncomplicated directives. All of this frequently requires the assistance of others on the health-care team, and patience with compassion above all else.

Environment and oral hygiene

Nyvad and Fejerskov [72] have reported that 'caries lesion progression can be arrested at any stage of lesion development in almost all individuals, provided that clinically plaque free conditions are obtained,' although they qualify this optimistic observation with the statement that 'there is no universal level of oral hygiene to be recommended.' They recommend also that self-performed plaque removal be supplemented by fluoridated toothpaste and occasional applications of topical fluoride. The fluoridated toothpaste will not prevent the initiation of caries, but it will slow down the progression of a lesion, especially when other risks are elevated [45] (see Chapter 13).

Unfortunately, oral hygiene provided for people who are dependent on others is rarely effective, in large part because of many conflicting priorities within the daily routines of most long-term care facilities [19, 58, 59]. Administrators of nursing facilities, keenly aware of their legal responsibilities, can usually obtain emergency dental care to relieve acute pain and infection for residents, yet most of them seem unable to assure the quality of oral care offered daily by their staff [60]. This administrative difficulty is compounded all too frequently by poor collaboration between the administrators and dental professionals or government inspectors [46]. Furthermore, in communities where dental services are paid mostly by fee-for-service, dentists and dental hygienists generally feel little incentive beyond a noncompelling sense of professional responsibility to attend patients in nursing facilities [10, 54]. Altogether, these factors provide a formidable barrier to adequate oral hygiene and applications of topical fluoride.

Oral care plans

Management strategies for controlling caries in frail and older people are more likely to be effective in our experience if based on a clear plan, a commitment to implementation, and an agreement on responsibilities [89, 102]. A complete assessment of the mouth and teeth is completed by a member of the dental team as soon as possible after a dependent person is admitted to a residential facility [9, 71, 113]. This will record the status of oral health, connect residents with the dental team as needed to address problems, and identify the level of assistance with daily oral hygiene required by each resident. Subsequently, an individualized oral care plan is formulated from the assessment with input from the dental team, and made readily accessible to the carers (see Table 18.1 for an example of a daily oral care plan appropriate for the

Table 18.1 Example of an oral care plan for the patient shown in Fig. 18.8.

1. Please approach Mr Chung gently from the front and ask permission to remove his upper denture and brush his lower teeth. Maintain eye contact during this request and do not touch his mouth until he grants permission. He usually responds slowly but agreeably to this request.
2. Ask him if he has any discomfort or pain in his mouth, and if he does, please inform a member of the dental team.
3. Wear gloves to remove his upper denture each night and brush all of the surfaces with the brush and cleaning gel provided. Brush the denture over a sink filled with water to protect the denture if it is dropped.
4. Store his denture in a dry container if he does not want to wear it when sleeping – occasionally he prefers to keep it in his mouth during the night.
5. Allow Mr Chung to sit comfortably in his chair and approach him from the front to maintain eye contact as much as possible. It is easier when brushing his teeth to stand on his right side, cradling his head with your left arm. However, this approach can confuse and distress him sometimes. Do NOT proceed if he seems distressed. It might be necessary to postpone the oral hygiene and return when he is more at ease and less distressed.
6. Brush his natural teeth in the lower jaw using the electric toothbrush and fluoridated toothpaste provided. Begin gently by brushing the tongue surfaces of his teeth before brushing the cheek and lip surfaces.
7. Allow Mr Chung at any time during the cleaning to rest and spit out into a cup if a sink is not nearby.
8. Report to a member of the dental team any bleeding from the gums (gingivitis) or other abnormality in or around his mouth.
9. Mr Chung should be encouraged NOT to eat sugary snacks or sweets more than once between meals, and never after his teeth are brushed before sleeping.

frail man in Fig. 18.6 with a complete maxillary denture and lower natural teeth).

The person assigned to the care of each resident must be instructed to (1) solicit complaints frequently, (2) wear gloves, (3) clean and store the denture, (4) clean all of the tooth surfaces with fluoridated toothpaste, (5) limit the consumption of sugar, and (6) report abnormalities. They should also be offered guidance on how to assist residents with oral hygiene in a nonthreatening way, typically by maintaining eye contact as much as possible, and if necessary postponing the hygiene and assessment session when a resident is distressed [14, 28].

Dry mouth

Caring for a frail person with rampant caries and a dry mouth who takes multiple medications can be very challenging and requires help usually from others on the interprofessional health-care team. The primary objective must be to address the discomfort from the dry mouth. A range of saliva substitutes is available, but none replaces all the properties of natural saliva (see 'Management of salivary gland hypofunction' section in Chapter 6). Sometimes patients get relief from the spray of a small atomizer bottle filled with water [101], or from the limited flow of saliva stimulated by chewing gum [94]. However, above all, people with a dry mouth and their carers must be warned about the cariogenic danger of frequent ingestions of sugar from any source, and advised only to use chewing gum and other stimulants that are sugar free.

Diet

There remains much uncertainty about how to modify the diets of older people and about the benefits of modifying diets to accommodate mouth problems [85]. Certainly, people with mouth sores or chewing difficulties are unlikely to forgo soft and highly processed foods for healthier but tougher to chew unprocessed foods [7], and people generally are reluctant to even consider changing their diet if they do not see the benefit of the change [21, 68]. It is necessary, therefore, to make the mouth comfortable by removing dental and prosthetic irritants, and to communicate openly with the patient and other members of the health-care team about the benefits overall of the change.

Hard fibrous foods, including bread, cheese, and nuts, can buffer acids in saliva by stimulating salivary flow but they are difficult to eat without strong teeth [86]. Consequently, patients with impaired dentitions need advice on how to select and eat quality food [64]. Cooked pasta, cheese sauce, and breasts of chicken stuffed with cheese are good examples of soft foods that increase the concentrations of calcium in the dental biofilm and probably protect against caries even when cooked and accompanied by other components of a meal [65]. The attraction to sugar decreases after eating, which highlights even more the importance of nutritious meals when frailty increases [20].

Restorative dentistry

Domiciliary care is often necessary when people who are frail need dental treatment. The atraumatic restorative technique (ART) can stabilize teeth for at least 1 year when patients are homebound or institutionalized [29]. The dentists in one small clinical study managed the treatment for elderly participants with a 'mouth mirror, periodontal probe, spoon-excavator, hatchet, spatula, carver, tweezers, scalers, masks, gloves, cotton rolls and pellets, wedges, interproximal strips, lubricant and glass-ionomer material' [40]. Although the majority (89%) of the carious lesions in this study could not be restored by ART, most (79%) of the dental restorations were placed and remained intact without discomfort for at least 13 months. In another two clinical studies of the ART – one involving patients who had radiotherapy [43], and the other elderly residents in a long-term care facility [51] – the restorations survived almost as well as restorations placed by a more traditional technique (see Chapter 19 for additional information about the ART).

Summary

Natural teeth, recent caries, a denture, poor oral hygiene, and anticholinergic medications are the typical characteristics of an elderly man or woman in most countries today, and they all portend more caries and associated problems. Rampant caries is very damaging in any age group, but the damage can be devastating to people who are frail and struggling to stabilize their physical and cognitive well-being. Caries in old age is increasing rather than abating as most people retain their natural teeth in an environment complicated of multimorbidity and polypharmacy. There is very limited awareness of this disease beyond the dental professions. Physicians, nurses, and dietitians, for example, encourage frail people to combat malnutrition by consuming sweet food and drink frequently through the day without the oral hygiene needed to control the proliferation of cariogenic bacteria. The challenge of this disease is daunting, but it can be managed effectively by a combination of clinical assessments, daily oral hygiene, sugar control, fluorides and minimally invasive surgical and restorative procedures. However, dentists and dental hygienists can oversee and implement this management protocol effectively only as part of an interprofessional health-care team centered on the needs of elderly people who are frail and dependent.

The mouth, like the rest of the body, cannot be left unwashed without grave consequences, including an elevated risk from poor oral hygiene of aspiration pneumonia and premature death. The mouth and teeth matter as much to people who are elderly and frail as to any other group

They too need to eat, smile, speak, and kiss; therefore, the very least that they should expect is the help they need to keep their teeth clean and healthy.

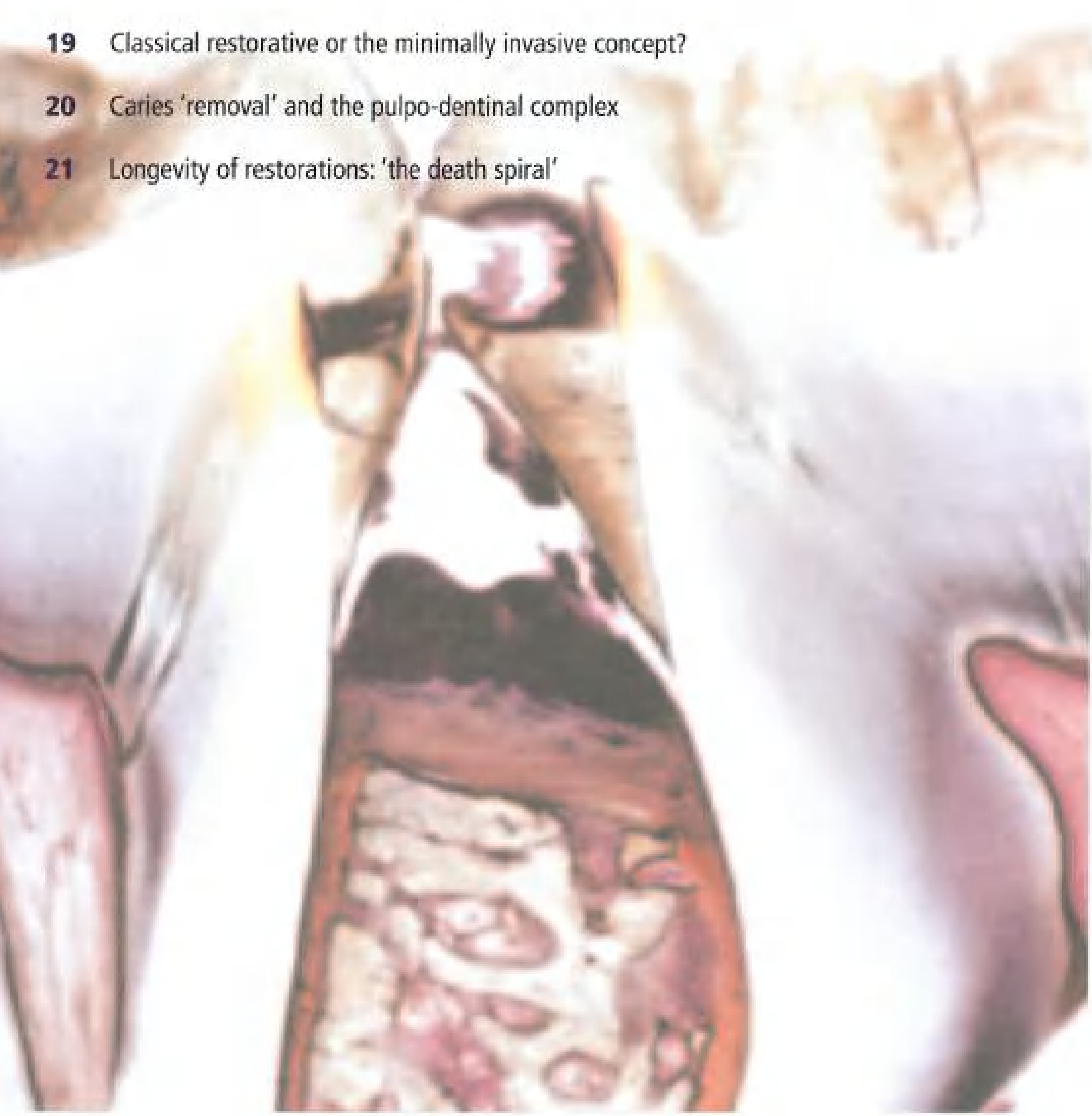
References

1. Agree EM, Glaser K. Demography of informal caregiving. In: Uhlenberg P, ed. *International handbook of population aging*. Dordrecht: Springer, 2009: 647–68.
2. Almståhl A, Kareem KL, Carlén A, Wårdh I, Lingström P, Wikström M. A prospective study on oral microbial flora and related variables in dentate dependent elderly residents. *Gerodontology* 2012; **29**: e1011–18.
3. Baelum V. What is an appropriate caries diagnosis? *Acta Odontol Scand* 2010; **68**: 65–79.
4. Batty GD, Li Q, Huxley R, Zoungas S, Taylor BA, Neal B, de Galan B, Woodward M, Harrap SB, Colagiuri S, Patel A, Chalmers J. Oral disease in relation to future risk of dementia and cognitive decline: prospective cohort study based on the Action in Diabetes and Vascular Disease: Preterax and Diamicron Modified-Release Controlled Evaluation (ADVANCE) trial. *Eur Psychiatry* 2013; **28**: 49–52.
5. Barnett K, Mercer SW, Norbury M, Watt G, Wyke S, Guthrie B. Epidemiology of multimorbidity and implications for health care, research, and medical education: a cross-sectional study. *Lancet* 2012; **380**: 37–43.
6. Bjørndal L. The caries process and its effect on the pulp: the science is changing and so is our understanding. *J Endod* 2008; **34**: S2–5.
7. Brennan DS, Singh KA. Compliance with dietary guidelines in grocery purchasing among older adults by chewing ability and socio-economic status. *Gerodontology* 2012; **29**: 265–71.
8. Brennan DS, Spencer AJ, Roberts-Thomson KF. Tooth loss, chewing ability and quality of life. *Qual Life Res* 2008; **17**: 227–35.
9. British Columbia Dental Association. *Caring for seniors' oral health*. Educational Presentations. 2010. http://www.bcdental.org/ (accessed November 7, 2014).
10. Bryant SR, MacEntee MI, Browne A. Ethical issues encountered by dentists in the care of institutionalized elders. *Spec Care Dentist* 1995; **15**: 79–82.
11. Budtz-Jørgensen E, Chung JP, Mojon P. Successful aging – the case for prosthetic therapy. *J Public Health Dent* 2000; **60**: 308–12.
12. Budtz-Jørgensen E, Chung JP, Rapin CH. Nutrition and oral health. *Best Pract Res Clin Gastroenterol* 2001; **15**: 885–96.
13. Cawthon PM, Marshall LM, Michael Y, Dam TT, Ensrud KE, Barrett-Connor E, Orwoll ES. Frailty in older men: prevalence, progression, and relationship with mortality. *J Am Geriatr Soc* 2007; **55**: 1216–23.
14. Chalmers JM. Behavior management and communication strategies for dental professionals when caring for patients with dementia. *Spec Care Dentist* 2000; **20**: 147–54.
15. Chalmers JM, Carter KD, Spencer AJ. Caries incidence and increments in community-living older adults with and without dementia. *Gerodontology* 2002; **19**: 80–94.
16. Chen X, Clark JJ, Naorungroj S. Oral health in nursing home residents with different cognitive statuses. *Gerodontology* 2013; **30**: 49–60.
17. Chogle SM, Goodis HE, Kinaia BM. Pulpal and periradicular response to caries: current management and regenerative options. *Dent Clin North Am* 2012; **56**: 521–36.
18. Christensen LB, Hede B, Nielsen E. A cross-sectional study of oral health and oral health-related quality of life among frail elderly persons on admission to a special oral health care programme in Copenhagen City, Denmark. *Gerodontology* 2012; **29**: e392–400.
19. Coleman P, Watson NM. Oral care provided by certified nursing assistants in nursing homes. *J Am Geriatr Soc* 2006; **54**: 138–43.
20. Drewnowski A, Mennella JA, Johnson SL, Bellisle F. Sweetness and food preference. *J Nutr* 2012; **142**: 1142S–6S.
21. [illegible], Broer J, ter Bogt NC, Beltman FW, Smit AJ, van der Meer K, Bemelmans WJ. Maintenance of lifestyle changes: 3-year results of the Groningen Overweight and Lifestyle study. *Patient Educ Couns* 2012; **88**: 149–55.
22. Eliasson L, Birkhed D, Österberg T, Carlén A. Minor salivary gland secretion rates and immunoglobulin A in adults and the elderly. *Eur J Oral Sci* 2006; **114**: 494–9.
23. Ervin RB, Dye BA. Number of natural and prosthetic teeth impact nutrient intakes of older adults in the United States. *Gerodontology* 2012; **29**: e693–702. http://onlinelibrary.wiley.com/doi/10.1111/j.1741-2358.2011.00546.x/full (accessed November 7, 2014).
24. Ettinger RL. Dental management of patients with Alzheimer's disease and other dementias. *Gerodontology* 2000; **17**: 8–16.
25. Fejerskov O, Baelum V, Østergaard ES. Root caries in Scandinavia in the 1980s and future trends to be expected in dental caries experience in adults. *Adv Dent Res* 1993; **7**: 4–14.
26. Fisher-Owens SA, Gansky SA, Platt LJ, Weintraub JA, Soobader MJ, Bramlett MD, Newacheck PW. Influences on children's oral health: a conceptual model. *Pediatrics* 2007; **120**: e510–20.
27. Fiske J, Davis DM, Frances C, Gelbier S. The emotional effects of tooth loss in edentulous people. *Br Dent J* 1998; **184**: 90–3; discussion 79.
28. Fiske J, Frenkel H, Griffiths J, Jones V. Guidelines for the development of local standards of oral health care for people with dementia. British Society of Gerodontology; British Society for Disability and Oral Health. *Gerodontology* 2006; **23** (Suppl 1): 5–32.
29. Frencken JE, Leal SC, Navarro MF. Twenty-five-year atraumatic restorative treatment (ART) approach: a comprehensive overview. *Clin Oral Investig* 2012; **16**: 1337–46.
30. Fure S. Ten-year cross-sectional and incidence study of coronal and root caries and some related factors in elderly Swedish individuals. *Gerodontology* 2004; **21**: 130–40.
31. Gerhardt U. Qualitative research on chronic illness: the issue and the story. *Soc Sci Med* 1990; **30**: 1149–59.
32. Gerritsen AE, Allen PF, Witter DJ, Bronkhorst EM, Creugers NH. Tooth loss and oral health-related quality of life: a systematic review and meta-analysis. *Health Qual Life Outcomes* 2010; **8**: 126. http://www.hqlo.com/content/8/1/126 (accessed November 7, 2014).
33. Ghezzi EM, Ship JA. Aging and secretory reserve capacity of major salivary glands. *J Dent Res* 2003; **82**: 844–8.
34. Ghezzi EM, Wagner-Lange LA, Schork MA, Metter EJ, Baum BJ, Streckfus CF, Ship JA. Longitudinal influence of age, menopause, hormone replacement therapy, and other medications on parotid flow rates in healthy women. *J Gerontol A Biol Sci Med Sci* 2000; **55**: M34–42.
35. Gill TM, Baker DI, Gottschalk M, Peduzzi PN, Allore H, Byers A. A program to prevent functional decline in physically frail, elderly persons who live at home. *N Engl J Med* 2002; **347**: 1068–74.
36. Gonda T, MacEntee MI, Persson R, Persson R, Kiyak A, Wyatt CCL. Predictors of multiple tooth loss among socio-culturally diverse elders. *Int J Prosthodont* 2013; **26**: 127–34.
37. Griep MI, Mets TF, Collys K, Ponjaert-Kristoffersen I, Massart DL. Risk of malnutrition in retirement homes elderly persons measured by the "mini-nutritional assessment". *J Gerontol A Biol Sci Med Sci* 2000; 55 (2): M57–63.
38. Health Canada. Summary report on the findings of the oral health component of the Canadian Health Measures Survey 2007–2009. Ottawa: Publications Health Canada, 2010. http://www.fptdwg.ca/assets/PDF/CHMS/CHMS-E-summ.pdf (accessed November 7, 2014).
39. Health Canada. Report on the findings of the oral health component of the Canadian Health Measures Survey 2007–2009. Ottawa: Publications Health Canada, 2010: Table 25. http://www.fptdwg.ca/assets/PDF/CHMS/CHMS-E-tech.pdf (accessed November 7, 2014).
40. Honkala S, Honkala E. Atraumatic dental treatment among Finnish elderly persons. *J Oral Rehabil* 2002; **29**: 435–40.
41. Hopcraft MS, Tan C. Xerostomia: an update for clinicians. *Aust Dent J* 2010; **55**: 238–44.
42. House of Lords Select Committee on Public Service and Demographic Change. *Ready for ageing?* Report. London: The Stationery Office Limited, 2013. http://www.publications.parliament.uk/pa/ld201213/ldselect/ldpublic/140/140.pdf (accessed November 7, 2014).
43. Hu JY, Chen XC, Li YQ, Smales RJ, Yip KH. Radiation-induced root surface caries restored with glass-ionomer cement placed in conventional and ART cavity preparations: results at two years. *Aust Dent J* 2005; **50**: 186–90.

44. Hultin M, Davidson T, Gynther G, Helgesson G, Jemt T, Lekholm U, Nilner K, Nordenram G, Norlund A, Rohlin M, Sunnegårdh-Grönberg K, Tranæus S. Oral rehabilitation of tooth loss: a systematic review of quantitative studies of OHRQoL. *Int J Prosthodont* 2012; 25: 543–52.
45. Innes N, Evans D. Caries prevention for older people in residential care homes. *Evid Based Dent* 2009; 10: 83–7.
46. Jiang CYW. *The implementation of oral health regulation in long-term care facilities.* Master of Science thesis. University of British Columbia, 2011. https://circle.ubc.ca/bitstream/handle/2429/40170/ubc_2012_spring_jiang_caroline.pdf?sequence (accessed November 7, 2014).
47. Kaye EK, Valencia A, Baba N, Spiro A III, Dietrich T, Garcia RI. Tooth loss and periodontal disease predict poor cognitive function in older men. *J Am Geriatr Soc* 2010; 58: 713–8.
48. Kinsella K, Velkoff VA. *An aging world: 2001.* Washington, DC: US Government Printing Office, 2001.
49. Lafortune G, Balestat G. Trends in severe disability among elderly people: assessing the evidence in 12 OECD countries and the future implications. OECD Health Working Paper 26. Paris: OECD, 2007. 10.1787/217072070078 (accessed November 7, 2014).
50. Lam OLT, McGrath C, Li LSW, Samaranayake LP. Effectiveness of oral hygiene interventions against oral and oropharyngeal reservoirs of aerobic and facultatively anaerobic Gram-negative bacilli. *Am J Infect Control* 2012; 40: 175–82.
51. Lo ECM, Luo Y, Tan HP, Dyson JE, Corbet EF. ART and conventional root restorations in elders after 12 months. *J Dent Res* 2006; 85: 929–32.
52. Luppa M, Wollny A, Eisele M, Zimmermann T, König H-H, Maier W. Age-related predictors of institutionalization: results of the German study on ageing, cognition and dementia in primary care patients (AgeCoDe). *Soc Psychiatry Psychiatr Epidemiol* 2012; 47: 263–70.
53. MacEntee MI. An existential model of oral health from evolving views on health, function and disability. *Community Dental Health* 2006; 23: 5–14.
54. MacEntee MI. Missing links in oral health care for frail elders. *J Can Dent Assoc* 2006; 72: 421–5.
55. MacEntee MI. Muted dental voices on interprofessional healthcare teams. *J Dent* 2011; 39 (Suppl 2): S34–40.
56. MacEntee MI, Wyatt CCL, McBride B. A longitudinal study of caries and cariogenic bacteria in an elderly population. *Community Dent Oral Epidemiol* 1990; 18: 149–52.
57. MacEntee MI, Hole R, Stolar E. The significance of the mouth in old age. *Soc Sci Med* 1997; 45: 1449–58.
58. MacEntee MI, Thorne S, Kazanjian A. Conflicting priorities: oral health in long-term care. *Spec Care Dentist* 1999; 19: 164–72.
59. MacEntee MI, Wyatt CCL, Beattie BL, Paterson B, Levy-Milne R, McCandless L, Kazanjian A. Provision of mouth-care in long-term care facilities: an educational trial. *Community Dent Oral Epidemiol* 2007; 35: 25–34.
60. MacEntee MI, Kazanjian A, Kozak JF, Hornby K, Thorne S, Kettratad M. A scoping review and research synthesis on financing and regulating oral care in long-term care facilities. *Gerodontology* 2012; 29: e41–52. http://onlinelibrary.wiley.com/doi/10.1111/j.1741-2358.2011.00575.x/full (accessed November 7, 2014).
61. Martin LG, Schoeni RF, Andreski PM. Trends in health of older adults in the United States: past, present, future. *Demography* 2010; 47 (Suppl): S17–40.
62. Mauriello SM. Risk modeling for root caries and mortality in older adults. Degree of Doctor of Education dissertation. NC State University, 2004. http://www.lib.ncsu.edu/resolver/1840.16/4579 (accessed November 7, 2014).
63. Mojon P, MacEntee MI. Estimates of time and propensity for dental treatment among institutionalised elders. *Gerodontology* 1994; 11: 99–107.
64. Moynihan PJ. Dietary advice in dental practice. *Br Dent J* 2002; 193: 563–8.
65. Moynihan PJ, Ferrier S, Jenkins GN. The cariostatic potential of cheese: cooked cheese-containing meals increase plaque calcium concentration. *Br Dent J* 1999; 187: 664–7.
66. Moynihan P, Bradbury J, Müller F. Dietary consequences of oral health in frail elders. In: MacEntee MI, Müller F, Wyatt C, eds. *Oral healthcare and the frail elder: a clinical perspective.* Ames, IA: Wiley-Blackwell, 2010: 73–94.
67. Murphy L. The chemical senses and nutrition in older adults. *J Nutr Elder* 2008; 27: 247–65.
68. Naka O, Anastassiadou V. Assessing oral health promotion determinants in active Greek elderly. *Gerodontology* 2012; 29: e827–34.
69. Nakayama Y, Washio M, Mori M. Oral health conditions in patients with Parkinson's disease. *J Epidemiol* 2004; 14: 143–50.
70. Nevalainen MJ, Närhi TO, Ainamo A. A 5-year follow-up study on the prosthetic rehabilitation of the elderly in Helsinki, Finland. *J Oral Rehabil* 2004; 31: 647–52.
71. Nunn J, Greening S, Wilson K, Gordon K, Hylton B, Griffiths J. *Principles on intervention for people unable to comply with routine dental care.* British Society for Disability and Oral Health, 2004. http://www.bsdh.org.uk/guidelines/PIDocument.pdf (accessed November 7, 2014).
72. Nyvad B, Fejerskov O. Assessing the stage of caries lesion activity on the basis of clinical and microbiological examination. *Community Dent Oral Epidemiol* 1997; 25: 69–75.
73. Nyvad B, ten Cate JM, Fejerskov O. Arrest of root surface caries in situ. *J Dent Res* 1997; 76: 1845–53.
74. Oandasan I, Reeves S. Key elements for interprofessional education. Part 1: the learner, the educator and the learning context. *J Interprof Care* 2005; 19 (Suppl 1): 21–38.
75. Orellana MF, Lagravère MO, Boychuk DGJ, Major PW, Flores-Mir C. Prevalence of xerostomia in population-based samples: a systematic review. *J Public Health Dent* 2006; 66: 152–8.
76. Papas AS, Vollmer WM, Gullion CM, Bader J, Laws R, Fellows J, Hollis JF, Maupomé G, Singh ML, Snyder J, Blanchard P. Efficacy of chlorhexidine varnish for the prevention of adult caries: a randomized trial. *J Dent Res* 2012; 91: 150–5.
77. Pearson A, Chalmers J. Oral hygiene care for adults with dementia in residential aged care facilities. *Joanna Briggs Inst Rep* 2004; 2: 65–113.
78. Porter SR, Scully C, Hegarty AM. An update of the etiology and management of xerostomia. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2004; 97: 28–46.
79. Preshaw PM, Walls AW, Jakubovics NS, Moynihan PJ, Jepson NJ, Loewy Z. Association of removable partial denture use with oral and systemic health. *J Dent* 2011; 39: 711–19.
80. Pruksapong M, MacEntee MI. Quality of oral health services in residential care: towards an evaluation framework. *Gerodontology* 2007; 24: 224–30.
81. Reason B, Terner M, Moses McKeag A, Tipper B, Webster G. The impact of polypharmacy on the health of Canadian seniors. *Fam Pract* 2012; 29: 427–32.
82. Rockwood K, Fox RA, Stolee P, Robertson D, Beattie BL. Frailty in elderly people: an evolving concept. *Can Med Assoc J* 1994; 150: 489–95.
83. Rowe JW, Kahn RL. Successful aging. *Gerontologist* 1997; 37: 433–40.
84. Sahyoun NR, Lin CL, Krall E. Nutritional status of the older adult is associated with dentition status. *J Am Diet Assoc* 2003; 103: 61–6.
85. Sanders TA. Diet and general health: dietary counselling. *Caries Res* 2004; 38 (Suppl 1): 3–8.
86. Scardina GA, Messina P. Good oral health and diet. *J Biomed Biotechnol* 2012; 2012: 720692. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3278661/pdf/JBB2012-720692.pdf (accessed November 7, 2014).
87. Scheinin A, Pienihäkkinen K, Tiekso J, Holmberg S. Multifactorial modeling for root caries prediction. *Community Dent Oral Epidemiol* 1992; 20: 35–7.
88. Schiffman SS. Effects of aging on the human taste system. *Ann N Y Acad Sci* 2009; 1170: 725–9.
89. Ship JA, Nolan NE, Puckett SA. Longitudinal analysis of parotid and submandibular salivary flow rates in healthy, different-aged adults. *J Gerontol A Biol Sci Med Sci* 1995; 50: M285–9.
90. Silverstein M, Cong Z, Li S. Intergenerational transfers and living arrangements of older people in rural China: consequences for psychological well-being. *J Gerontol B Psychol Sci Soc Sci* 2006; 61: S256–66.
91. Simons D, Kidd EA, Beighton D. Oral health of elderly occupants in residential homes. *Lancet* 1999; 353: 1761.
92. Simons D, Baker P, Jones B, Kidd EA, Beighton D. An evaluation of an oral health training programme for carers of the elderly in residential homes. *Br Dent J* 2000; 188: 206–10.

93. Simons D, Brailsford S, Kidd EA, Beighton D. Relationship between oral hygiene practices and oral status in dentate elderly people living in residential homes. *Community Dent Oral Epidemiol* 2001; **29**: 464–70.
94. Simons D, Brailsford SR, Kidd EA, Beighton D. The effect of medicated chewing gums on oral health in frail older people: a 1-year clinical trial. *J Am Geriatr Soc* 2002; **50**: 1348–53.
95. Slade GD, Spencer AJ, Roberts-Thomson KF, eds. *Australia's dental generations: the National Survey of Adult Oral Health 2004–06.* Dental Statistics and Research Series No. 34. Canberra: Australian Institute of Health and Welfare, 2007. http://www.aihw.gov.au/WorkArea/DownloadAsset.aspx?id=10737421983 (accessed November 7, 2014).
96. Smith RG, Burtner AP. Oral side-effects of the most frequently prescribed drugs. *Spec Care Dentist* 1994; 14: 96–102.
97. Steele JG, Sheiham A, Marcenes W, Fay N, Walls AW. Clinical and behavioural risk indicators for root caries in older people. *Gerodontology* 2001; **18**: 95–101.
98. Steele JG, Treasure ET, O'Sullivan I, Morris J, Murray JJ. Adult Dental Health Survey 2009: transformations in British oral health 1968–2009. *Br Dent J* 2012; **213**: 523–7.
99. Steinbach S, Hundt W, Vaitl A, Heinrich P, Forster S, Burger K, Zahnert T. Taste in mild cognitive impairment and Alzheimer's disease. *J Neurol* 2010; **257**: 238–46.
100. Strömberg E, Hagman-Gustafsson ML, Holmén A, Wårdh I, Gabre P. Oral status, oral hygiene habits and caries risk factors in home-dwelling elderly dependent on moderate or substantial supportive care for daily living. *Community Dent Oral Epidemiol* 2012; **40**: 221–9.
101. Thomson WM, Ikebe K, Tordoff JM, Campbell AJ. Dry mouth and medications. In: MacEntee MI, Müller F, Wyatt C, eds. *Oral healthcare and the frail elder: a clinical perspective.* Ames, IA: Wiley-Blackwell, 2010: 51–71.
102. Thorne S, Kazanjian A, MacEntee MI. Oral health in long-term care: the implications of organizational culture. *J Aging Studies* 2001; 15: 271–83.
103. Turner MD, Ship JA. Dry mouth and its effects on the oral health of elderly people. *J Am Dent Assoc* **138**(9 Suppl): 15S–20S. [Erratum: *J Am Dent Assoc* 2008; **139**: 252–3.]
104. US Census Bureau. International data base, October 2013. http://www.census.gov/ipc/www/idb/summaries.html (accessed November 7, 2014).
105. Van Spall HGC, Toren A, Kiss A, Fowler RA. Eligibility criteria of randomized controlled trials published in high-impact general medical journals: a systematic sampling review. *JAMA* 2007; **297**: 1233–40.
106. Vanobbergen J, De Visschere L, Daems M, Ceuppens A, Van Emelen J. Sociodemographic determinants for oral health risk profiles. *Int J Dent* 2010; **2010**: 938–6. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2836788/pdf/IJD2010-938936.pdf (accessed November 7, 2014).
107. Vaupel JW. Biodemography of human ageing. *Nature* 2010; **464**: 536–42.
108. Walls AW, Steele JG. The relationship between oral health and nutrition in older people. *Mech Ageing Dev* 2004; **125**: 853–7.
109. Walls AW, Meurman JH. Approaches to caries prevention and therapy in the elderly. *Adv Dent Res* 2012; **24**: 36–40.
110. Wårdh I, Jonsson M, Wikström M. Attitudes to and knowledge about oral health care among nursing home personnel – an area in need of improvement. *Gerodontology* 2012; **9**: e787–92.
111. White DA, Tsakos G, Pitts NB, Fuller E, Douglas GV, Murray JJ, Steele JG. Adult Dental Health Survey 2009: common oral health conditions and their impact on the population. *Br Dent J* 2012; **213**: 567–72.
112. WHO. *Global status report on noncommunicable diseases 2011.* Geneva: World Health Organization, 2012. www.who.int/nmh/publications/ncd_report_summary_en.pdf (accessed November 7, 2014).
113. Wyatt CC. A 5-year follow-up of older adults residing in long-term care facilities: utilisation of a comprehensive dental programme. *Gerodontology* 2009; **26**: 282–90.
114. Zuanazzi D, Souto R, Mattos MB, Zuanazzi MR, Tura BR, Sansone C, Colombo AP. Prevalence of potential bacterial respiratory pathogens in the oral cavity of hospitalised individuals. *Arch Oral Biol* 2010; **56**: 21–8.

Part V
Operative intervention



19

Classical restorative or the minimally invasive concept?

E.A.M. Kidd, J. Frencken, B. Nyvad, C.H. Splieth, and N.J.M. Opdam

Operative dentistry and caries control

What constitutes the treatment of caries?

Chapters 13–18 have concentrated on the nonoperative control of caries. The point has been made that any lesion, cavitated or noncavitated, provided the pulp is not irreparably damaged, can be controlled and lesion progression arrested by regular disturbance of the biofilm and application of fluoride. This is treatment of caries. Sometimes restorations are part of this treatment.

Why and when are operative treatments (restorations) required?

From a cariological perspective, restorations are required when the patient cannot access the active cavitated lesion with any cleaning aid. Thus, from a caries control point of view, restorations facilitate plaque control.

Cavitated occlusal lesions

Several authors have shown that when an occlusal lesion has turned into a cavity (see Figs 3.37 and 3.39) the dentin is always involved in the process [37, 170]. Most of these lesions are visible in dentin on a radiograph (see Figs 3.38 and 3.40) and they contain microorganisms. They can be considered as active when the dentin is leathery or soft. The histological picture, presented in Figs 5.49, 5.50, and 5.59, shows how the lesions form following the direction of the enamel prisms and when the weakened tissue breaks away, the resulting hole is undercut and difficult to clean and may therefore need a filling. Sometimes all the undermined enamel breaks away and the hole is accessible for cleaning (see Fig. 3.36). Now, a filling may not be required to arrest the lesion.

Approximal surfaces

Where a cavitated carious lesion is present on an approximal surface the adjacent tooth may prevent effective plaque removal by either a brush or dental floss. Now the lesion is likely to progress, although progression may vary depending on individual and local factors [104, 106].Therefore, approximal surfaces should always be examined carefully in the clinic for the presence or absence of cavitation.

A radiograph will not show whether a cavity is present, but several clinical studies conducted since the early 1970s

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

Table 19.1 Clinical studies relating radiographic appearance to cavitation in permanent teeth.

Study	Number and characteristics of subject in sample group	Study design	Percentage of approximal cavitated surfaces found, increasing radiographic depth scores with number in parentheses				
			R0	R1	R2	R3	R4
Rugg-Gunn [142]	370 approximal surface with open contacts in 13-year-old children	Standardized bitewing radiographs taken, followed by direct visual assessment of open contacts (one observer)	0.8% (283)	20.7% (58)	47% (17)	100% (12)	—
Bille and Thylstrup [14]	Children aged 8–15 years, 158 surfaces restored	Clinical assessment during cavity preparation recorded by seven observers	0% (6)	14% (50)	20% (35)	52% (58)	100% (9)
Mejàre et al. [103]	63 teenagers, 598 surfaces in premolar and molar teeth	Teeth radiographed before orthodontic extraction, followed by direct visual inspection (three observers)	1% (463)	11% (16)	31% (13)	100% (6)	—
Thylstrup et al. [165]	660 approximal lesions restored in adults and children	Clinical tissue changes at time of operative treatment recorded by 263 observers	30% (13)	7% (72)	11% (143)	52% (330)	88% (102)
Mejàre and Malmgren [102]	43 children aged 7–18 years	Clinical tissue changes recorded during cavity preparation following tooth separation (one observer)	—	— (28)	61% (32)	78%	—
Pitts and Rimmer [134]	211 children, aged 5–15 years, 1468 surfaces assessed	Visual inspection following tooth separation	0% (1323)	0% (100)	10.5% (19)	40.9% (22)	100% (4)
De Araujo et al. [25]	168 high-school students; standardized radiographs taken	Direct visual examination following tooth separation	—	13% (19)	26% (27)	90% (19)	—
Seddon [152]	Patients aged 6–22 years	Cavity recorded on impression following separation (one observer)	7% (44)	6% (48)	15% (97)	48% (52)	100% (10)
Lunder and von der Fehr [93]	Patients aged 17–18 years	Cavity recorded on impression and stone die made (two observers)	—	—	30% (23)	65% (23)	—
Akpata et al. [3]	108 molar and premolar teeth in patients aged 17–48 years, two adjacent carious surfaces were chosen and the deeper was restored	Direct visual assessment of adjacent surface following tooth separation (two observers)	—	0% (16)	19% (31)	79% (43)	100% (18)
Hintze et al. [69]	390 approximal surfaces in 53 young adults aged 20–37 years	Direct visual assessment of adjacent surface following tooth separation (four observers). Only 16–25 found to be cavitated	3% (n values not given)	5%	8%	35%	78—100%
Ratledge [139]	54 approximal surfaces in 32 adult patients aged 19–76 years, referred for operative treatment	Cavity recorded on impression following separation (one observer)	—	—	—	85% 54	

have related the radiographic appearance to the likelihood of cavitation in permanent teeth. These studies are listed in Table 19.1. Figure 19.1 shows the radiographic appearances referred to in Table 19.1. This research assists the dentist in knowing when a lesion may be cavitated and, therefore, when operative intervention may be a necessary part of caries control. R4 lesions (inner dentin) should always be treated operatively. R3 lesions (outer third of dentin) may or may not be cavitated. At this stage cavitation is more likely in a caries-active patient [93] and when the adjacent gingival papilla is inflamed [38, 140]. Separating the teeth (see Fig. 11.29) will allow gentle use of a probe to confirm whether a cavity is present [69]. R1 and R2 lesions (enamel lesions) are unlikely to be cavitated, and it would be quite wrong to place fillings. These lesions should be treated non-operatively and reassessed for lesion progression or arrest.

Free smooth surfaces

A cavity on a free smooth surface, in contrast to occlusal or approximal cavities, may be easily reached by a toothbrush, although, when the process is undermining the enamel, removing of the overhanging enamel margins by grinding and polishing should be considered to aid cleaning the whole area (Fig. 19.2a and b). This particular figure makes a very important point. The patient, by careful use of the toothbrush and fluoride toothpaste, is arresting the lesions. But how ugly the teeth are! Fillings may not be needed to arrest caries in this case, but they will certainly improve the appearance, as is seen in Fig. 19.2c. This dramatic improvement in appearance, smile, is one of the particular pleasures of restorative dentistry. Patient and dentist are understandably delighted, but it behooves both to remember that the filling restores appearance. It is tooth cleaning and fluoride that are

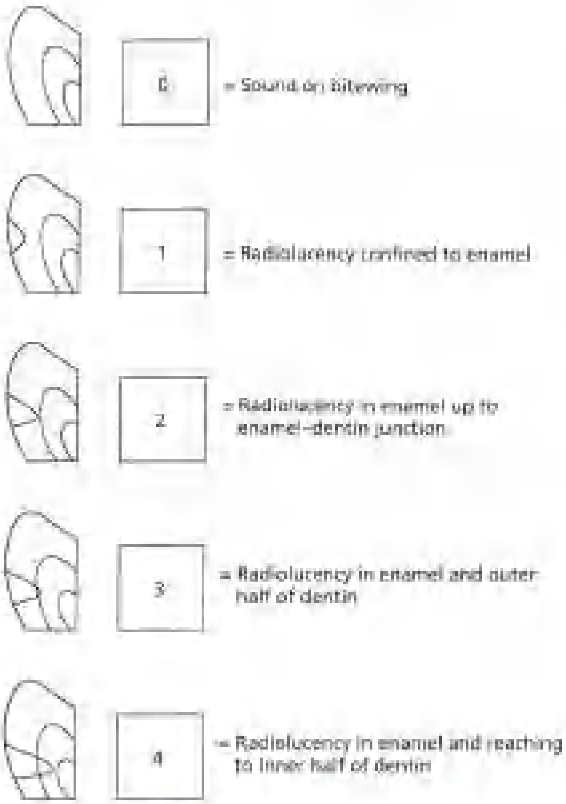


Figure 19.1 Diagrammatic representation of approximal demineralization as seen on bitewing radiographs.

controlling caries and preventing its recurrence. The lesions in Figs 3.47 and 3.48 are not visible when the patient smiles and, here, fillings are not required for cosmetic reasons.

G.V. Black and the classical restorative concept

Now it is time for a little history and the story of a most remarkable dentist, a man who is rightly thought of as the father of modern operative dentistry (Fig. 19.3). That man was an American called Green Vardiman Black, born of pioneering farming stock in Illinois in 1836. Regarded by his family as somewhat lazy and stupid, he left school after only 22 months of formal education. When he was only 17 he left home to study medicine under the direction of an older brother.

He met a dentist and gave up the medical training to study dentistry apprenticed to this dentist in his practice. After a few weeks he felt he had learnt all he could and when only 21 years old he set up in dental practice. He enlisted in the Union army in the Civil War but was invalided out and set up another practice in Jacksonville, Illinois. Here, his prodigious dental career took off; he became a founder member of the Missouri State Dental Association and joined the faculty of the Dental College, lecturing in pathology. He was now practitioner, scholar, scientist, and teacher at work and at home he was father, husband, musician, library president, and much more.

He studied extensively: languages, mathematics, and sciences. He was a friend of W.D. Miller, who worked on the

Figure 19.2 (a) Cervical lesions covered by plaque. (b) Same cavities 14 days later after removing overhanging enamel with a diamond finishing bur and instruction in cleaning. Teeth were brushed twice a day with a toothbrush and toothpaste with fluoride. From a cariological point of view these teeth are now stable, but to improve their appearance they are to be restored with composite. (c) Completed restorations. The small color difference is due to the teeth being dry and will disappear after some hours when they are wet with saliva.

Figure 19.3 Green Vardiman Black, 1836–1915.

chemico-parasitic theory of caries and he also studied bacteriology. He wrote a dental anatomy textbook and worked extensively on the pathology of caries. He devised a dental engine for cutting teeth, wrote articles on cavity preparation and worked on amalgam because he was well aware that the filling material of the day, cohesive gold, was too expensive for many patients. Logically, he designed and made the instruments for cavity preparation and placing materials.

Between 1864 and 1915 he published some 1300 scientific papers and lectures. In 1908 he published his textbook of *Operative Dentistry*, in two volumes, the first devoted entirely to pathology. He was Dean of Northwestern Dental School between 1897 and 1914 and died in 1915, aged 79 years, on the farm in Illinois.

Although thought of as the father of operative dentistry, he is so much more than this. He stressed the extreme importance of pathology [15]:

> *The idea that dental practice is purely mechanical and not dependant on knowledge of the pathology of dental caries should be abandoned forever.*

He described plaque and related the white spot lesion to plaque stagnation, continually stressing toothbrushing to control caries. Interestingly, he stressed the importance of the student studying psychology and sociology. As far as the deciduous dentition was concerned, he emphasized that the child should not be frightened and showed mothers how to brush children's teeth. He lamented he had no suitable filling material for deciduous teeth and opened lesions to allow parents to clean. His aim was to arrest lesion progression. All these gems are to be found in Volume 1, the pathology text, and if at all possible you should look at this remarkable work and consider how much this apparently stupid boy achieved!

As far as operative dentistry is concerned, he stressed the enamel lesion does not require to be cut, but he advocated cutting the lesion in dentin even before there is a cavity. Today, we would totally disagree with this, but Black considered the infection must be cut away to arrest the process, an opinion that unfortunately still prevails in some dental schools. He also advocated *extension for prevention*, which he described as planning the extension of the filling so that cavity margins are placed in cleansable areas to prevent the recurrence of decay. Thus, proximally, the outline prepared extends well into the embrasures so that chewing food results in the food spilling over the margin and removing plaque (so-called self-cleansing) and the patient can clean the margin. Occlusally, the fissure is completely run out, so the filling margin finishes on a smooth cleansable area. At the cervical margin the cavity is extended into the gingival crevice and taken around the tooth so that the outline finishes in the self-cleansed area.

Extension for prevention has no place in modern dentistry. It has been much criticized in recent years as unnecessary tooth destruction, but it must be remembered that in Black's time the prevalence and incidence of caries was much higher and materials were limited to gold, amalgam, and temporary cements; there were no fissure sealants and no adhesive materials.

Minimal intervention concept

The approach of minimal intervention dentistry stresses a preventive, caries control philosophy, just as G.V. Black did when he stressed, time and time again, that caries of enamel could be controlled by toothbrushing. Today, the provision of nonoperative treatments should be based on early diagnosis of lesions judged as active, followed by energetic nonoperative care and reassessment, based on the ability to control caries in both enamel and dentin. The whole aim is to maintain healthy teeth for life, and thus to minimize the need for operative intervention. However, when restorations are required, interventions should be as conservative (minimally invasive) as possible, preserving as much of the natural tooth as possible [58, 169].

Despite best efforts, cutting a tooth will weaken it and a restorative cycle is started once the first restoration is

Figure 19.4 Restoration is not required in this second premolar. The lesions will not be cavitated and can be arrested by cleaning alone.

placed [40]. Restorations should have a good longevity and support, and if possible strengthen the remaining tooth tissue. For these reasons, strong and wear resistant restorative materials should be selected together with adhesive techniques to bond to the tooth–restoration complex.

Unfortunately, recent evidence has indicated that, even when using the most advanced adhesive techniques, bonding of composite resin fillings to dentin may be rather short-lived (see [166] for a review). Therefore, every attempt should be made to avoid premature or unnecessary operative intervention. Ten years ago the premolar in Figure 19.4 was selected for operative intervention in a State Board Examination in the USA. Although this has been called minimal intervention dentistry, because the cavity prepared is small, the editors of this book would call it wanton tooth destruction.

What were the factors behind the change of approach?

Since G.V. Black wrote his 1908 textbook, three factors in particular have facilitated the minimal intervention approach to operative care: a lower rate of caries progression in some countries, increased knowledge of factors that govern the caries process, and the advent of adhesive materials. How G.V. Black would have relished the advent of adhesive materials, tooth colored, and not requiring undercuts (amalgam and cohesive gold) or near-parallel walls (gold inlays) to retain them.

What is happening in your dental school?

Take a few moments to consider what is happening in your dental school. Has the minimal intervention concept, with its emphasis on nonoperative treatment, been embraced? For many years only operative dentistry has been synonymous with caries treatment. Caries was 'treated' by filling holes in teeth. This approach is not valid scientifically, but many of your teachers will have been brought up under this regime, and it is surprisingly difficult to shed this misconception.

It may be useful to consider the following questions in relation to your school and discuss them with your teachers. You are then in a position to assess the attitudes of those who teach you and assess how you are responding.

1. How is cariology taught? Is the course purely lecture based or do those who supervise your clinical work with patients show you how to put science into practice?
2. Are you taught to distinguish and chart active and arrested caries and consider the consequences?
3. Are you routinely expected to assess the risk of your patients developing caries lesions? If you do this, how does it modify your treatment plan?
4. Are you expected to show your patients how to institute effective plaque control? Are toothbrushes and floss available so that you can provide them with cleaning aids appropriate to their needs? Do your teachers encourage this and give you credit for it?
5. Are you encouraged to advise patients on appropriate use of fluoride?
6. Are diet sheets available on your clinic?
7. Do you ever measure salivary flow on your patients? If you do, what do you do with the information?
8. Are all your clinical teachers committed to nonoperative treatment? Do you enjoy doing this form of dentistry or would you rather be doing operative treatment?
9. Is there a points system in your school to assess the quantity of work you carry out? If there is, are points awarded for nonoperative as well as operative treatment?
10. If only operative treatment counts towards these requirements, does this influence your attitude towards nonoperative treatment? Do you feel it is a waste of time?
11. Do you recall your patients over a period of years so you can assess the success or otherwise of the treatment?
12. How do your patients react when you suggest a filling is not needed but you can help them arrest an active carious lesion? Are they pleased? Do you get the impression they wish you to take responsibility and fill the tooth? What are they expecting from you?

Sealants

Occlusal sealants

Introduction

Sealing of caries-affected pits and fissures was prompted by the development of adhesive techniques that allowed difficult-to-clean surfaces to be effectively sealed off from the metabolic actions of the biofilm. At that time, in the early 1970s, caries progression rates were still high in most

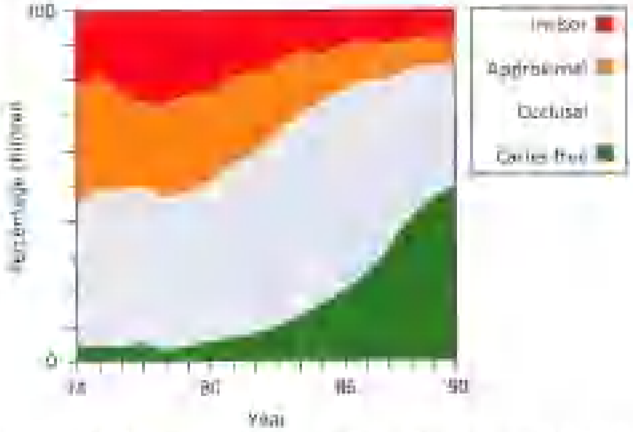


Figure 19.5 Distribution of 12-year-old Danish children according to caries severity 1974–1991. Note the caries decline over these years and how occlusal caries has not declined as much as approximal and incisor caries. Adapted from [150].

industrialized countries, and a 'preventive' approach sealing all erupting permanent molars resulted in a significant caries preventive effect of up to 50% [1, 105]. Today, after the caries decline, it is questionable whether such 'preventive' use of sealants is justified [1, 159]. Thus, although occlusal surfaces continue to carry the main burden of caries in low-caries populations [100, 150, 159] (Fig. 19.5) and may comprise up to 70% of the total caries experience in children and adolescents [16], we do not have scientific evidence to prove how different caries levels may influence the effectiveness of an occlusal sealant. Although pit and fissure sealants are superior to other commonly applied caries-controlling measures such as fluoride varnish applications [68], we do not know if this holds true in low-caries-risk children. Therefore, until such information is available, and for reasons of cost effectiveness [86], it seems sensible to advocate the use of occlusal sealants mainly for 'therapeutic' purposes in active noncavitated lesions that have failed to respond to caries control by conventional nonoperative procedures [56, 159]. Purely 'preventive' sealants might occasionally be indicated in high risk individuals or groups of individuals with difficult social circumstances and/or poor compliance. In any case, sealants should always be accompanied by intensive preventive efforts to control the overall caries activity of the patient.

One of the reasons for the high caries levels of occlusal surfaces is that the fissure is difficult to clean, especially during eruption. Although caries does not normally develop in the deepest parts of the groove–fossa system (see Chapter 5, Fig. 5.53), the entrance to the fissure offers favorable conditions for plaque accumulation, and hence caries initiation [18]. To make matters more difficult, permanent molars may take 1–2 years to erupt. During this time, they do not reach the occlusal plane, and conventional brushing results in insufficient plaque removal. For all these reasons, blocking this area with a sealant seems logical. However, it is important to realize that sealants alone do not reduce the caries activity and that sealant application is a sign that plaque control was insufficient. Other sites in the dentition, where plaque removal is also inadequate, remain prone to caries because the local cariogenic environment has not been changed. In an observational study on the success of sealants performed by general practitioners in Germany, children judged to have a high caries risk due to existing fillings or carious defects exhibited high caries rates on occlusal surfaces in molars despite the use of sealants [67].

In Chapter 13 an alternative to the sealant approach is described in a Danish study (the Nexø study [18, 19]) that chooses a more etiologically based approach of controlling occlusal caries. They trained children and parents to brush the erupting molars by bringing the brush in at right angles to the arch so that it is possible to disturb the dental plaque despite the tooth not having reached the occlusal plane. Sealants were only indicated when this nonoperative approach failed and early lesions were diagnosed. This program resulted in minimal caries levels of 0.23 DMFS in 12-year old children with very low rates of sealants application [36].

In summary, sealants are mostly indicated when active noncavitated caries lesions in pits and fissures cannot be controlled by adequate plaque control, specifically during the stages of tooth eruption when cleaning is more difficult. Preventive sealants might occasionally be indicated in high-risk individuals or groups of individuals with difficult social circumstances and/or poor compliance. In any case, application of sealants should always be accompanied by additional preventive measures to reduce the caries activity.

Materials

Fissure sealants are either resin or glass–ionomer cement-based materials. The caries-preventive effect relies upon the establishment of a tight seal to prevent plaque formation. The differences in the success rates of these two materials have been debated over the last decade [101]. Resin-based sealants require strict moisture control to ensure bonding using the acid etch technique. Glass–ionomer materials, on the other hand, are mineral based and adhere to the tooth surface chemically. Their mechanical properties are inferior to the resin-based sealants, resulting in lower retention rates, particularly if low-viscosity glass–ionomers are used [89, 154]. For this reason, resin-based sealants were sometimes considered the materials of choice [1]. However, high-viscosity glass–ionomers are now the glass–ionomer of choice because their retention rates have increased tremendously [20].

Several studies have suggested that glass–ionomer cements exert a cariostatic effect even after they have disappeared macroscopically. This might be based on remnants of the cement in the fissure, blocking the deeper parts and

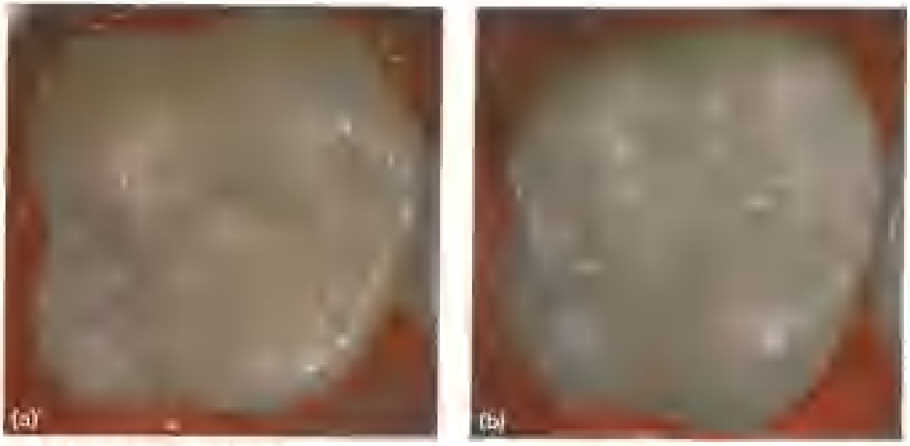


Figure 19.6 Glass-ionomer sealant in an erupting tooth: (a) demineralized enamel in tooth 2.6 of a 7-year-old girl; (b) occlusal surface sealed with Fuji IX GP Extra®. Courtesy of Dr S. Leal.

allowing more efficient plaque removal [51], as well as increased levels of fluoride ion released from the material into the local environment [45, 128]. Nevertheless, with respect to caries prevention, systematic reviews [2, 10, 110, 178] concluded there were no consistent differences in outcomes between the two materials.

Despite this, there is one situation where the use of glass-ionomer cement is preferable and that is for erupting teeth where isolation from saliva during sealant placement is a problem [176] (Fig. 19.6). The risk of caries in occlusal surfaces of permanent molars is always highest during eruption [145], especially in high caries individuals. In such conditions, a high-viscosity glass-ionomer cement seems to achieve better retention rates, and retention can be further improved by applying the material with finger pressure [11, 53].

Techniques for resin-based sealants

Moisture control is essential to achieve a bond. The use of rubber dam facilitates this, but its application may not be possible in the erupting tooth. There is some evidence that careful isolation with cotton wool rolls, together with skilled use of the suction tip and air/water spray, gives similar results to rubber dam in terms of retention [67, 95, 176]. After cleaning the tooth with a pointed bristle brush and cleaning paste, the surface should be etched with 37% orthophosphoric acid for 15 s (Fig. 19.7a). Further etching may not result in better outcomes [35, 175]. The etching pattern should be checked for a chalky-white appearance after drying (Fig. 19.7b). Any exposure of the etched surfaces to saliva will reduce the retention of the sealant by forming a coating that cannot be removed by rinsing. In case of saliva contamination, the tooth should be thoroughly rinsed, dried, and re-etched before proceeding.

The bottle with the resin sealant material has to be shaken before application to mix all the components. This leads to the inclusion of air bubbles, which stay in the bottle when it is allowed to settle for a minute upside down. The material should be applied with a small brush or small instrument (Fig. 19.7c), which allows a controlled infiltration and avoids overfilling the fissure. After light-curing (Fig. 19.7d), the occlusion should be checked and premature contacts should be removed (Fig. 19.7e).

Technique for glass–ionomer sealant

After cleaning pits and fissures with cleaning paste and pointed brush, the surface is conditioned for 10–15 s with a conditioner, usually a polyacrylic acid. This is followed by washing the conditioner off the tooth surface and drying it with a dry cotton wool pellet. Drying with an air spray is not permitted as it dehydrates the surface and reduces the chemical bond of glass–ionomer to enamel. Then the mixed glass–ionomer (hand-mix powder–liquid) or a material extruded from a capsule is applied to the pits and fissures and pressed down using an index finger coated with petroleum jelly (see Fig. 19.11f). The occlusion is checked in the normal way using articulation paper and excess material should be removed with an excavator rather than with rotary instruments. This is because the sealant has not reached its final hardness and a drill would abrade too much sealant material. Occlusion of sealants in erupting teeth cannot be checked in this way. Hence, a sealant should only cover the deeper parts of the pits and fissures system. To protect the water balance in the newly placed glass–ionomer sealant and to further increase its hardness for a certain time, the glass–ionomer surface is protected with a thin layer of petroleum jelly.

Outcomes

Well-conducted randomized clinical trials have described a high caries-preventive effect of sealants in first permanent molars. However, these trials were performed with strictly

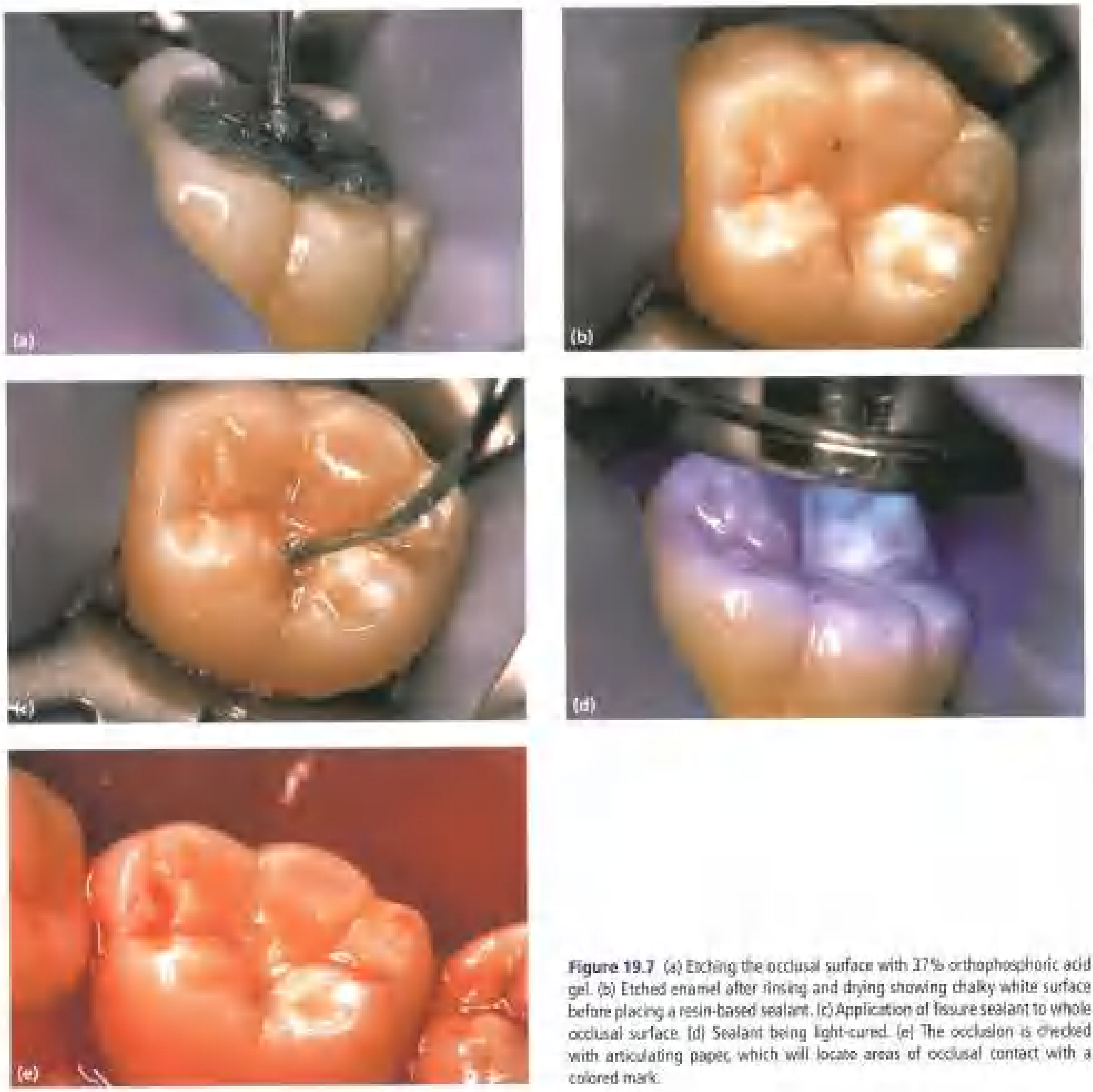


Figure 19.7 (a) Etching the occlusal surface with 37% orthophosphoric acid gel. (b) Etched enamel after rinsing and drying showing chalky white surface before placing a resin-based sealant. (c) Application of fissure sealant to whole occlusal surface. (d) Sealant being light-cured. (e) The occlusion is checked with articulating paper, which will locate areas of occlusal contact with a colored mark.

controlled designs, by highly motivated researchers, who applied sealants under optimal conditions, on patients likely to keep the essential recall appointments. Thus, the studies on which the systematic reviews are based show the very best results that can be achieved (efficacy). Despite the ideal conditions, the trials show a wide range of caries reduction (33–71%) [101].

In the real world of general dental practice, the outcomes (effectiveness) may differ from these ideal situations. Field studies allow a more realistic picture of the situation when sealants are introduced as a population-wide preventive measure. In a German observational study, sealants that had been placed by general practitioners under the conditions of the National Health System on first permanent molars were recorded at 12 and 15 years of age. The mean annual rates of loss of retention and caries (6% each) were much worse than figures coming from randomized controlled clinical trials [67]. Thus, the prevented traction

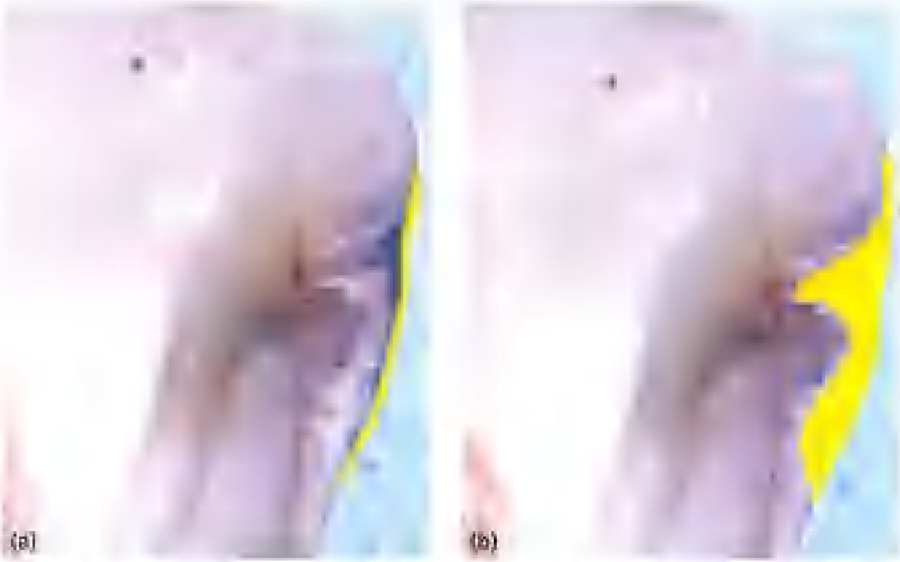


Figure 19.8 Differences between a sealed and an infiltrated caries lesion. While an approximal sealant, colored yellow, covers the surface (a) caries infiltration aims to fill the microporosities within the caries lesion (b) [39]. Reproduced with permission of George Warman Publications.

and the cost/benefit ratio of sealants are potentially reduced in the real world. Likewise, it may be speculated that glass-ionomer sealants are more successful than resin sealants in the real world, but we do not have much scientific evidence to support that assumption.

How long should sealants last?

The placement of a sealant should be considered a modification of a rough surface into a smooth one, facilitating plaque removal. The sealant is placed in first instance because the child and parents have been shown to be insufficiently capable of controlling caries lesion development. The placement of sealants and restorations should to go hand in hand with education on how to maintain healthy teeth. Good education will yield success and reduce the need for the sealant to aid plaque control after a while. In many countries, caries prevalence and experience has dropped and has been low and stable for many years.

Sealants degrade over time, and the dental practitioner should check the sealant regularly for unwanted plaque stagnation in areas where the material may have fractured. Based on the perceived caries risk of the particular child, previously sealed pits and fissures should either be resealed (high caries risk) or the partly retained sealant be made plaque stagnation free (low caries risk), using a drill. It is to be hoped that, over time, plaque control will improve, and if a sealant lasts for, say 5 years, it should not be necessary to continually replace it. Hopefully, it will have served its purpose of tiding the child over a period of poor plaque control.

Approximal sealing and infiltration

Although occlusal caries lesions predominate in children and adolescents, these surfaces are accessible for cleaning, fluoride application, and minimally invasive restorations. On approximal surfaces, however, caries is more difficult to detect, and preventive and restorative efforts are more complicated to perform [97]. Even at high levels of caries control, approximal surfaces remain an important site where caries lesions develop [7].

Caries progression in approximal surfaces tends to be rather slow, especially in permanent teeth [106, 149]. Initial caries lesions and fillings constituted 86% of the total caries experience [7]. These figures should encourage nonoperative approaches and monitoring with careful clinical inspection and occasional bitewing radiographs. However, cleaning of approximal surfaces is demanding, and the effect of self-performed use of dental floss is questionable (Chapter 15). Therefore, alternative preventive measures may be needed for proximal surfaces. This concept has resulted in the development of either sealing or infiltration techniques for approximal surfaces. Figure 19.8 illustrates the difference between the two. When lesions are sealed, a layer of resin is applied to cover the lesion, following the same principle as used in sealing occlusal lesions. In infiltration techniques, a strong acid (hydrochloric acid) is used to etch and remove part of the surface layer of the lesion to make it permeable to the infiltrating resin [108]. Now the resin is applied and penetrates the lesion [129].

The *sealing technique* (Fig. 19.9) uses conventional resin-based sealants for noncavitated lesions. A 2-year clinical

Figure 19.9 Approximal sealing of a D2 lesion on distal surface of tooth 24: (a) radiograph; (b) application of a rubber ring for separation; (c) removal after 4-5 days, cleaning and inspection of the lesion to insure noncavitation; (d) rubber dam isolation, etching of proximal surface and application of sealant or adhesive patch; (e) final polish.

trial compared sealing on one side of the arch with fluoride varnish application on the other. Results showed no difference in progression between the two groups [60]. A subsequent study [96] used a slightly different protocol. Teeth were separated with orthodontic rubber rings for a few days. This allowed an accurate diagnosis of the caries lesions and facilitated sealant application. The contra-lateral control side was managed with self-performed flossing at home without additional fluoride applications. The sealing technique was superior to instructing patients to floss in a population with considerable caries progression. In a low-caries population, however, regular recalls, professional fluoride varnish applications, and self-performed flossing at home lead to the same low caries progression as contra-lateral approximal sealants [6]. Sealing approximal lesions is difficult owing to problems in controlling the sealant material [146]. To aid application, a pre-cured adhesive patch has been tried [6].

Figure 19.10 Resin infiltration after etching and drying: a foil applicator is in place to allow accurate placement of the etchant and protect the adjacent tooth. This is removed after etching, the tooth washed, ethanol applied, and thoroughly dried. Now a new foil applicator is inserted and the infiltrant applied. The foil is now removed, the tooth dried with compressed air, and the infiltrate light-cured.

The *caries infiltration* approach (Fig. 19.10) uses a highly hydrophobic resin material and requires absolute moisture control, using rubber dam and alcohol evaporation. A 3-year study showed 4% of treated lesions progressed on radiograph compared with 42% of control lesions [108]. In a 3-year clinical trial comparing infiltration with sealing, both techniques were significantly better than placebo treatment in controlling caries progression of proximal lesions, but there were no significant differences between them [98]. The sealing and infiltration techniques have yet to be evaluated in general practice.

Indications and reservations

Sealing and infiltration techniques are difficult to perform and expensive of materials and surgery time. Moreover, sealed and infiltrated lesions cannot be detected on bitewing radiographs, and this makes it difficult to monitor such lesions in the clinic. For these reasons they would not be applied as a purely preventive approach, but possibly used for active approximal noncavitated lesions, which have a considerable risk of progression. Their use in clinical practice has to be monitored on a long-term basis and, as in all sealant programs, must be accompanied by cost–benefit analyses.

Where caries control measures, including sealants, have been unable to arrest lesion development and a cavity in dentin has formed that the patient cannot clean, some form of restoration is required to facilitate plaque control and restore the function of the cavitated tooth. A number of such approaches are now presented starting with the most minimally invasive one.

Atraumatic restorative treatment

Definition and history

Atraumatic restorative treatment (ART) is a minimal intervention approach to both preventing dental caries and arresting its progression. It consists of two components: sealing caries-prone pits and fissures, and restoring cavitated dentin lesions with sealant-restorations [48]. The placement of an ART sealant involves the application of a high-viscosity glass–ionomer that is pushed into the pits and fissures under finger pressure. An ART restoration involves the removal of soft, decomposed, carious tooth tissue with hand instruments. This is followed by restoration of the cavity with an adhesive dental material that simultaneously seals any remaining pits and fissures that remain at risk. The restorative material recommended in 2014 for use with ART is a high-viscosity glass–ionomer, preferably one that has been tested in clinical studies and has been found to provide high survival rates. Resin-modified glass–ionomer has also been used as the restorative material with ART in a pilot study, showing high survival results [42].

ART was initially developed in response to the need to find a method of preserving decayed teeth in people of all ages in both developing countries and disadvantaged communities where resources such as electricity, piped water, and finance were scarce. Without this intervention, such teeth would decay further until they were lost through extraction. The approach that ultimately became known as ART was pioneered by JE Frencken in the mid 1980s as part of a community oral health care program of the Dental School in Dar es Salaam, Tanzania. To support the newly established dental school, western donors had given 'mobile' cast-iron dental chairs, and drill and suction devices. To become operational in rural Tanzania this equipment required an electrical generator, petrol, and a vehicle to transport it. Unfortunately, it became apparent that the community oral health care training in the dental school, based on the donated 'mobile' equipment, was impractical.

So, what should be done? Students needed to be trained in community dentistry and there was much dental decay causing pain and suffering in rural Tanzania. Drastic changes were needed: thinking 'outside of the envelope' was required.

The first step taken was an investigation into the types of hand instruments available in clinics in rural Tanzania and their suitability to further open small tooth cavities and to widen bigger ones. Cavities prepared with these instruments and filled initially with zinc phosphate cement and later with polycarboxylate cement showed promising results. In a number of restorations the polycarboxylate cement was visibly abraded away, but the main outcome was that all people were free of toothache. The enthusiastic patient response and the apparent success of this restorative technique were encouraging. The results of the pilot study were presented at the scientific meeting of the Tanzanian Dental Association in 1986, and the ART approach was born.

Based on the encouraging results of the pilot study, a field study was started in Tanzania where a permanent restorative material, a medium-viscosity glass–ionomer cement, was used instead of polycarboxylate cement. Unpublished results indicated a high level of restoration retention and a low level of occlusal abrasion of the glass–ionomer after 3 years. The breakthrough for ART came during the first major clinical trial in which the ART approach was compared with the traditional amalgam approach in rural Khon Kaen, Thailand, in the early 1990s [52, 132]. This study gained attention from world leaders in oral health and resulted in the adoption of ART by the World Health Organization on World Health Day in 1994. Since this time ART has been scientifically evaluated in various parts of the world using improved materials and methods. The rationale for using ART sealants and ART restorations will now be discussed.

Fissure sealing and minimal operative intervention

Atraumatic restorative treatment sealants

The technique of applying an ART sealant does not differ much from that of glass–ionomer sealants (see "Technique for glass–ionomer sealant" section and Fig. 19.11). ART sealants can be applied in an out-of-surgery environment because no electricity and running water are required. The pits and fissures are cleaned by running an explorer through them, after children have cleaned their teeth with toothbrush and fluoridated toothpaste. Isolation is ensured using cotton wool rolls. If a powder–liquid high-viscosity glass–ionomer is used, ensure that the mixing process is carried out according to the manufacturer's instruction. Excess glass–ionomer is removed with an applier/carver and/or a medium-size excavator. In out-of-surgery environments, it may not be practical to reassess ART sealants for many years. Although it looks easy to apply an ART sealant, the practitioner should carefully acquire the necessary skills.

The ART sealants using high-viscosity glass–ionomers are usually placed under finger pressure. The fissure penetration depth and marginal leakage of ART glass–ionomer sealants were not different from those obtained using a resin-based sealant material [155]; neither were they different when the glass–ionomer was inserted with a ball-ended burnisher compared with finger pressure [11]. If applied properly and retained for a substantial period, ART sealants have a long-lasting caries-preventive effect. The failure rates of ART high-viscosity glass–ionomer and resin sealants after 3 years were 1.7% and 1.1% respectively [21]. After 5 years the difference was 3% and 15% respectively [12], and no significant difference was reported in initially erupting molar teeth between the two types of sealants after 5 years [9].

Atraumatic restorative treatment restorations

When the lesion has progressed into the dentin and a frank cavity is present that the patient cannot clean, a restoration may be required to facilitate plaque control. The selection of cases for ART is not different from those selected for conventional restorative treatment. A proper diagnosis, in all cases, is of paramount importance. The minimum opening of a sizable dentin lesion in an occlusal surface that is indicated for treatment with ART was estimated to be 1.6 mm in diameter [117]. Cavities with a very small opening may pose difficulties. Experience has shown that hand instruments fail to access very small cavitated dentin lesions, particularly those in the buccal pit of lower permanent molars. The approach in these circumstances is to open the cavity as much as possible, remove all debris and the biofilm, and cover the dentin lesion and pits and fissures with a high-viscosity glass–ionomer ART sealant. The systematic review on sealing over carious lesions [61] and that on the fate of microorganisms left behind when sealants are placed over carious lesions [122] support this treatment (see Chapter 20).

Cavity cleaning

The rationale for the use of hand instruments for cavity cleaning with ART is based on tooth anatomy and the nature of the caries process. In enamel carious lesions the demineralization follows the direction of the enamel prisms. It is of particular interest to look at the direction of the enamel prisms in relation to occlusal and approximal surfaces, since these differ. In occlusal lesions, the direction of the enamel prisms results in the carious cavity being narrower at its opening than in its deeper aspects, giving it a pyramidal-shape (Fig. 19.12). Further progression of the carious lesion results in demineralized enamel that is either unsupported or poorly supported by the underlying dentin (Fig. 19.12). This enamel can easily be fractured using hand instruments, creating an opening large enough for excavators to enter and remove decomposed dentin. Knowledge of this process and the recognition of the different stages of enamel and dentin demineralization *at the tooth surface* are essential in applying the ART approach properly (Fig. 19.13). There is no need to remove all unsupported enamel, only that which is required for access or which is thin and prone to fracture (Fig. 19.14). A dental hatchet, a gingival margin trimmer or pyramidal-shaped instrument designed specifically for this task (enamel access cutter) can be used (Fig. 19.15). In approximal lesions, the direction of the prisms does not lead to a pyramidal-shaped lesion, and access can sometimes be diffi-

Figure 19.11 ART sealant step by step using a high-viscosity glass–ionomer (Fuji IX, capsulated). (a) Tooth 46 with a pit and fissure system that required a sealant protection. (b) Remove debris from the pits and fissures with a sharp probe. (c) Condition the occlusal surface and pits and fissures with a cotton wool pellet, dipped in polyacrylic acid. (d) Wash the occlusal surface and pits and fissures with a wet cotton wool pellet. (e) Dry the occlusal surface and pits and fissures with a dry cotton wool pellet. (f) Press the glass–ionomer mixture into the pits and fissures with the index finger. (g) Remove finger after 10–15 s. Mixture has been pushed towards the periphery of the occlusal surface. (h) Check the bite. (i) Remove excess glass–ionomer material with hand instruments. (j) Apply a layer of petroleum jelly over the ART sealant. (k) Ask the patient not to eat for at least 1 h. Courtesy of Dr S. Leal.

Figure 19.12 A small cavity opening with partly demineralized enamel. The destruction at the enamel–dentin junction is wider than at the cavity opening, giving the lesion a pyramid shape. Courtesy of Dr E Verdonschot.

Figure 19.13 A cavitated dentin lesion in the occlusal surface of the first molar. Note the whitish coloring around the lesion opening. This is a sign of partly demineralized enamel that will easily fracture off after slight pressure with a dental hatchet (see lines of cleavage, Fig. 19.12). In doing so, the cavity opening will increase in size and will allow easy access to the excavator for removal of infected dentin. Also note the cavitated lesion in the buccal surface. Courtesy of Dr B Monse.

cult if attempted through the marginal ridge. For the same reason, it is also difficult to open small cavities in buccal pits and fissures with hand instruments, as previously discussed. If too much force needs to be applied to open a cavity further and a rotary handpiece is not available, it is better to place an ART sealant. In a conventional dental clinic a rotary handpiece should be used to open the cavity further if hand instruments fail to do it. An appropriate amount of demineralized dentin is now removed with an excavator, as discussed in Chapter 20.

Figure 19.14 Further opening of a cavitated dentin lesion using a hatchet. (a) Look at the enamel buccal to the lesion: it is demineralized and very thin. (b) Place the dental hatchet at the edge of the cavity opening and press slightly. (c) The enamel has now fractured. Continue removing enamel that is demineralized.

Figure 19.15 Small cavitated dentin lesion in a lower first molar. (a) The enamel access cutter is used to further open the cavity. (b) The end of this pyramidal-shaped instrument is placed in the cavity opening and the instrument is turned anticlockwise several times, grinding down the thin enamel that forms the opening.

Atraumatic aspects

Why was the caries management approach using hand instruments termed *atraumatic restorative treatment*? At the 6 months evaluation of the Thailand study in 1992 it became very apparent that the children that had been treated by ART happily participated, whereas those treated by the conventional rotary handpiece approach were very reluctant to do so. Many of these latter children ran away when they saw the operators, thinking that they needed to be treated again. On asking children of both groups how they had remembered the treatment from 6 months previously, it became clear that there was a high level of acceptance by those treated using ART and an unwillingness to be treated again by those in the traditional rotary handpiece group. Hence, the term *atraumatic* was adopted, not only because of its low level of pain or discomfort, but also because of its minimal destruction of tooth tissue. Later on, after many dentists reported feeling more relaxed when carrying out ART restorative procedures, 'reduction of operator stress' was added as a third reason for using the term *atraumatic*.

Table 19.2 Overview of studies that compared dental anxiety and dental pain between the ART and the conventional treatment approach [59]

Reference	Comparison	Age	Operator background	Variable measured	Conclusion
Schriks and van Amerongen [148]	ART vs rotary instruments	6-yr-olds	Dental students and dentists	*Discomfort*, heart rate and modified Venham index (observations)	ART caused less discomfort
Rahimtoola *et al.* [138]	ART vs rotary instruments	6–16-yr-olds	Dentists	*Pain*: Questions: did you feel any pain during treatment?	ART caused less pain
De Menezes Abreu *et al.* [28]	ART vs rotary instruments	4–7-yr-olds	Pedodontist specialist	*Pain*: Wong–Baker FACES pain rating scale	ART caused less pain
De Menezes Abreu *et al.* [29]	ART vs rotary instruments vs ultraconservative treatment	6–7-yr-olds	Pedodontist specialist	*Pain*: Wong–Baker FACES pain rating scale	No difference in levels of pain among treatments. Local anesthesia was more frequent given in the rotary instrument group
Topaloglu-Ak *et al.* [167]	• ART vs rotary instruments • ART vs ART with chemo-mechanical gel	6–7-yr-olds	Pedodontist specialist	*Anxiety*: Venham picture test	No difference in levels of anxiety between treatments
Mickenautsch *et al.* [110]	ART vs rotary instruments	Children and adults	Dentists and dental therapists	*Anxiety*: Children's fear survey schedule Corah's dental anxiety scale	Both children and adults treated with the ART were less dental-anxious
De Menezes Abreu *et al.* [30]	ART vs rotary instruments vs ultraconservative treatment	6–7-yr-olds	Pedodontist specialist	*Anxiety*: Facial image scale	No difference in levels of anxiety among treatments

Reproduced with permission of Springer Science + Business Media.

Dental anxiety and dental pain with atraumatic restorative treatment

Analysis of clinical trials that have compared patients' comfort and level of anxiety during ART in comparison with the conventional approach show no consistent trend (Table 19.2). Some studies report less pain and anxiety with ART, and others do show no difference compared with traditional rotary-driven treatment. Students should note this table is not here for you to memorize it, but it shows that much careful evaluation of ART has been published.

Local anesthesia with atraumatic restorative treatment

Local anesthesia is still a normal part of contemporary practice, particularly when using rotary equipment. It is now generally accepted that local anesthesia is seldom required when using hand instruments (ART) to manage dental caries [72, 171]. This reduces dental anxiety in children and may reduce the level of stress in dentists when treating children.

Tooth tissues saving with atraumatic restorative treatment

It is obvious that hand instruments, unlike rotary instruments, have a limited ability to remove sound tooth tissue. It is no surprise, therefore that single-surface cavities prepared by hand instruments were significantly smaller in size than those prepared through rotary instrumentation [137]. It has also been reported that surfaces adjacent to cavitated approximal surfaces are usually severely damaged when the cavity is instrumented with a bur unless the adjacent surface is protected [94, 116, 135], even to the extent that the iatrogenic damage was considered a caries risk factor [135]. Iatrogenic damage to approximal surfaces of neighboring teeth in the process of treating class II lesions has also been reported using hand instruments [84]. However, scratches were small compared with the damage caused by the use of a bur.

It can be concluded that the 'atraumatic' of ART implies an approach that causes little or no pain/discomfort to the patient even without anesthesia, which removes only useless tooth tissue and which minimizes damage to adjacent tooth surfaces when compared with the use of rotary instruments.

Restorative materials used with atraumatic restorative treatment

The definition of ART includes the use of all adhesive restorative materials and adhesive systems. However, in practice, most ART studies have used glass-ionomer cement, although resin-based materials have also been used. The type of glass-ionomer currently recommended is a high-viscosity one (powder to polyalkenoate liquid ratio

≥3.4:1.0). Medium-viscosity glass–ionomer (powder to polyalkenoate liquid ratio between 2.1:1.0 and 3.3:1.0), available at low prices in many countries, should not be used, as the survival rates of ART restorations and ART sealants using this type of glass–ionomer are significantly lower than those using high-viscosity glass–ionomers [173]. In addition, it is advisable to use a high-viscosity glass–ionomer that has been tested in clinical studies of long duration. There are manufacturers that have advertised their high-viscosity glass–ionomer for use with ART without having that material put to the clinical tests. Clinicians should be aware of this situation. A well-cleaned cavity can result in a poor restoration when a substandard high-viscosity glass–ionomer is inserted.

A high-viscosity glass–ionomer is marketed in a powder–liquid form and in capsules. The quality of ART sealants and ART restorations is compromised when less than the required amount of powder is used to produce the mixture [33]. A 50% reduction in the required powder per drop of liquid reduced the compressive strength of the mixed high-viscosity glass–ionomers by 50%. This is unacceptable. Therefore, dentists using hand-mixed glass–ionomers should ensure that all powder is incorporated into the liquid; there is no compromise here. It is unethical for a professional to be sloppy in mixing glass–ionomers. However, producing a good mixture regularly is not always easy. Therefore, it is necessary for the dental team to be trained in this procedure before placing glass–ionomers. In the dental practice, encapsulated high-viscosity glass–ionomers can be used, which, in general, have better mechanical properties than the hand-mixed ones [34, 114].

The atraumatic restorative treatment approach step by step using high-viscosity glass–ionomer

Equipment required

Unlike traditional dental treatment, only basic dental equipment is required for the ART approach. This meant that the approach can be used in many different environments, although the precise equipment may be dictated by the working conditions. These can loosely be divided into the use of ART in a well-equipped dental clinic and ART placed in outreach situations, such as in schools or homes. The basic equipment includes an appropriate support for the patient and for the operator, a source of intraoral lighting, dental instruments, restorative materials, and other relevant consumable materials.

Dental instruments and consumable materials

The instruments used in the ART approach have been carefully selected and are based on the steps involved in placing an ART restoration or ART sealant. No instrument surplus to the essential requirements is used. Almost all the instruments are those commonly found in dental surgeries and are readily available from most dental instrument suppliers. The essential instruments are a mouth mirror, a probe, tweezers, a dental hatchet, an enamel access cutter, excavators, and an applier/carver (Fig. 19.16). ART instruments are available through companies like Henry Schein, Hu-Friedy, and Duflex. Dental practitioners should buy quality instruments made of hard steel that keeps the working part of the instruments sharp for long periods. If the working end of an instrument has become blunt, it needs to be sharpened. In the dental clinic, the suction device can be used to isolate the tooth requiring attention. The consumable materials required include cotton wool rolls, cotton wool pellets, petroleum jelly, tumbler/cup, wooden wedges, matrix bands or plastic strip, articulation paper, and the glass–ionomer cement.

Figure 19.16 A set of ART instruments consists of a mouth mirror, an explorer, a pair of tweezers, an enamel access cutter, a dental hatchet, excavators (small and medium size), and an applier/carver.

Atraumatic restorative treatment sealant and restoration protocols

In order to achieve optimal outcomes it is essential that all the necessary steps be followed. These are presented in Figs 19.11 and 19.17.

Operators

The reader may have gained an idea that providing ART sealants and ART restorations is simple and easy to learn. However, experience of teaching ART courses to groups of dentists and dental therapists in many countries has shown this is not the case. There is a profound need for an understanding of modern cariology and the dynamics of the caries process in addition to the chemistry and proper handling of glass–ionomers in order to operate effectively and appreciate the advantages of ART. It has also been noticed that many dentists and dental therapists, independent of age, need to practice the techniques under supervision. It boosts their confidence as they learn to treat cavitated dentin lesions they

Figure 19.17 ART restoration of a dentinal lesion, step by step. (a) Notice the discoloration around the cavity opening, which indicates that the caries has extended under the enamel. This unsupported enamel is demineralized and will break off easily under slight pressure (see Chapter 5 and Fig. 19.12). (b) Opening of cavity further for improved access with the blade of the hatchet. (c) Caries removal using a small excavator. (d) The conditioner is applied in the cleaned cavity and pits and fissures with a cotton wool pellet. (e) Carefully dried cavity before placing the filling. (f) Incremental cavity pits and fissures are filled with glass–ionomer cement. (g) Firm finger pressure is applied over the occlusal surface. This is called 'press-finger technique'. (h) Excess filling material visible at the outer margins of the occlusal surface. (i) ART restoration after the bite has been adjusted. The filling material is not yet covered with petroleum jelly. (j) Completed restoration. The cavity is filled and the pits and fissures are sealed. Courtesy of Drs J. Frencken and C. Holmgren.

previously considered unrestorable without use of a drill and a modern surgery. ART courses also contain information on the nonoperative management of dental caries, evidence-based results of oral health procedures, and how to manage failed ART sealants and ART restorations. Therefore, an ART course can last up to 5 days depending upon the previous experience of the participants.

Effectiveness of atraumatic restorative treatment sealants and restorations

This will be considered in Chapter 21. To summarize the results of many clinical trials, it can be concluded that:

- ART sealants have a high caries-preventive effect.
- ART using high-viscosity glass–ionomer can safely be used in single-surface cavities in both primary and permanent posterior teeth.
- ART using high-viscosity glass–ionomer cannot be routinely used in multiple-surface cavities in primary posterior teeth.
- Insufficient information is available for conclusions about ART restorations in multiple surfaces in permanent posterior teeth and anterior teeth in both dentitions.

Causes of failure of atraumatic restorative treatment restorations

ART restorations fail for the same reasons as restorations produced using other materials. Evaluation criteria aim to assess the mechanical condition of the restoration over time as well as the biological condition of the remaining tooth tissue. The mechanical condition is partly dependent on the physical properties of the restorative material and partly on its handling by the operator. There are a number of reasons why glass–ionomer material can become dislodged:

- insufficient removal of demineralized enamel and decomposed dentin;
- improper mixing of the glass–ionomer powder–liquid;
- level of humidity and temperature of mixing glass–ionomer;
- incomplete filling of the cavity with hand-mixed glass–ionomer;
- saliva and/or blood contamination;
- insufficient or no conditioning of the cleaned tooth cavity;
- level of cooperation of the child.

Insufficient fracture toughness of the glass–ionomer in multiple-surface restorations is thought to be the reason for the high percentage of dislodgement of multiple-surface ART restorations in primary teeth [86, 87, 163]. The mechanical properties of high-viscosity glass–ionomers can be increased further by applying heat during the setting procedure using a high-intensity LED curing light unit [115]. This increased fracture toughness *in vitro*, and clinical trials are planned.

The operator appears to be a major factor in the survival of ART restorations. Where studies have evaluated four or more operators [54, 55, 57, 137, 163], some were found to perform worse than their colleagues. The operator effect seems to indicate that the dentists and dental therapists require skill, diligence, and comprehension in order to perform quality ART restorations [62]. For this reason, it is mandatory to follow an ART training course before applying ART in the field and clinic.

Atraumatic restorative treatment in the elderly

From its onset, one of the indications for the appropriate use of the ART approach concerned the elderly, particularly those living in institutions and those who are homebound. Unfortunately, very few studies have investigated the potential of ART in providing dental care to these people. The first such study was carried out on people in their seventies who were homebound because of physical, mental, or emotional problems [71]. The majority of carious lesions present were so extensive that classical restorative care for these elderly people was no longer possible. After 1 year 79% of the ART restorations placed were considered successful. ART was well received and the recipients were very satisfied with the care provided at home. A second study was performed on root-surface carious lesions amongst, on average, 85-year-olds who had undergone radiotherapy. After 2 years there was no significant difference in survival rates between ART restorations and those produced through the traditional approach, using high-viscosity glass-ionomer: 66.2% versus 65.2% respectively [73]. Further work investigated the survival of ART restorations in root surfaces among institutionalized elderly with an average age of 78.8 years in comparison with that of traditional treatment using a resin-modified glass-ionomer. The 1-year survival rate for traditional restorations was 91.7% and it was 87% for ART restorations [88].

The potential use of ART to manage elderly patients in hospitals, institutions, or their own homes has been insufficiently researched. Considering the worldwide increase of elderly people with natural dentitions in the coming decades, studies covering the impact of the ART approach, as part of a package of (medical) oral care for use among the elderly, should receive serious attention (see Chapter 18).

Atraumatic restorative treatment and people with a disability

A systematic review on the effectiveness of treatments provided to people with a disability concluded that investigation into the potential of ART should be carried out [115]. One of the aims of using ART is to reduce the number of people with disabilities that have to undergo simple restorative treatment under general anesthesia. For example, people with a severe form of autism cannot accept the noise of the drill and ART has turned out to be a good alternative.

Atraumatic restorative treatment in the public services

The first report that described the use of the ART approach in a public service system originated from South Africa. ART was introduced there because of preventive, restorative, and economic advantages, patient-friendliness, and the potential to increase the coverage of dental care needs in a population. The adoption of ART was associated with training, research, and follow-up supervision. Since then, the ART approach has been introduced in several countries as an appropriate caries management concept.

The experiences in South Africa, Mexico, Tanzania, Egypt, the Latin American countries, and Cambodia [22] show that the proper implementation of ART in the public oral health services is mainly hampered by two factors: the availability of ART instruments and the availability of quality glass-ionomers. In this context, it is worth noting that dentists employed both in public services and in private practice in Egypt were able to perform ART restorations in their private practices but less so in public facilities. This was because of the reduced availability of glass-ionomer cement and proper hand instruments in the public service clinics, materials which they could purchase for use in their own private practice [43].

Strategies for successful incorporation of ART into public oral health services should, therefore, include:

- organization of training courses in ART for trainer dentists;
- regular complete ART courses in countries that have already organized such courses;
- support for course participants through ensuring the constant supply of quality high-viscosity glass-ionomer restorative material;
- installation of a system for monitoring treatments provided in public oral health services;
- organization of meetings for updating dental practitioners about monitored results;
- cooperation between universities and the health ministries in developing the ART oral health projects [143].

Finally, introducing ART as part of the Basic Package of Oral Care [56] increases the chance for rendering essential palliative, preventive, and restorative care to many communities in need.

Atraumatic restorative treatment and dental education

The principles of ART perfectly fit the concept of minimum intervention dentistry. It is obvious that populations stand to benefit from ART if the approach is being taught at dental schools, as is done in Brazil [118], the USA [79], and many other countries. A number of textbooks on ART [48, 77] and chapters on ART in textbooks on minimal intervention dentistry [49], preventive and community dentistry [70], cariology [50], and pediatric dentistry [47] have been published.

Concluding remarks on atraumatic restorative treatment

Since its conception some 25 years ago, ART has traveled the world. It has become part of the dental curriculum in countries as far apart as China, Vietnam, Indonesia, Turkey, Egypt, South Africa, Tanzania, Netherlands, France, UK, USA, Mexico, Ecuador, Venezuela, and Brazil to name a few. The Fédération Dentaire Internationale accepted ART as one of the treatment methods within the concept of minimal intervention dentistry at their annual meeting in Vienna in 2002 [44]. ART has gained in popularity among general dental practitioners in developed nations. General dental practitioners in the USA [151] and the UK [17] use ART to treat children restoratively. In the Netherlands, ART is used to treat children and anxious people. Thus, ART is no longer confined to environments where electricity and piped water are unavailable but has become a contemporary caries management approach that can be applied in any dental care clinic.

Conventional minimal intervention methods

Materials available

In the conventional surgery setting the available materials for direct restorations are amalgam, composite resin, and glass–ionomer cement. Indirect restorations for caries treatment can be considered obsolete owing to the unfavorable cost–benefit balance related to the high risk of failure in caries-active patients and the substantial amount of tooth substance loss necessary for the indirect technique. When larger defects have to be restored in caries-active patients, a direct restoration should be placed together with an intensive nonoperative caries control program. When the balance of the mouth is reestablished and caries activity has been controlled, an indirect restoration can be considered. It will have the advantage of more control in restoring anatomy, occlusion, and proximal contacts. This restoration can last a lifetime in a caries-inactive patient.

Amalgam, composite resin, and glass–ionomer restorations

Amalgam restorations have been placed successfully for years but are now in demise owing to the increased use of resin composites. The continued use of amalgam is challenged for environmental reasons [75]. However, composite resins and resin-modified glass–ionomers may have a negative influence on general health due to exposure to resins, particularly due to the release of monomers at the surface and when improperly cured. These discussions are beyond the scope of this textbook but, on a population level, amalgam, composite resin, and glass–ionomer cements can all be considered safe when properly placed.

The most obvious advantages of amalgam are its long-lasting dental record, low cost, and ease of use, whereas its most important disadvantages are its lack of adhesive technique and its appearance. In many countries resin composites are the materials of choice for direct restorations. As will be seen in Chapter 21, the longevity of modern resin composite restorations is comparable to amalgam restorations, although this result may depend on the caries challenge and the size of the restoration. Amalgam restorations may last longer in caries-active patients such as children receiving fillings due to primary caries [13, 156]. However, large amalgam restorations may show more failure due to fracture than large composite restorations do [127]. In low caries-risk patients, composite resin had a better performance in the long term [127]. Patient factors, such as caries activity, probably play a more important role in the longevity of posterior restorations than the materials selected do [27].

Glass–ionomer is often recommended as a suitable material for the restoration of carious cavities because of its fluoride release [120]. Some clinical studies have shown a cariostatic effect of glass–ionomer restorations on the neighboring surfaces of primary teeth [32, 136, 168]. Others have shown a decreased development of recurrent caries alongside cervical glass–ionomer restorations, especially in high caries-risk people where saliva flow is reduced [31, 99]. Overall, retention in both enamel and dentin of cervical restorations placed with a type II restorative glass–ionomer cement was superior to resin-based materials, according to a systematic review [131]. For root caries lesions that need to be treated operatively, a glass–ionomer is considered the first option.

In the deciduous dentition, single-surface glass–ionomer restorations, especially when placed with the ART technique, have been proven to be a successful treatment [25]. The added advantages in using ART are a local anesthetic is not required and the technique causes less anxiety than traditional concepts do. For restoring large-sized cavities, glass–ionomer lacks the mechanical properties to achieve a durable restoration. For such cavities, resin composite, placed with a total etch technique, should be used. Therefore, in the permanent dentition, the use of encapsulated high-viscosity glass–ionomer should be restricted to single-surface cavities in caries-active patients and for the restoration of cervical (root) lesions. Glass–ionomer cement is also the material of choice for temporary restorations, such as in the stepwise excavation technique (see 'Stepwise excavations studies' section in Chapter 20). Choosing a glass–ionomer cement that is a different color to the tooth will help the dentist distinguish the dental material from the tooth when removing the filling.

For other larger defects, composite resin restorations, placed with a total etch technique, have the best prognosis. Developments in composite resin technology have yielded new materials, such as nanocomposites or low-shrinkage materials. Initial results claim superiority, but this has not been shown in clinical studies [147]. It has been suggested that a layer of glass–ionomer might be placed beneath composite resin – the so-called sandwich technique. However, total etch restorations have a better longevity, mainly due to fewer fractures, than sandwich restorations [148].

Relevant technical aspects of minimally invasive management

Preservation of tooth structure

Where a cavitated carious lesion is to be restored operatively, it is sufficient to remove an appropriate amount of demineralized tissue (see Chapter 20) and make the preparation accessible for the filling procedures. For occlusal (Fig. 19.18) and free smooth surface defects, visual access is easily achieved leading to minimal-sized preparations. Where a cavitated lesion is surrounded by demineralized enamel, this can be included in the preparation or left in place on the assumption that a good caries control regime can arrest lesion progression. On occlusal surfaces, the demineralized enamel can be sealed – called a sealant restoration [153].

The decision as to where the preparation outline should be located is influenced by the risk of demineralized enamel becoming cavitated, aesthetic considerations, and the need for a bevel at the restoration outline. Bevels on composite restorations can improve appearance, making it easier to merge the filling into the tooth. Although laboratory research favors bevels to improve cavity seal [123], clinical studies have not shown better outcomes for beveled restorations [78, 177].

In approximal lesions on posterior and anterior teeth, minimally prepared, box-type preparations are the best operative procedure. They provide good visibility for the removal of completely demineralized carious tissue and for the adequate insertion of the restorative material. Tunnel preparations have been recommended for the treatment of approximal carious lesions in order to be minimally invasive. This approach leaves the proximal surface and marginal ridge intact as much as possible. However, to reach the cavitated carious lesion, usually situated below the contact point, the opening in the occlusal surface needs to be widened so much that a thin marginal ridge often remains that fractures easily. In addition, there is considerable risk of damaging the adjacent tooth and it is not easy technically to seal the cavity. The longevity of these restorations was not good either [141, 160, 161]. For all these reasons, tunnel preparations are not advised. The rise and fall of this restoration is a salient lesson. It was devised for the best of reasons, to save tooth structure. However, careful clinical evaluation showed these restorations failed and the design is now rarely used [174]. The take-home message is: by all means think and innovate, but clinically evaluate and report as well.

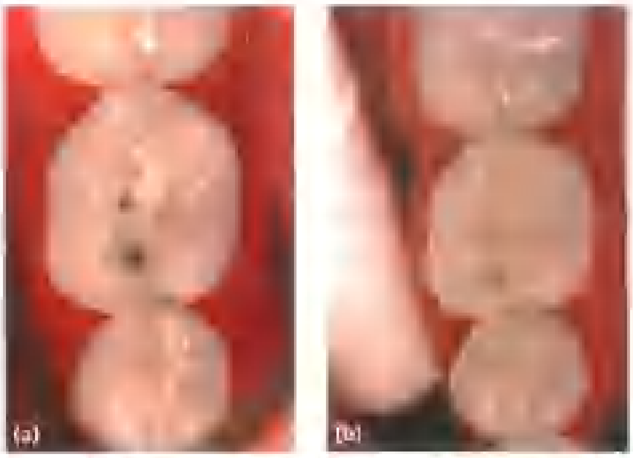


Figure 19.18 (a) Cavitated lesions visible in the occlusal surface. (b) The preparation after excavation; note distinct differences in lesion extension between the active lesion in the central fossa compared with the slowly progressing microcavitated lesion in the mesial fossa. The lesion on the mesial surface was not included in the preparation because it was arrested.

Figure 19.19 Examples of damaged enamel surface in molar adjacent to preparation in premolar. Due to a low caries activity, this damage did not subsequently result in cavity formation.

Protection of the surface of an adjacent tooth

When lesions are located on an approximal tooth surface, the cavity is just cervical to the contact point. For this reason, when the cavity is prepared, there is a risk of damaging the adjacent tooth (Fig. 19.19). When treating a high caries-risk patient, this adjacent tooth surface may well have a noncavitated lesion. If these lesions, with weakened enamel surfaces, are touched by rotary instruments, this will promote and enhance the caries progression of the adjacent tooth, resulting in new cavitated lesions. This might have happened with the distal surface of the first molar in Fig. 19.4. From the literature it is known that damage to the neighboring tooth is very common [90, 94], and strenuous efforts must be made to avoid this. It has also been shown that there is a 2.5 times increased risk for subsequent restoration on the adjacent tooth surface the moment a proximal surface is restored [135]. However, once again, the individual caries risk of the patient may be even more salient than the iatrogenic damage with respect to what happens next. Again, we stress that the nonoperative caries control measures are the most important part of the treatment.

In order to protect adjacent tooth surfaces, two measures are available:

- The use of a protective band placed around the adjacent tooth (Fig. 19.20).
- The use of sonic special preparation tips (KAVO) that have a nonworking side directed towards the adjacent tooth and a working side that is able to remove thin layers of enamel as well as making a bevel along the proximal outline (Fig. 19.21). In vitro research showed that damage to adjacent teeth is reduced with the use of Sonicsys tips, while marginal adaptation is good [124].

When the adjacent tooth surface contains a restoration, the filling may be damaged. When restoration surfaces are touched, the anatomy of the restoration should be polished and adjusted before the matrix is placed. This may reduce the damage and might lead to a better anatomy of the proximal surface (Fig. 19.22).

Figure 19.20 A band is placed around the second premolar to protect its approximal surface, while the carious lesion on the distal surface of the second premolar is opened with a diamond bur.

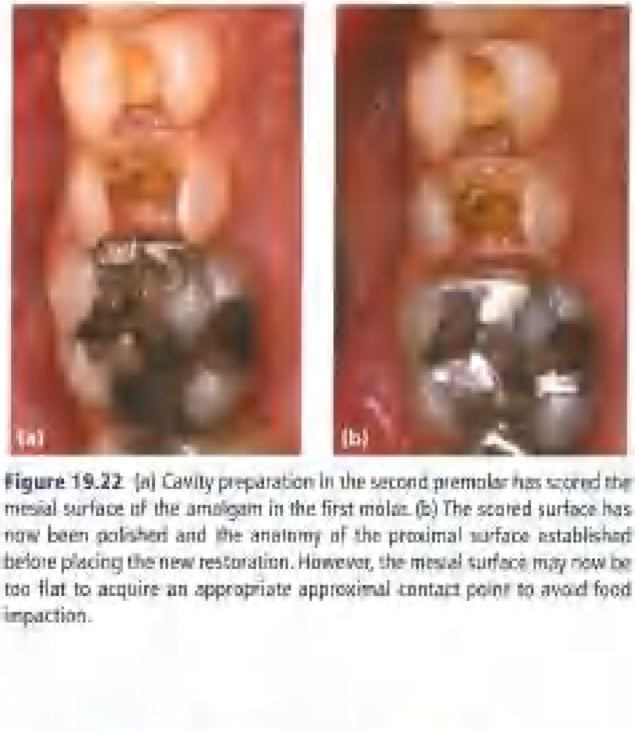


Figure 19.22 (a) Cavity preparation in the second premolar has scored the mesial surface of the amalgam in the first molar. (b) The scored surface has now been polished and the anatomy of the proximal surface established before placing the new restoration. However, the mesial surface may now be too flat to acquire an appropriate approximal contact point to avoid food impaction.

Figure 19.21 Phases in a preparation technique for protecting the adjacent tooth surface. (a) A wedge is placed and initial opening of the lesion is made using the bur. (b) Gingival beveling after using the the Sonysis device (Kavo). (c) The Sonysis tip in use. This instrument only cuts on one side. The side next to the adjacent tooth is smooth and can do no damage.

Establishing a contact point

Achieving a good contact point is very important because food will be forced between the teeth where there is an open contact and tends to lodge in the embrasure. This is annoying for the patient and promotes recurrent caries. It was relatively easy to establish a good contact point when handling amalgam. Provided a matrix was placed and burnished against the adjacent tooth, condensation of the amalgam resulted in a tight contact. When composite resin became available, the consistency of the material meant that now it was not possible to establish the contact by simply pushing the material against the matrix band, and other techniques were required. Nowadays, special separation rings (Fig. 19.23) are available that actively separate adjacent teeth, resulting in a tighter and properly placed contact point [91, 92].

Seal and cleansability of the margins

Restorations are placed to aid plaque control. It is thus obvious that the restoration should merge imperceptibly with the tooth and be easy to clean. Nowhere is this more difficult to achieve than at the cervical margin, the very area where plaque will stagnate and caries can occur. A particularly critical area is the cervical margin of the approximal restoration. If a void is left, this will result in an uncleansable gap exceeding the critical width of 250 μm [81, 164]. In the case of a caries-active patient, this is likely to result in recurrent caries. Therefore, the dentist should put every effort into achieving a void-free outline. It has been suggested that syringeable composites and inserting the tip of the compule deep into the cavity may help to achieve this. Also, the use of a first layer of flowable composite has been described using the so-called 'snow-plough' technique (Fig. 19.24). In this technique the flowable composite is not cured until a layer of hybrid composite is added [125]. It should be noted, however, that there is little experimental proof as to which technique is best for achieving a void-free cavity margin. It is likely that the skills and dedication of the operator play an important role.

Figure 19.23 Examples of different types of separation rings. In each, the principle is the same. The spring-loaded ring forces the teeth apart. The thin metal matrix is carefully burnished to the adjacent tooth, the cervical margin of the band is firmly wedged to ensure a tight fit, and the restoration placed. When the ring is removed, the separated teeth move together and a tight contact results.

Figure 19.24 The 'snow-plough' technique: (a) inserting the flowable composite after applying a sectional matrix; (b) flowable composite in place; (c) inserting the hybrid composite; (d) restoration after curing; (e) finished restoration.

Clinical examples

- Occlusal sealant-restoration (Fig. 19.25). The rationale behind this restoration is that the carious cavity is restored with composite resin, and contrary to the 'extension for prevention concept' of G.V. Black, the residual fissure system is sealed to maintain tooth structure and to aid plaque control. The procedure is called preventive resin restoration [153]. The same approach is used when the cavity is treated using ART and high-viscosity glass-ionomer (Fig. 19.26).
- Approximal box restoration (Fig. 19.27).
- Cervical composite restoration (Fig. 19.28).
- Restoration of root caries with glass-ionomer cement (Fig. 19.29).
- The larger lesion (Fig. 19.30).

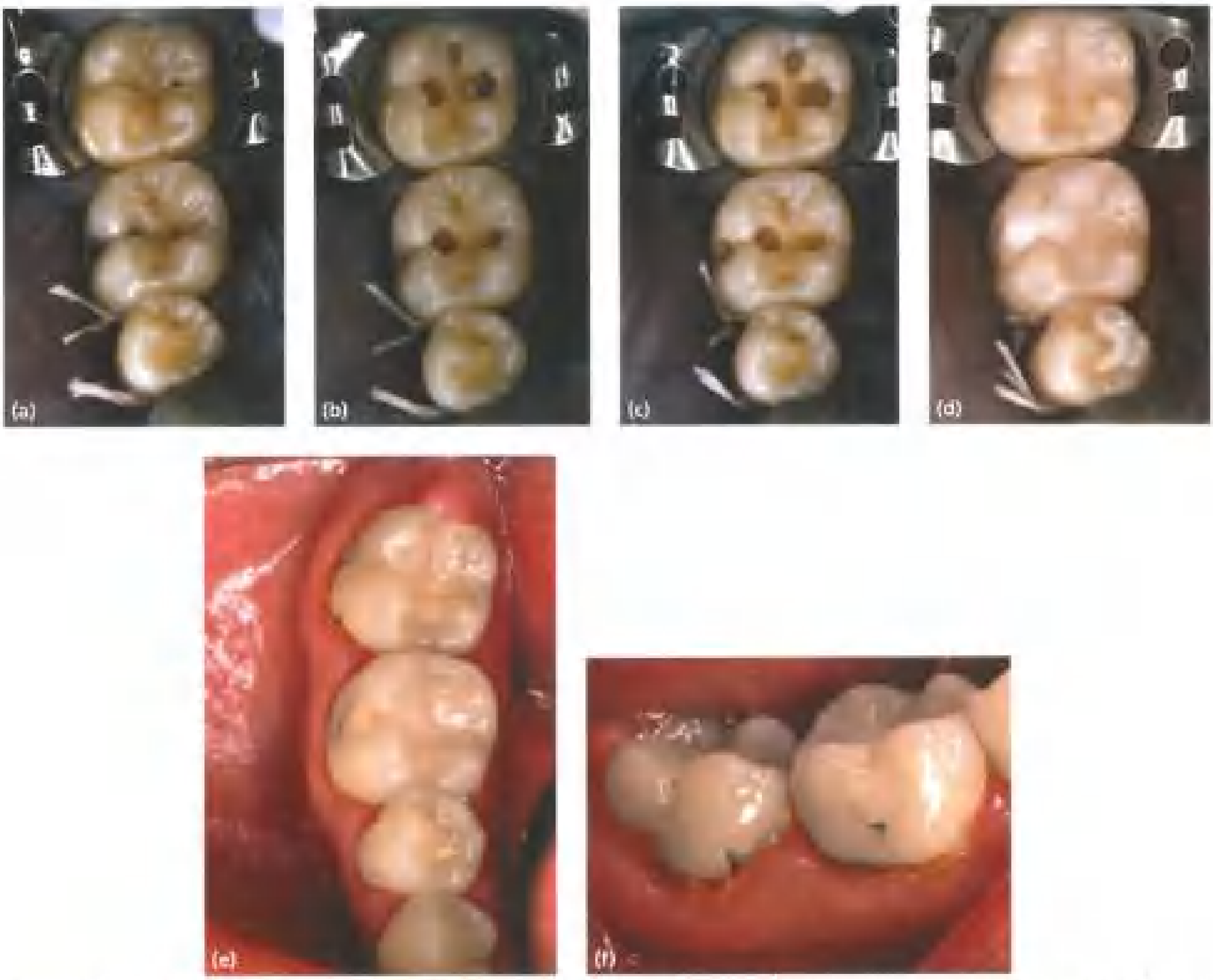


Figure 19.25 Occlusal sealant restoration. (a) Cavitated lesions in molars in a 12-year-old girl (1997). Rubber dam applied. (b) Preparations after opening the lesions with a diamond bur. Opening of the distal fossa in the molars might not have been needed because the lesions were inactive. (c) Lesions after excavation. (d) Restored lesions – a three-step etch-and-rinse adhesive was used together with a hybrid composite. A white sealant was placed on the rest of the occlusal surfaces. The sealants might not have been needed, since there was no active caries. (d) The restorations after 15 years; the patient is now 28 years old. Note that the sealants have partly been abraded away. (e) A clinical picture from the buccal aspect, shows darkly stained arrested lesions, the scars of previous periods of active caries.

Figure 19.26 ART occlusal sealant restoration. (a) Cavity cleaned according to ART in tooth deciduous molar of a 4-year-old girl. (b) Not only the cavity is restored, but also the adjacent pits and fissures have been sealed using Ketac Molar Easymix®, providing extra protection. Courtesy of Dr S. Leal.

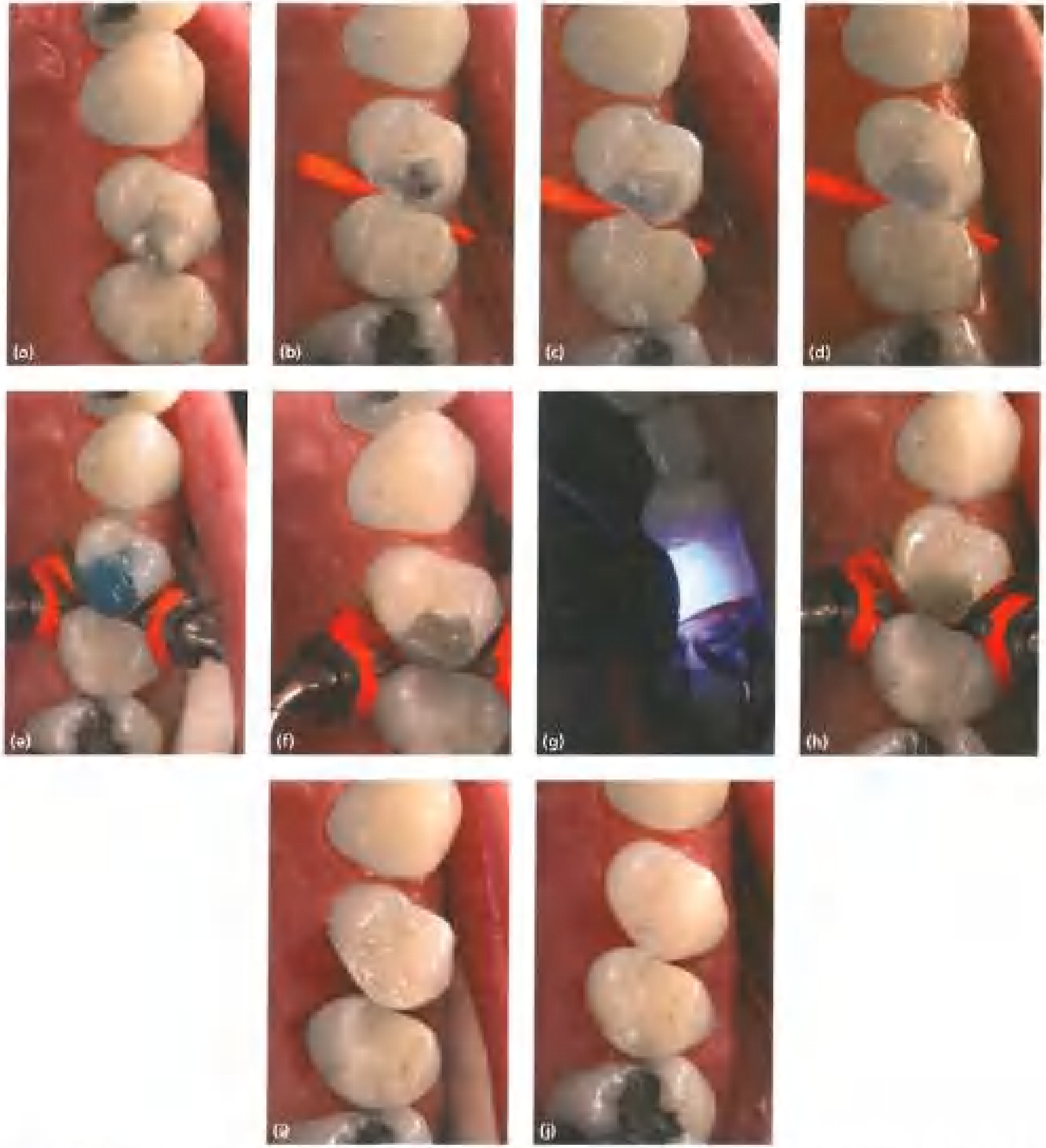


Figure 19.27 Approximal box restoration. (a) Deep cavitated caries lesion distally in the first upper premolar extending close to the pulp; see radiograph in (kii). (b) Dentin lesion after opening and removal of enamel with a diamond bur. (c) After removing soft dentin at the enamel–dentin junction using a round bur and water coolant. A 2 mm zone is created along the enamel–dentin junction to provide sound dentin for bonding. The central soft caries has not yet been removed. (d) The cavity after careful removal of most of the soft dentin, leaving a layer centrally covering the pulp, aiming at indirect pulp capping. In this case the central carious dentin was not protected by a liner. (e) Matrix, wedge, and separation ring applied. The etchant is in place. (f) The first layer of flowable composite is inserted but not cured. (g) The first layer of hybrid composite is inserted and both layers are cured together. (h) The first two layers have been cured. (i) The restoration after removal of the matrix. (j) The restoration after finishing. (k) Three radiographs: (ki) 3 years before treatment, (kii) just before treatment, and (kiii) after treatment.

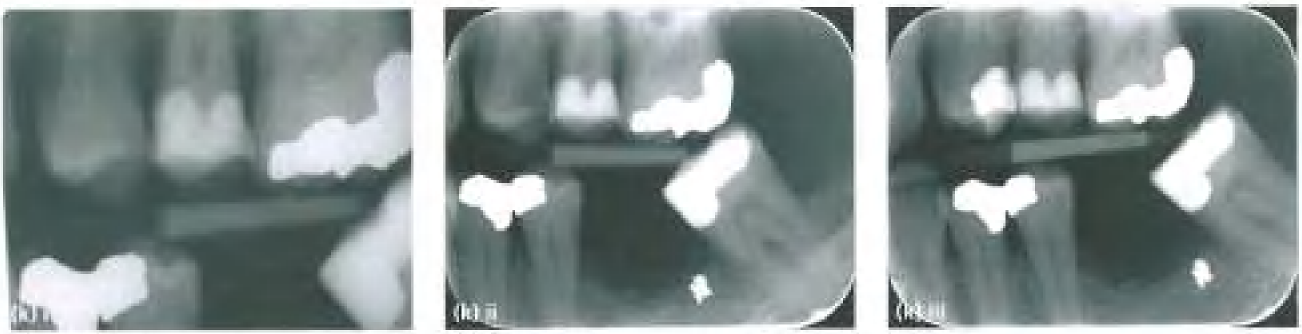


Figure 19.27 *(Continued)*

Figure 19.28 Cervical composite restoration. (a) Clinical examination of 32-year-old male shows cervical lesions covered by biofilm, in spite of 1 year of nonoperative treatment focusing on improved cleaning with fluoride toothpaste. It was decided to place restorations to aid cleaning. (b) Cavity preparation with minimal loss of dental hard tissues. (c) Restoration with three-step total etch technique and direct composite resin.

Figure 19.29 Restoration of root caries with glass ionomer cement: (a) caries lesion in upper canine, poor plaque control; (b) after excavation; (c) after injection of the cement, a special matrix is placed and surplus is removed; (d) after 5 min waiting, the matrix is removed; (e) finishing using a fine-grit diamond bur; (f) applications of the protective varnish; (g) finished restoration; (h) restoration after 3 years.

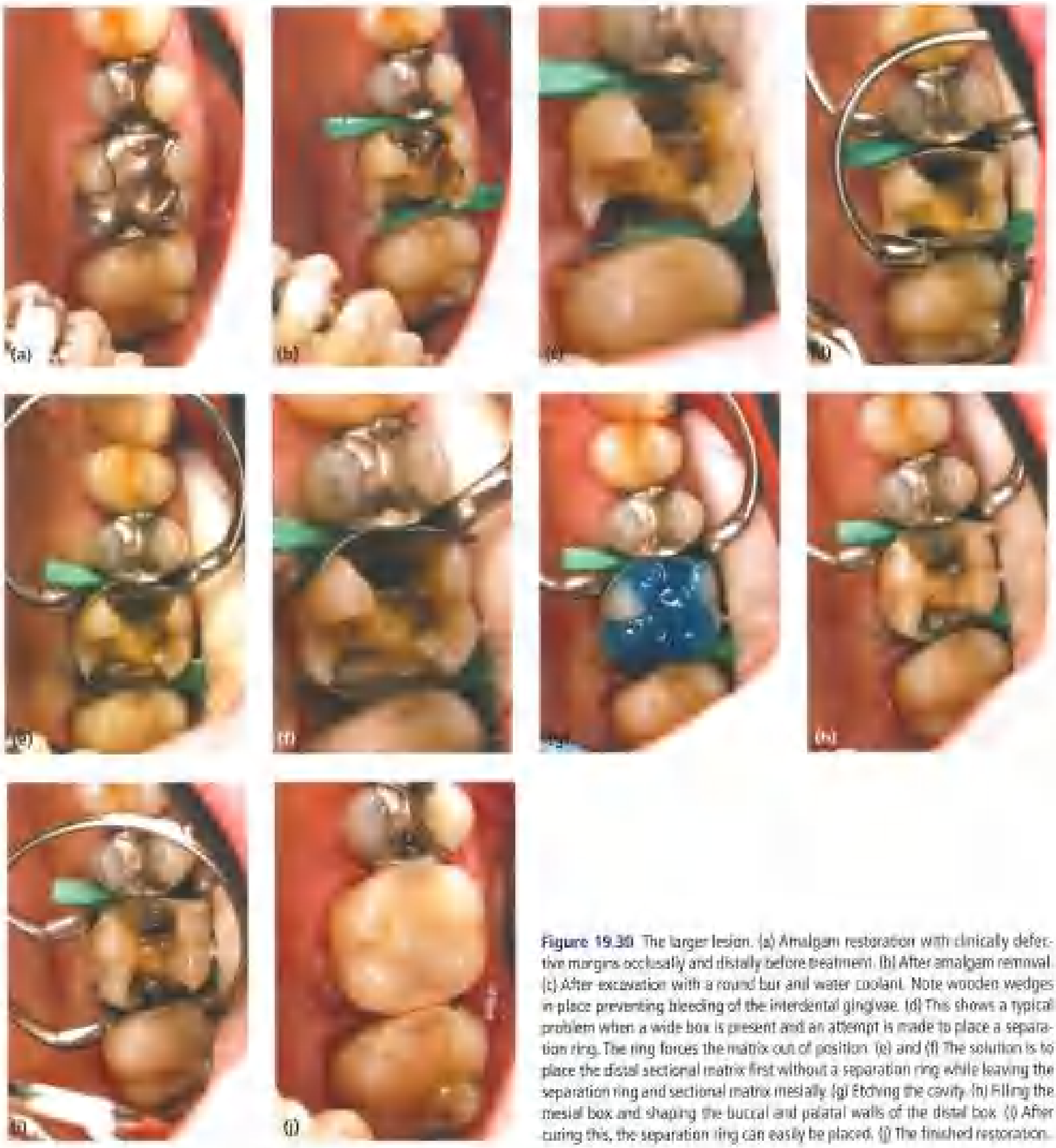


Figure 19.30 The larger lesion. (a) Amalgam restoration with clinically defective margins occlusally and distally before treatment. (b) After amalgam removal. (c) After excavation with a round bur and water coolant. Note wooden wedges in place preventing bleeding of the interdental gingivae. (d) This shows a typical problem when a wide box is present and an attempt is made to place a separation ring. The ring forces the matrix out of position. (e) and (f) The solution is to place the distal sectional matrix first without a separation ring while leaving the separation ring and sectional matrix mesially. (g) Etching the cavity. (h) Filling the mesial box and shaping the buccal and palatal walls of the distal box. (i) After curing this, the separation ring can easily be placed. (j) The finished restoration.

Replacement or repair of failed restorations

Replacement of existing restorations is the core business of most general dental practices in many developed countries [58]. The reasons for judged failure of restorations are discussed in Chapter 21 and can be summarized thus:

- biological failure such as recurrent caries;
- technical failure diagnosed by the dentist, such as a fractured restoration, fractured tooth around the filling, a deficient contact point, a poorly adapted restoration;
- failure as judged by the patient, such as poor appearance.

It is very important that the dentist decides why the restoration has failed, because this is essential if the correct treatment is to be carried out. The reason for failure must be discussed with the patient. For instance, if the problem is recurrent caries then the patient's role is salient. If, on the other hand, the problem is technical, how will the dentist avoid making exactly the same mistake in the new restoration?

Should a failed restoration be totally replaced or repaired? There is much to recommend repair as the minimally invasive option. It is known that when a restoration is removed it is all too easy to overcut and remove sound tooth structure [41]. This is particularly likely when adhesive restorations are to be removed. Amalgam is nonadhesive; a plug in a hole and with care the restoration can be pushed away from the margin having removed the middle part of the filling. This must not be done with an adhesive restoration because there is a potential for fracturing the tooth that the restoration is bonded to. The restoration must be carefully dissected out, and this requires skill. In addition, when restorations are repaired there is less danger of pulpal damage, and the parts of the restoration that are satisfactory are preserved so that new technical failures are not introduced. It is reasonable to suggest that, if a considerable part of the existing restoration is clinically acceptable, a repair should be the first choice rather than complete replacement (Figs 19.31, 19.32, 19.33, 19.34, and 19.35). Repaired restorations are likely to survive as long as those completely replaced [58].

Figure 19.31 Lingual crack caused by polymerization shrinkage of composite. Therapy? None, as long as the patient does not have complaints.

Figure 19.32 Marginal breakdown of composite restorations. Therapy? No cavity preparation required, just local cleaning, etching, adhesive application, and composite completion.

Figure 19.33 (a) The distobuccal cusp is fractured. (b) A bevel is placed in the enamel and the cusp replaced with composite. (c) The completed and polished restoration.

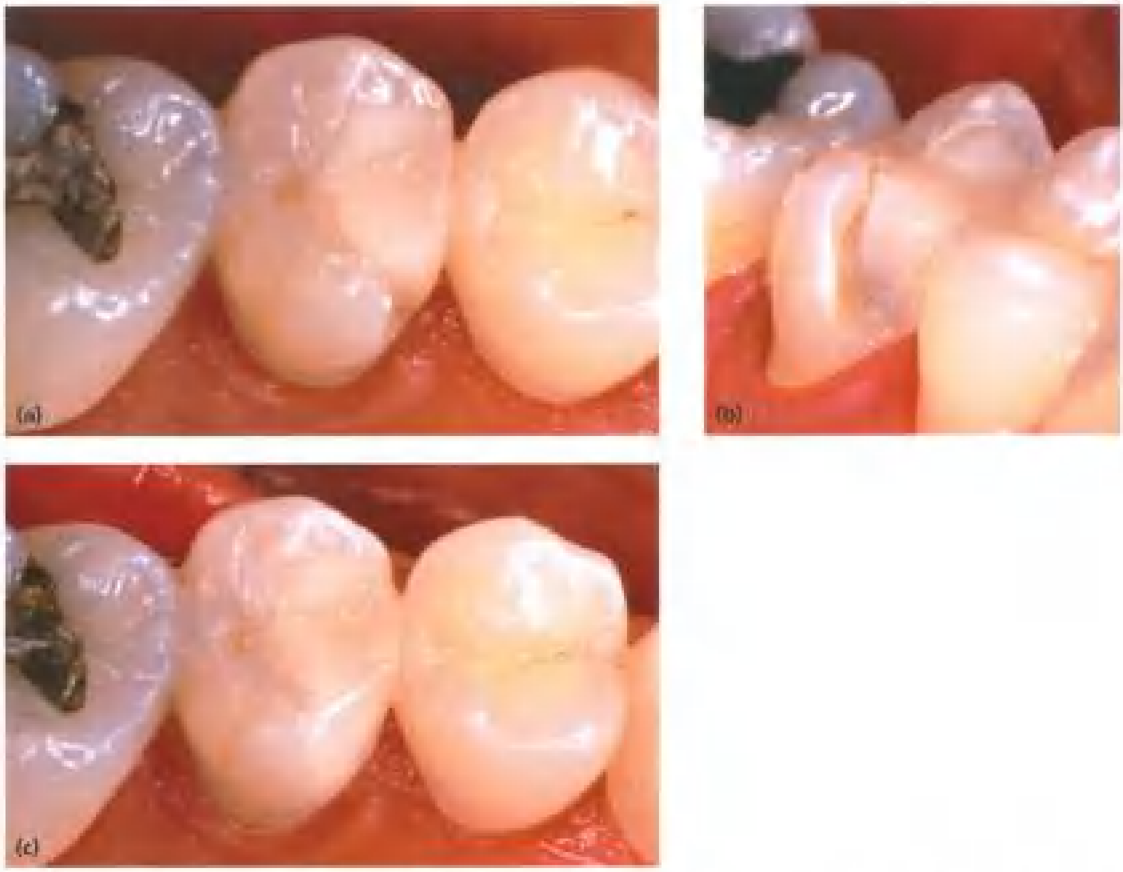


Figure 19.34 (a) The enamel has fractured on the lingual side of the proximal box. (b) The defect is cleaned, etched, bonded, and filled. (c) The completed repair.

Figure 19.35 Tooth 14 has a 12-year-old mesial–occlusal–distal composite restoration. On the radiograph a cervical recurrent carious lesion is present. (a) Note the small fracture of the marginal ridge of the composite restoration in tooth 15 mesially. (b) A distal box is prepared and the mesial contour of 15 is reshaped. (c) Placement of sectional matrix, wooden wedge, and separation ring results in tight approximal contact. (d) A syringeable hybrid composite was used to complete the restoration.

Minimal intervention and the deciduous dentition

A remarkable caries decline been achieved in the permanent dentition in children and adolescents in industrialized countries. Dental care for children in many countries is a well-funded priority, but others, such as the UK or Germany, accept a lamentable situation in the deciduous teeth of their young, vulnerable kindergarten population. Dentists admit that children are stressful to treat and that they do not have time for them [133, 158]. Early childhood caries (ECC) and treatment under general anesthetic increase [80]. Dentists may not restore deciduous teeth, and the 'care' index (a ratio of restored to unrestored deciduous teeth) has dropped from minimal levels to close to nothing [119]. Some restorations in children with many lesions either fail or do not make a clinical difference, resulting in toothache and abscess being a common phenomenon in children [112]. It is not surprising that a reduction in the quality of life for children due to dental problems has been recorded [24, 83] and that associations between caries problems and middle-ear and respiratory infections have been reported [4].

Experts in some countries engage in fierce debates as to what approaches should be undertaken to improve the situation [82]. The following sections will discuss what is special about children and deciduous teeth. While there is agreement on the importance of caries control measures, especially the importance of parental brushing with fluoride toothpaste (see Chapter 15), there is argument as to the optimum restorative practice. We attempt to unravel the various arguments.

Function and longevity of deciduous teeth: do they matter?

Deciduous teeth are temporary, only being in the mouth for 6–9 years (Table 19.3). During this time the dentist should ensure a problem-free survival. Of course, they can easily be extracted, but premature loss of the second deciduous molar often results in a mesial drift of the first permanent molar, secondary crowding in the permanent dentition, and subsequent expensive orthodontic treatment [23]. Just as important as these considerations are the trauma to the child and the parents of possible toothache followed by the unpleasant experience of tooth extraction. Frightening the child can have serious consequences for subsequent care. Anterior teeth do not have a space-maintaining function, but they are valuable for the development of the orofacial function, speech development, and biting food. Kindergarten children experience the social importance of a pleasant smile instead of a toothless grin.

Table 19.3 Eruption times and lifespan of deciduous teeth.

	Eruption time (years)		Lifespan (years)
	Deciduous	Permanent	
Central incisor	0.5	7	6.5
Lateral incisor	0.75	8	7.25
Canine	1.5	9/12ᵃ	7.5/10.5ᵃ
First molar/premolar	1	10	9
Second molar/premolar	2	11	9

ᵃUpper/lower arch.

Anatomical considerations

The enamel and dentin are thinner than in permanent teeth (Fig. 19.36). The teeth are smaller, with broader contacts, and the pulp chambers are proportionately larger relative to the size of the crown. These dimensions mean it takes less time for the lesion to reach the pulp in deciduous teeth than in permanent teeth.

Thus, noninvasive or minimally invasive approaches potentially face greater problems than in the permanent dentition. The chances of arresting a lesion have to be

Figure 19.36 Anatomical differences between a deciduous (left) and a permanent (right) molar. Dentin (a) and enamel (b) thickness is less in deciduous teeth partly due to voluminous pulp horns in deciduous teeth.

Figure 19.37 The radiograph shows an interradicular radiolucency (arrow) indicating irreversible inflammation of the pulp and subsequent necrosis. Pulpal treatment or extraction is required. The radiograph does not reveal inflammation but indicates that conservative treatment alone will not suffice in this case.

balanced against the risk of progression and subsequent necrosis of the pulp, pain, perhaps an abscess, and then often an extraction. Restorative treatment, on the other hand, must consider the state of the pulp. Is there irreversible pulpitis? This clinical diagnosis relies heavily on history, and this is not easy to obtain from the very young child. Radiographs are an important aid to detect carious lesions early or diagnose pulp necrosis with apical/interradicular infection (Fig. 19.37), but radiographs cannot assess the inflammatory situation of the pulp with deep carious lesions.

Minimal intervention approaches

Pain is of great importance and has to be managed first. Teeth with symptoms of irreversible pulpitis do not settle after caries removal but require removal of the pulp or extraction of the tooth. Pain-free, cavitated lesions that are not cleansable will progress because an aciduric biofilm favors the progression of caries [162] and finally results in pain and complete breakdown of the tooth. Thus, a management of the caries process is needed. This can be achieved by different management strategies, including:

- inactivation of lesions without caries removal;
- sealing techniques with no caries removal;
- partial caries removal and restoration;
- complete caries removal and restoration (not minimally invasive).

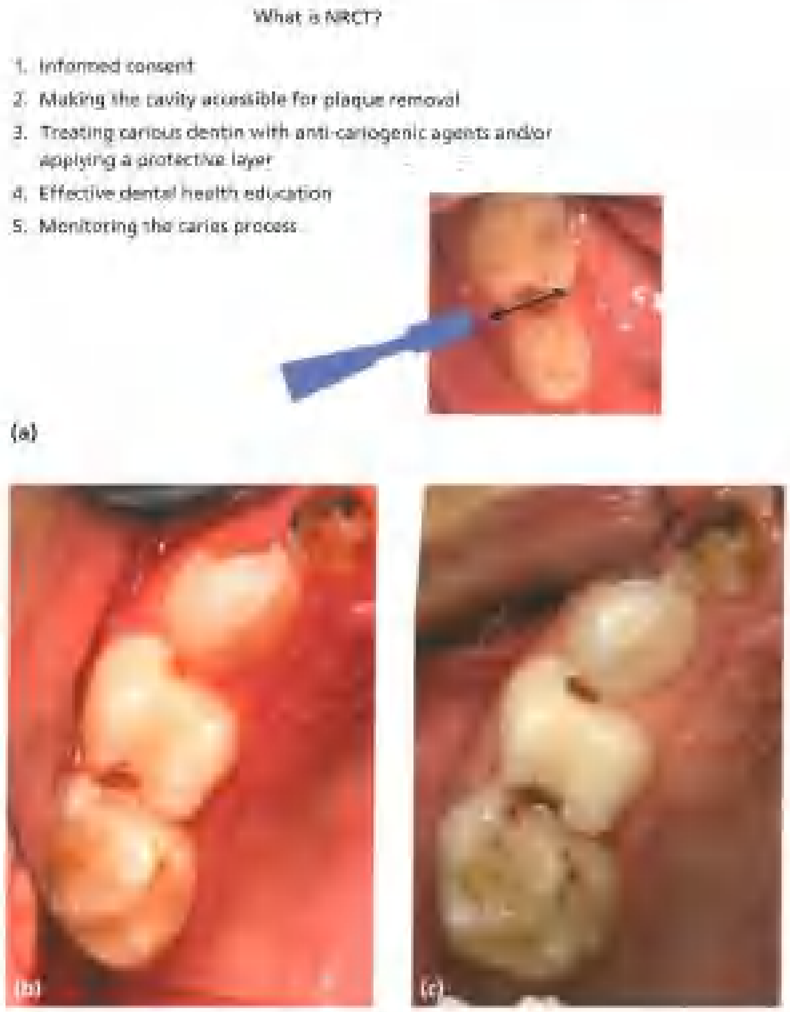
Inactivation of lesions without caries removal

This biologically based concept of caries control (see also Chapters 13 and 17) is applicable in both deciduous and permanent teeth. The method has been employed most impressively in ECC patients where extensive active caries lesions on smooth surfaces of anterior teeth become inactivated (Fig. 19.38a and b). A solely restorative approach is bound to fail in such cases. Thus, the only option to control caries lesion development is to shift the responsibility to the parents in an intensive and open motivational talk followed by concrete training in brushing their child's teeth. The other option of multiple extractions and/or metal crowns can be successful for the deciduous dentition, but it will fail dramatically if caries control has not been instituted by the time the permanent teeth erupt. When the parents take their responsibility, plaque can be removed within 2 min, gingivitis recedes within 10 days, and the formerly active, demineralized lesions are converted to shiny, arrested lesions within a few months (Fig. 19.38b).

The advantage of deciduous teeth is that the thin enamel easily breaks away in the natural process of the disease, which often results in an automatic arrest due to self-cleaning. Slicing uses this biological approach for proximal lesions in deciduous molars. The slicing helps to inactivate the lesion by making it accessible for toothbrushing at home. This approach is a classical example of nonoperative caries control, called by some nonrestorative cavity treatment (NRCT) [63] (Fig. 19.39). The marginal ridge has to be removed, but the contact point area is not opened to hold the tooth in position and prevent a further mesial shift and space loss. The parents and, if applicable, the child have to perform regular brushing perpendicular to the dental arch to ensure sufficient plaque removal and topical fluoride application via fluoridated toothpaste. At the dental office, additional fluoride application might be helpful, but daily brushing of the open cavity at home is essential for the success of this technique. The obvious advantages are the minimal cooperation needed from the child, which results in better compliance by the children [144].

This approach is well suited for sizable cavities, but what about small-sized cavities, and could this treatment be performed in an out-of-surgery environment? Making use of the success of ART in (young) children, a protocol was tested that consisted of restoring small-sized cavities with

Figure 19.38 (a) ECC (early childhood caries) is a severe problem with heavy plaque, gingivitis, and active white spot and cavitated lesions. (b) Another case has been inactivated by the introduction of toothbrushing with fluoridated toothpaste.



What is NRCT?

1. Informed consent
2. Making the cavity accessible for plaque removal
3. Treating carious dentin with anti-cariogenic agents and/or applying a protective layer
4. Effective dental health education
5. Monitoring the caries process

Figure 19.39 NRCT. (a) The NRCT method, direction of cleaning, and the brush. (b) After slicing. The marginal ridges have been partly removed on the second molar mesial and completely removed on the first molar mesial/distal, allowing respectively access to the secondary caries lesion (second molar) and the primary caries lesions (first molar). Note the loss of contact has been limited (V-shaped sliced surfaces). Now the parents need to learn how to brush. (c) Half a year after slicing. The same case 6 months later, brushing is not perfect, plaque is still present, but the lesions are arrested. Courtesy of Rene Gruythuysen.

ART, widening medium-sized cavities with a hatchet, and cleaning the medium- and large-sized cavities with toothbrush and fluoridated toothpaste daily. After 3.5 years, the tooth survival rate of this ultraconservative treatment protocol was equally high as that of cavitated teeth treated using the traditional protocol with amalgam and those treated with the ART protocol [111] (Fig. 19.40).

The open cavity cleaning is based on regular brushing by the parents and/or children under supervision. Supervised by teachers, initial 3–4-year-old children were able to arrest 45% of dentin caries lesion in anterior teeth as a result of daily toothbrushing with fluoridated toothpaste and school-based dental education over a period of 3 years [85]. An intensive education of the parents about the nature of the caries process and their role in disrupting it is essential. Unfortunately, randomized clinical trials for the outcome of slicing are not published at the moment.

Figure 19.40 Ultraconservative treatment protocol. Small-sized cavities are treated according to the ART approach, medium-sized cavities are enlarged using a hatchet, and medium- and large-sized cavities are cleaned with toothbrush and toothpaste daily. The picture shows the situation 1 year after treatment. Note that the ART restorations perform well and that the caries process in the open cavities has been arrested. Courtesy of Dr S. Leal.

Figure 19.41 The Hall crown. (a) Before cementation; no caries removal and no occlusal or proximal reduction. (b) The crown directly after cementation. Inevitably the bite is 'high.' (c) Six weeks later. The bite has nearly reestablished. Courtesy of Nicolla Innes.

Another rediscovered minimally invasive approach is the impregnation with silver ions in the form of silver diamine fluoride [59, 130]. We use the term 'rediscovered' here because this was originally suggested by G.V. Black, who used silver nitrate for its antimicrobial properties. The dentin will turn black, which limits the uses in anterior teeth, and the evidence for its effectiveness over time is still weak [59]. Moreover, there are concerns about the toxicity of the products. The silver impregnation has been launched to support slicing even with suboptimal oral hygiene regimes, but the clinical effects over and above slicing alone are not known [130].

Sealing techniques with no caries removal

Fissure sealing over active white spot caries lesions has been practiced for many years. However, in children, good cooperation for successful adhesive techniques is sometimes difficult and it leaves the remaining enamel unprotected, especially approximally. Although metal crowns might not be considered a minimally invasive technique at first sight, when they are placed without prior caries removal or preparation, they are easy to apply, and this restorative treatment is well accepted by patients. The technique is called the Hall crown (Fig. 19.41) and proved to be successful in the only randomized clinical trial carried out in general dental practice so far [76]. In contrast to this, standard restorative care using glass-ionomer cement in control teeth exhibited higher failure rates after 5 years. (It should be noted that conventional fillings in deciduous teeth can be very successful when dentists use compomers instead of glass-ionomer cement. The longevity of restorations in deciduous teeth will be discussed fully in Chapter 21.)

Thus, prefabricated metal crowns, as used in the Hall technique, can disrupt the carious process by shutting down the substrate supply, although the children will leave the dental practice with an open bite that resolves in time [172].

Unfortunately, no clinical trials are published that compare metal crowns with minimally invasive approaches such as slicing to allow cleaning. Although metal crowns are very successful for the limited life of deciduous teeth, they do not reduce caries activity. This may result in continuous problems for the permanent dentition.

Partial caries removal and restoration

The aim is to remove sufficient carious tissue to enable an effective marginal seal for a restoration that will inhibit further progression of residual caries (see Chapter 20). Sometimes this is followed by a reentry after several months to allow further excavation prior to definitive restoration. This stepwise excavation has been shown to reduce the risk of pulpal exposure and encourage the formation of tubular sclerosis and tertiary dentin. On reentry, the lesions appear harder, darker, and drier. Whether reentry is required when the seal is tight is questioned (see the 'Do we need to reenter?' section in Chapter 20). Interestingly, partial caries removal without reentry may be particularly successful in the primary dentition. In a study of 60 children with poor cooperation, 96% of primary molars with deep lesions receiving this treatment survived for at least 3 years without pain, swelling, or radiographic signs of periapical pathology [64].

Complete caries removal and restoration

Removing all demineralized and infected carious tissue and restoring the tooth to function was the standard approach for many years, but this can be demanding of the child and the dentist, involving local anesthesia, use of high-speed handpieces, and good moisture control. All the mentioned disadvantages are absent when the dental practitioner resorts to using the ART approach. The many studies describing the survival of ART restorations in primary teeth hardly mention sepsis as a cause of failure [59]. If removal of all completely demineralized caries tissue exposes the pulp, a pulpotomy is required. However, together with a subsequent metal crown, this maximally invasive procedure gives predictable results with acceptable success rates (80%) [157], while multiple-surface fillings fail at a high rate.

Choice of treatment

All noninvasive or minimally invasive approaches work in the deciduous dentition. However, it is essential to realize that children cannot perform the required improvements in oral hygiene on their own. The parents have to consciously take this responsibility. On the other hand, the acceptance of noninvasive and minimally invasive approaches is helpful in children to accustom them to dental procedures and achieve a reduction in caries activity, which is the most important factor for future oral health. In particular, in the shallow or superficial lesions found in ECC, these approaches can obviate the need for treatment under general anesthesia. Approximal lesions can be opened by slicing to facilitate this arrest (NRCT). However, this can only be achieved if the child accepts rotary instruments. A more child-friendly approach might be the widening of cavities with hand instruments (hatchet), but this approach can only be performed if the enamel is thin and unsupported. Deeper, enclosed lesions in deciduous molar can be sealed with metal crowns with the minimally invasive Hall technique provided there is no irreversible pulpal inflammation. Partial caries removal and well-sealed restorations also prevent caries progression. The choice of treatment very much depends on the background caries activity of the patient, the skills of the dentist, the country, culture, and prevailing health-care system, including the financial incentives, in which the dental practitioner is operating.

Sometimes cases are treated under general anesthetic (GA), but the long-term outcome is very mixed. Pulpotomies and metal crowns placed under GA are successful for the restored teeth [5, 121], while fillings exhibit higher failure rates. However, the results of restorative treatment under GA are frustrating [46]. New lesions develop, fillings fail, and further treatment is required. This is not at all surprising because these treatments are often performed on severe cases with low compliance. A high caries activity persists and this will finally result in the loss of teeth, deciduous and permanent teeth. Metal crowns placed under GA can only ensure normal exfoliation of the affected teeth. It will not protect other or future teeth. In some countries, such as Germany, patient compliance and improvement in oral homecare are legally compulsory prior to invasive measures such as professional periodontal treatment. Dentists are advised to stress nonoperative, caries control treatments prior to massive restorative treatment, especially under GA.

What is not acceptable is supervised neglect of carious cavities in deciduous teeth. It is not acceptable to do nothing and just hope for a pain-free exfoliation. This is sometimes disguised as a nonoperative or minimally invasive treatment. While this statement is true in communities where children and parents have access to oral care facilities, it might be difficult to adhere to in less fortunate communities. Based on World Health Organization data, over 80% of cavities in deciduous teeth of 5-year-olds in high-income countries were not treated and that percentage was 95% for peers in low-income countries [8]. What happened to these cavitated teeth over time in communities with a low level of oral care organization? When followed for a period of 3.5 years in (on average) 8-year-old children, only 7% of cavitated caries lesions in deciduous teeth were restored. Of the 93% of cavitated teeth that were not restored, 81.5% exfoliated without any symptom, leaving four out of five cavitated teeth causing toothache, abscess, or a fistula [74]. Many of these cavitated teeth with symptoms might have exfoliated symptom free if parents and children in this community had resorted to regular plaque removal from open cavities and diet control. It is essential to realize that all approaches, minimally invasive or maximally invasive, will fail in the end when caries cannot be controlled, and the key to this reduction is active cooperation by parents in home care and/or teachers in school-health programs.

References

1. Ahovuo-Saloranta A, Hiiri A, Nordblad A, Mäkelä M, Worthington HV. Pit and fissure sealants for preventing dental decay in the permanent teeth of children and adolescents. *Cochrane Database Syst Rev* 2008; (4): CD001830.
2. Ahovuo-Saloranta A, Forss H, Walsh T, Hiiri A, Nordblad A, Mäkelä M, Worthington HV. Sealants for preventing dental decay in the permanent teeth. *Cochrane Database Syst Rev* 2013; (3): CD001830.
3. Akpata ES, Farid MR, Al-Saif K, Roberts EAU. Cavitation at radiolucent areas on proximal surfaces of posterior teeth. *Caries Res* 1996; 30: 313–6.
4. Alaki SM, Burt BA, Garetz SL. Middle ear and respiratory infections in early childhood and their association with early childhood caries. *Pediatr Dent* 2008; 30: 105–10.
5. Al-Eheideb AA, Herman NG. Outcomes of dental procedures performed on children under general anesthesia. *J Clin Pediatr Dent* 2003; 27: 181–3.
6. Alkilzy M, Berndt C, Splieth CH. Sealing proximal surfaces with polyurethane tape: three-year evaluation. *Clin Oral Invest* 2011; 15: 879–84.
7. Alm A, Wendt LK, Koch G, Birkhed D. Oral hygiene and parent-related factors during early childhood in relation to approximal caries at 15 years of age. *Caries Res* 2008; 42: 28–36.
8. Baelum V, van Palenstein Helderman WH, Hugoson A, Yee R, Fejerskov O. A global perspective on changes in the burden of caries and periodontitis: implications for dentistry. *J Oral Rehabil* 2007; 34: 872–906.
9. Barja-Fidalgo F, Maroun S, de Oliveira BH. Effectiveness of a glass ionomer cement used as a pit and fissure sealant in recently erupted permanent first molars. *J Dent Child (Chic)* 2009; 76: 34–40.
10. Beiruti N, Frencken JE, van't Hof MA, van Palenstein Helderman WH. Caries-preventive effect of resin-based and glass ionomer sealants over time: a systematic review. *Community Dent Oral Epidemiol* 2006; 34: 403–9.
11. Beiruti N, Frencken JE, Mulder J. Comparison between two glass-ionomer sealants placed using finger pressure (ART approach) and a ball burnisher. *Am J Dent* 2006; 19: 159–62.
12. Beiruti N, Frencken JE, van't Hof MA, Taifour D, van Palenstein Helderman WH. Caries-preventive effect of a one-time application of composite resin and glass ionomer sealants after 5 years. *Caries Res* 2006; 40: 52–9.
13. Bernardo M, Luis H, Martin MD, Leroux BG, Rue T, Leitão J, DeRouen TA. Survival and reasons for failure of amalgam versus composite posterior restorations placed in a randomized clinical trial. *J Am Dent Assoc* 2007; 138: 775–83.
14. Bille J, Thylstrup A. Radiographic diagnosis and clinical tissue changes in relation to the treatment of approximal carious lesions. *Caries Res* 1982; 16: 1–6.
15. Black GV. *Operative dentistry*, Vol. 1, *Pathology of the hard tissues of the teeth*. Chicago, IL: Medico-Dental Publishing Co., 1908.
16. Brown LJ, Kaste LM, Selwitz RH, Furman LJ. Dental caries and sealant usage in U.S. children, 1988–1991: selected findings from the third national health and nutrition examination survey. *J Am Dent Assoc* 1996; 127: 335–43.
17. Burke FJ, McHugh S, Shaw L, Hosey MT, Macpherson L, Delargy S, Dopheide B. UK dentists' attitudes and behaviour towards atraumatic restorative treatment for primary teeth. *Br Dent J* 2005; 199: 365–9.
18. Carvalho JC, Ekstrand KR, Thylstrup A. Dental plaque and caries on occlusal surfaces of first permanent molars in relation to stage of eruption. *J Dent Res* 1989; 68: 773–9.
19. Carvalho JC, Thylstrup A, Ekstrand KR. Results after 3 years of non-operative occlusal caries treatment of erupting permanent first molars. *Community Dent Oral Epidemiol* 1992; 20: 187–92.
20. Chen X, Du MQ, Fan MW, Mulder J, Huysmans MCDNJM, Frencken JE. Effectiveness of two new types of sealants: retention after two years. *Clin Oral Investig* 2012; 16: 1443–50.
21. Chen X, Du MQ, Fan MW, Mulder J, Huysmans MCDNJM, Frencken JE. Caries-preventive effect of sealants produced with altered glass-ionomer materials, after 2 years. *Dent Mater* 2012; 28: 554–60.
22. Chher T, Hak S, Courtel F, Durward C. Improving the provision of the Basic Package of Oral Care (BPOC) in Cambodia. *Int Dent J* 2009; 59: 47–52.
23. Choonara SA. Orthodontic space maintenance—a review of current concepts and methods. *SADJ* 2005; 60: 113, 115–17.
24. Cunnion DT, Spiro A III, Jones JA, Rich SE, Papageorgiou CP, Tate A, Casamassimo P, Hayes C, Garcia RI. Pediatric oral health-related quality of life improvement after treatment of early childhood caries: a prospective multisite study. *J Dent Child* 2010; 77: 4–11.
25. De Amorim RG, Leal SC, Frencken JE. Survival of atraumatic restorative treatment (ART) sealants and restorations: a meta-analysis. *Clin Oral Investig* 2012; 16: 429–41.
26. De Araujo FB, Rosito DB, Toigo E, dos Santos CK. Diagnosis of approximal caries: radiographic versus clinical examination using tooth separation. *Am J Dent* 1992; 5: 245–8.
27. Demarco FF, Corrêa MB, Cenci MS, Moraes RR, Opdam NJ. Longevity of posterior composite restorations: not only a matter of materials. *Dent Mater* 2012; 28: 87–101.
28. De Menezes Abreu DM, Leal SC, Frencken JE. Self-report of pain by children treated according to the atraumatic restorative treatment and the conventional restorative treatment — a pilot study. *J Clin Pediatr Dent* 2009; 34: 151–5.
29. De Menezes Abreu DM, Leal SC, Mulder J, Frencken JE. Pain experience after conventional, atraumatic, and ultraconservative restorative treatments in 6- to 7-yr-old children. *Eur J Oral Sci* 2011; 119: 163–8.
30. De Menezes Abreu DM, Leal SC, Mulder J, Frencken JE. Dental anxiety in 6–7-year-old children treated in accordance with conventional restorative treatment, ART and an ultra-conservative treatment protocol. *Acta Odontol Scand* 2011; 69: 410–16.
31. De Moor RJ, Stassen IG, van't Veldt Y, Torbeyns D, Hommez GM. Two-year clinical performance of glass ionomer and resin composite restorations in xerostomic head- and neck-irradiated cancer patients. *Clin Oral Investig* 2011; 15: 31–8.
32. Donly KJ, Segura A, Wefel JS, Hogan MM. Evaluating the effects of fluoride-releasing dental materials on adjacent interproximal caries. *J Am Dent Assoc* 1999; 130: 817–25.
33. Dowling AH, Fleming GJ. Is encapsulation of posterior glass-ionomer restoratives the solution to clinically induced variability introduced on mixing? *Dent Mater* 2008; 24: 957–66.
34. Dowling AH, Fleming GJ. Are encapsulated anterior glass-ionomer restoratives better than their hand-mixed equivalents? *J Dent* 2009; 37: 133–40.
35. Duggal MS, Tahmassebi JF, Toumba KJ, Mavromati C. The effect of different etching times on the retention of fissure sealants in second primary and first permanent molars. *Int J Paediatr Dent* 1997; 7: 81–6.
36. Ekstrand KR, Christiansen ME. Outcomes of a non-operative caries treatment programme for children and adolescents. *Caries Res* 2005; 39: 455–67.
37. Ekstrand KR, Kuzmina I, Bjørndal L, Thylstrup A. Relationship between external and histologic features of progressive stages of caries in the occlusal fossa. *Caries Res* 1995; 29: 243–50.
38. Ekstrand KR, Bruun G, Bruun M. Plaque and gingival status as indicators for caries progression on approximal surfaces. *Caries Res* 1998; 32: 41–5.
39. Ekstrand KR, Martignon S, Bakhshandeh A, Ricketts DN. The non-operative resin treatment of proximal caries lesions. *Dent Update* 2012; 39: 614–22.
40. Elderton RJ. Clinical studies concerning re-restoration of teeth. *Adv Dent Res* 1990; 4: 4–9.
41. Elderton RJ. Preventive (evidence-based) approach to quality general dental care. *Med Princ Pract* 2003; 12 (Suppl 1): 12–21.
42. Ercan E, Dulgergil T, Soyman M, Dalli M, Yildirim I. A field trial of two restorative materials used with atraumatic restorative treatment in rural Turkey: 24-month results. *J Appl Oral Sci* 2009; 17: 307–14.

43. Farag MEH. Atraumatic restorative treatment and oral health in Upper Egypt. PhD Thesis. University of Nijmegen, 2012.
44. Fédération Dentaire Internationale. FDI policy statement: minimal intervention in the management of dental caries. FDI, Ferney-Voltaire, France, 2002.
45. Forsten L. Fluoride release and uptake by glass-ionomers and related materials and its clinical effect. *Biomaterials* 1998; 19: 503–8.
46. Foster T, Perinpanayagam H, Pfaffenbach A, Certo M. Recurrence of early childhood caries after comprehensive treatment with general anesthesia and follow-up. 2006; 73: 25–30.
47. Frencken JE. Tratamento restaurador atraumático (ART): um conceito contemporâneo para o manejo da cárie dentária. In: Da Toledo OA, ed. *Odontopediatria fundamentos para a prática clínica*. São Paulo: Premier, 2012.
48. Frencken JE, Holmgren CJ. *Atraumatic restorative treatment for dental caries*. Nijmegen: STI, 1999.
49. Frencken JE, Holmgren CJ. The atraumatic restorative treatment (ART) approach. In: Albrektsson T, Bratthall D, Glantz PO, Lindhe J, eds. *Tissue preservation in caries treatment*. Berlin: Quintessence Verlag-GMBH, 2001.
50. Frencken JE, van Amerongen WE. The atraumatic restorative treatment (ART) approach to manage dental caries. In: Fejerskov O, Kidd E, eds. *Dental caries: The disease and its clinical management*. Oxford: Blackwell Munksgaard, 2008.
51. Frencken JE, Wolke J. Clinical and SEM assessment of ART high-viscosity glass-ionomer sealants after 8–13 years in 4 teeth. *J Dent* 2010; 38: 59–64.
52. Frencken JE, Songpaisan Y, Phantumvanit P, Pilot T. An atraumatic restorative treatment (ART) technique: evaluation after one year. *Int Dent J* 1994; 44: 460–4.
53. Frencken JE, Pilot T, Songpaisan Y, Phantumvanit P. Atraumatic restorative treatment (ART): rationale, technique, and development. *J Public Health Dent* 1996; 56: 135–40.
54. Frencken JE, Makoni F, Sithole WD, Hackenitz E. Three-year survival of one-surface ART restorations and glass-ionomer sealants in a school oral health programme in Zimbabwe. *Caries Res* 1998; 32: 119–26.
55. Frencken JE, Makoni F, Sithole WD. ART restorations and glass ionomer sealants in Zimbabwe: survival after 3 years. *Community Dent Oral Epidemiol* 1998; 26: 372–81.
56. Frencken JE, Holmgren CJ, van Palenstein Helderman WH. *Basic Package of Oral Care*. Nijmegen: WHO Collaborating Centre, 2002.
57. Frencken JE, van't Hof MA, Taifour D, Al-Zaher I. Effectiveness of the ART and traditional amalgam approach in restoring single-surface cavities in posterior teeth of permanent dentitions in school children after 6.3 years. *Community Dent Oral Epidemiol* 2007; 35: 207–14.
58. Frencken JE, Peters MC, Manton DJ, Leal SC, Gordan VV, Eden E. Minimal intervention dentistry for managing dental caries – a review. *Int Dent J* 2012; 62: 223–43.
59. Frencken JE, Leal SC, Navarro MF. Twenty-five-year atraumatic restorative treatment (ART) approach: a comprehensive overview. *Clin Oral Investig* 2012; 16: 1337–46.
60. Gomez SS, Basili CP, Emilson CG. A 2-year clinical evaluation of sealed noncavitated approximal posterior carious lesions in adolescents. *Clin Oral Investig* 2005; 9: 239–43.
61. Griffin SO, Oong E, Kohn W, Vidakovic B, Gooch BF, Bader J, Clarkson J, Fontana MR, Meyer DM, Rozier RG, Weintraub JA, Zero DT. The effectiveness of sealants in managing caries lesions. *J Dent Res* 2008; 87: 169–74.
62. Grossman ES, Mickenautsch S. Microscope observations of ART excavated cavities and restorations. *S Afr Dent J* 2002; 57: 359–63.
63. Gruythuysen RJM. Non-restorative cavity treatment. Managing rather than masking caries activity. *Ned Tijdschr Tandheelkd* 2010; 117: 173–8.
64. Gruythuysen RJM, van Strijp AJP, Wu M-K. Long-term survival of indirect pulp treatment performed in primary and permanent teeth with clinically diagnosed deep carious lesions. *J Endod* 2010; 36: 1490–3.
65. Harris NO, Garcia-Godoy F. *Primary preventive dentistry*. 5th ed. Stamford, CT: Appleton & Lange, 1999.
66. Heller KE, Reed SG, Bruner FW, Eklund SA, Burt BA. Longitudinal evaluation of sealing molars with and without incipient dental caries in a public health program. *J Public Health Dent* 1995; 55: 148–53.
67. Heyduck C, Meller C, Schwahn C, Splieth CH. Effectiveness of sealants in adolescents with high and low caries experience. *Caries Res* 2006; 40: 375–81.
68. Hiiri A, Ahovuo-Saloranta A, Nordblad A, Mäkelä M. Pit and fissure sealants versus fluoride varnishes for preventing dental decay in children and adolescents. *Cochrane Database Syst Rev* 2010; (3): CD003067.
69. Hintze H, Wenzel A, Danielsen B, Nyvad B. Reliability of visual examination, fibre-optic transillumination, and bite-wing radiography, and reproducibility of direct visual examination following tooth separation for the identification of cavitated carious lesions in contacting approximal surfaces. *Caries Res* 1998; 32: 204–9.
70. Hiremath SS. *Preventive dentistry and community dentistry*. New Delhi: Elsevier, 2007.
71. Honkala S, Honkala E. Atraumatic dental treatment among Finnish elderly persons. *J Oral Rehabil* 2002; 29: 435–40.
72. Honkala E, Behbehani J, Ibricevic H, Kerosuo E, Al-Jame G. The atraumatic restorative treatment (ART) approach to restoring primary teeth in a standard dental clinic. *Int J Paediatr Dent* 2003; 13: 172–9.
73. Hu JY, Chen XC, Li YQ, Smales RJ, Yip KH. Radiation-induced root surface caries restored with glass-ionomer cement placed in conventional and ART cavity preparations: results at two years. *Aust Dent J* 2005; 50: 186–90.
74. Hu X, Chen X, Fan M, Mulder J, Frencken JE. What happens to cavitated teeth over time? A 3.5-year prospective cohort study in China. *Int Dent J* 2013; 63: 183–8.
75. International Association for Dental Research. IADR releases summary of dental materials innovation workshop, 2013. http://www.iadr.org/files/public/IADR_DentalMaterialsResearchAgenda.pdf (accessed November 7, 2014).
76. Innes NP, Evans DJ, Stirrups DR. Sealing caries in primary molars: randomized control trial, 5-year results. *J Dent Res* 2011; 90: 1405–10.
77. Imparato JCP. *Tratamento restaurador atraumático (ART): técnicas de mínima intervenção para o tratamento da doença cárie dentária*. Curitiba, Brazil: Editora Maio, 2005.
78. Isenberg BP, Leinfelder KF. Efficacy of beveling posterior composite resin preparations. *J Esthet Dent* 1990; 2: 70–3.
79. Kateeb ET. Factors related to the use of atraumatic restorative treatment (ART) in pre and post pediatric dentistry programs and in pediatric dentistry practices in the US. PhD thesis. University of Iowa, 2012.
80. Kawashita Y, Kitamura M, Saito T. Early childhood caries. *Int J Dent* 2011; 2011: 725320.
81. Kidd EA, Beighton D. Prediction of secondary caries around tooth-colored restorations: a clinical and microbiological study. *J Dent Res* 1996; 75: 1942–6.
82. Kidd EAM. Should deciduous teeth be restored? Reflections of a cariologist. *Dent Update* 2012; 39: 159–66.
83. Leal SC, Bronkhorst EM, Fan M, Frencken JE. Untreated cavitated dentine lesions: impact on children's quality of life. *Caries Res* 2012; 46: 102–6.
84. Lenters M, van Amerongen WE, Mandari GJ. Iatrogenic damage to the adjacent surfaces of primary molars in three different ways of cavity preparation. *Eur Arch Paed Dent* 2006; 7: 6–10.
85. Lo ECM, Schwarz E, Wong MCM. Arresting dentine caries in Chinese preschool children. *Int J Paediatr Dent* 1998; 8: 253–60.
86. Lo ECM, Holmgren CJ. Provision of atraumatic restorative treatment (ART) restorations to Chinese pre-school children – a 30-month evaluation. *Int J Paed Dent* 2001; 11: 3–10.
87. Lo ECM, Luo Y, Fan MW, Wei SHY. Clinical investigation of two glass-ionomer restoratives used with the Atraumatic Restorative Treatment approach in China: two-years results. *Caries Res* 2001; 35: 458–63.
88. Lo EC, Luo Y, Tan HP, Dyson JE, Corbet EF. ART and conventional root restorations in elders after 12 months. *J Dent Res* 2006; 85: 929–32.
89. Locker D, Jokovic A, Kay EJ. Prevention. Part 8: the use of pit and fissure sealants in preventing caries in the permanent dentition of children. *Br Dent J* 2003; 195: 375–8.
90. Long TD, Smith BG. The effect of contact area morphology on operative dental procedures. *J Oral Rehabil* 1988; 15: 593–8.
91. Loomans BA, Opdam NJ, Roeters FJ, Bronkhorst EM, Burgersdijk RC, Dörfer CE. A randomized clinical trial on proximal contacts of posterior composites. *J Dent* 2006; 34: 292–7.
92. Loomans BA, Opdam NJ, Roeters FJ, Bronkhorst EM, Plasschaert AJ. The long-term effect of a composite resin restoration on proximal contact tightness. *J Dent* 2007; 35: 104–8.
93. Lunder N, von der Fehr FR. Approximal cavitation related to bite-wing image and caries activity in adolescents. *Caries Res* 1996; 30: 143–7.

94. Lussi A, Gygax M. Iatrogenic damage to adjacent teeth during classical approximal box preparation. *J Dent* 1998; 26: 435–41.

95. Lygidakis NA, Oulis KI, Christodoulidis A. Evaluation of fissure sealants retention following four different isolation and surface preparation techniques: four years clinical trial. *J Clin Pediatr Dent* 1994; 19: 23–5.

96. Martignon S, Ekstrand KR, Ellwood R. Efficacy of sealing proximal early active lesions: an 18-month clinical study evaluated by conventional and subtraction radiography. *Caries Res* 2006; 40: 382–8.

97. Martignon S, Chavarría N, Ekstrand KR. Caries status and proximal lesion behaviour during a 6-year period in young adult Danes: an epidemiological investigation. *Clin Oral Investig* 2010; 14: 383–90.

98. Martignon S, Ekstrand KR, Gomez J, Lara JS, Cortes A. Infiltrating/sealing proximal caries lesions: a 3-year randomized clinical trial. *J Dent Res* 2012; 91: 288–92.

99. McComb D, Erickson RL, Maxymiw WG, Wood RE. A clinical comparison of glass ionomer, resin-modified glass ionomer and resin composite restorations in the treatment of cervical caries in xerostomic head and neck radiation patients. *Oper Dent* 2002; 27: 430–7.

100. McDonald SP, Sheiham A. The distribution of caries on different tooth surfaces at varying levels of caries – a compilation of data from 18 previous studies. *Community Dent Health* 1992; 9: 39–48.

101. Mejàre I. Indications for fissure sealants and their role in children and adolescents. *Dent Update* 2011; 38: 699–703.

102. Mejàre I, Malmgren B. Clinical and radiographic appearance of proximal carious lesions at the time of operative treatment in young permanent teeth. *Scand J Dent Res* 1986; 94: 19–26.

103. Mejàre I, Gröndahl HG, Carlstedt K, Grever AC, Ottosson E. Accuracy at radiography and probing for the diagnosis of proximal caries. *Scand J Dent Res* 1985; 93: 178–84.

104. Mejàre I, Källestål C, Stenlund H, Johansson H. Caries development from 11 to 22 years of age: a prospective radiographic study. *Caries Res* 1999; 33: 93–100.

105. Mejàre I, Lingström P, Petersson LG, Holm AK, Twetman S, Källestål C, Nordenram G, Lagerlöf F, Söder B, Norlund A, Axelsson S, Dahlgren H. Caries-preventive effect of fissure sealants: a systematic review. *Acta Odontol Scand* 2003; 61: 321–30.

106. Mejàre I, Stenlund H, Zelezny-Holmlund C. Caries incidence and lesion progression from adolescence to young adulthood: a prospective 15-year cohort study in Sweden. *Caries Res* 2004; 38: 130–41.

107. Meyer-Lueckel H, Kielbassa AM. Surface layer erosion of natural caries lesions with phosphoric and hydrochloric acid gels in preparation for resin infiltration. *Caries Res* 2007; 41: 223–30.

108. Meyer-Lueckel H, Bitter K, Paris S. Randomized controlled clinical trial on proximal caries infiltration: three-year follow-up. *Caries Res* 2012; 46: 544–8.

109. Mickenautsch S, Yengopal V. Caries-preventive effect of glass ionomer and resin-based fissure sealants on permanent teeth: an update of systematic review evidence. *BMC Res Notes* 2011; 4: 22.

110. Mickenautsch S, Frencken JE, van't Hof M. Atraumatic restorative treatment and dental anxiety in outpatients attending public oral health clinics in South Africa. *J Public Health Dent* 2007; 67: 179–84.

111. Mijan M, de Amorim RG, Leal SC, Mulder J, Oliveira L, Creugers NHJ, Frencken JE. The 3.5-year survival rates of primary molars treated according to three treatment protocols: a controlled clinical trial. *Clin Oral Invest* 2014; 18: 1061–9.

112. Milsom KM, Tickle M, Blinkhorn AS. Dental pain and dental treatment of young children attending the general dental service. *Br Dent J* 2002; 192: 280–4.

113. Molina GF, Leal SC, Frencken JE. Strategies for managing carious lesions in patients with disabilities – a systematic review. *J Disabil Oral Health* 2011; 12: 159–67.

114. Molina GF, Cabral RJ, Mazzola I, Brain Lascano L, Frencken JE. Mechanical performance of encapsulated restorative glass-ionomer cements for use with atraumatic restorative treatment (ART). *J Appl Oral Sci* 2013; 21: 243–9.

115. Molina GF, Cabral RJ, Mazzola I, Brain Lascano L, Frencken JE. Biaxial flexural strength of high-viscosity glass-ionomer cements heat-cured with an LED lamp during setting. *BioMed Res Int* 2013; 2013: 838460.

116. Moopnar M, Faulkner KD. Accidental damage to teeth adjacent to crown-prepared abutment teeth. *Aust Dent J* 1991; 36: 136–40.

117. Navarro MF, Rigolon CJ, Barata TJ, Bresciani E, Fagundes TC, Peters MC. Influence of occlusal access on demineralized dentin removal in the atraumatic restorative treatment (ART) approach. *Am J Dent* 2008; 21: 251–4.

118. Navarro MF, Modena KC, Freitas MC, Fagundes TC. Transferring ART research into education in Brazil. *J Appl Oral Sci* 2009; 17 (Suppl): 99–105.

119. NDIP. Scotland's National Dental Inspection Programme 2007. http://www.scottishdental.org/index.aspx?o=2155&recordid=474 (accessed November 17, 2011).

120. Ngo HC, Mount G, Mc Intyre J, Tuisuva J, Von Doussa RJ. Chemical exchange between glass-ionomer restorations and residual carious dentine in permanent molars: an in vivo study. *J Dent* 2006; 34: 608–13.

121. O'Sullivan EA, Curzon ME. The efficacy of comprehensive dental care for children under general anesthesia. *Br Dent J* 1991; 171: 56–8.

122. Oong EM, Griffin SO, Kohn WG, Gooch BF, Caufield PW. The effect of dental sealants on bacteria levels in caries lesions: a review of the evidence. *J Am Dent Assoc* 2008; 139: 271–8.

123. Opdam NJ, Roeters JJ, Kuijs R, Burgersdijk RC. Necessity of bevels for box only class II composite restorations. *J Prosthet Dent* 1998; 80: 274–9.

124. Opdam NJ, Roeters JJ, van Berghem E, Eijsvogels E, Bronkhorst E. Microleakage and damage to adjacent teeth when finishing class II adhesive preparations using either a sonic device or bur. *Am J Dent* 2002; 15: 317–20.

125. Opdam NJ, Roeters JJ, de Boer T, Pesschier D, Bronkhorst E. Voids and porosities in class I micropreparations filled with various resin composites. *Oper Dent* 2003; 28: 9–14.

126. Opdam NJ, Bronkhorst EM, Roeters JM, Loomans BA. Longevity and reasons for failure of sandwich and total-etch posterior composite resin restorations. *J Adhes Dent* 2007; 9: 469–75.

127. Opdam NJ, Bronkhorst EM, Loomans BA, Huysmans MC. 12-year survival of composite vs. amalgam restorations. *J Dent Res* 2010; 89: 1063–7.

128. Ovrebo RC, Raadal M. Microleakage in fissures sealed with resin or glass ionomer cement. *Scand J Dent Res* 1990; 98: 66–9.

129. Paris S, Meyer-Lueckel H, Kielbassa AM. Resin infiltration of natural caries lesions. *J Dent Res* 2007; 86: 662–6.

130. Peng JJ, Botelho MG, Matinlinna JP. Silver compounds used in dentistry for caries management: a review. *J Dent* 2012; 40: 531–41.

131. Peumans M, Kanumilli P, De Munck J, Van Landuyt K, Lambrechts P, Van Meerbeek B. Clinical effectiveness of contemporary adhesives: a systematic review of current clinical trials. *Dent Mater* 2005; 21: 864–81.

132. Phantumvanit P, Songpaisan Y, Pilot T, Frencken JE. Atraumatic restorative treatment (ART): survival of one-surface restorations in the permanent dentition. *J Public Health Dent* 1996; 56: 141–45.

133. Pine CM, Adair PM, Burnside G, Nicoll AD, Gillett A, Borges-Yáñez SA, Broukal Z, Brown J, Declerck D, Ping FX, Gugushe T, Hunsrisakhun J, Lo EC, Naidu R, Nyandindi U, Poulsen VJ, Rassameemasmaung S, Splieth C, Sutton BK, Soo TC, Whelton H. Barriers to the treatment of childhood caries perceived by dentists working in different countries. *Community Dent Health* 2004; 21: 112–20.

134. Pitts NB, Rimmer PA. An in vivo comparison of radiographic and directly assessed clinical caries status of posterior approximal surfaces in primary and permanent teeth. *Caries Res* 1992; 26: 146–52.

135. Qvist V, Johannessen L, Bruun M. Progression of approximal caries in relation to iatrogenic preparation damage. *J Dent Res* 1992; 71: 1370–3.

136. Qvist V, Laurberg L, Poulsen A, Teglers PT. Longevity and cariostatic effects of everyday conventional glass-ionomer and amalgam restorations in primary teeth: three-year results. *J Dent Res* 1997; 76: 1387–96.

137. Rahimtoola S, van Amerongen E. Comparison of two tooth-saving preparation techniques for one-surface cavities. *J Dent Child* 2002; 69: 16–26.

138. Rahimtoola S, van Amerongen E, Maher R, Groen H. Pain related to different ways of minimal intervention in the treatment of small caries lesions. *J Dent Child* 2000; 67: 123–7.

139. Ratledge DK. A clinical and laboratory investigation of the tunnel restoration. Thesis. University of London, 1999.

140. Ratledge DK, Kidd EAM, Beighton D. A clinical and microbiological study of approximal carious lesions. Part 1: the relationship between cavitation, radiographic lesion depth, the site-specific gingival index and the level of infection of the dentin. *Caries Res* 2001; **35**: 3–7.
141. Ratledge DK, Kidd EAM, Treasure ET. The tunnel restoration. *Br Dent J* 2002; **193**: 501–6.
142. Rugg-Gunn AJ. Approximal carious lesions. A comparison of the radiological and clinical appearances. *Br Dent J* 1972; **133**: 481–4.
143. Ruiz O, Frencken JE. ART integration in oral health care systems in Latin American countries as perceived by directors of oral health. *J Appl Oral Sci* 2009; **17**: 106–13.
144. Santamaria RM, Innes NP, Machiulskiene V, Evans DJ, Splieth CH. Caries management strategies for primary molars: 1-yr randomized control trial results. *J Dent Res* 2014; **93**: 1062–9.
145. SBU. Caries diagnosis, risk assessment and non-invasive treatment of early caries lesions. A systematic review. SBU Report No 188. Swedish Council on Health Technology Assessment, 2007.
146. Schmidlin PR, Göhring TN, Roos M, Zehnder M. Wear resistance and surface roughness of a newly devised adhesive patch for sealing smooth enamel surfaces. *Oper Dent* 2006; **31**: 115–21.
147. Schmidt M, Kirkevang LL, Hørsted-Bindslev P, Poulsen S. Marginal adaptation of a low-shrinkage silorane-based composite: 1-year randomized clinical trial. *Clin Oral Investig* 2011; **15**: 291–5.
148. Schriks MCM, van Amerongen WE. Atraumatic perspectives of ART. Psychological and physiological aspects of treatment with and without rotary instruments. *Community Dent Oral Epidemiol* 2003; **31**: 15–20.
149. Schwartz M, Gröndahl HG, Pliskin JS, Boffa J. A longitudinal analysis from bite-wing radiographs of the rate of progression of approximal carious lesions through human dental enamel. *Arch Oral Biol* 1984; **29**: 529–36.
150. Schwarz E, Vigild M, Skak-Iversen L. Danish child oral health status in two decades of organized child oral health. In: Friis-Hasché E, ed. *Child oral health care in Denmark – a great success in health promotion*. Copenhagen: Copenhagen University Press, 1994: 38–44.
151. Seale NS, Casamassimo PS. Access to dental care for children in the United States. A survey of general practitioners. *J Am Dent Assoc* 2003; **134**: 1630–40.
152. Seddon RP. The detection of cavitation in carious approximal surfaces in vivo by tooth separation and an impression techniques. Thesis. University of London, 1989.
153. Simonsen RJ, Stallard RE. Sealant-restorations utilizing a diluted filled composite resin: one year results. *Quintessence Int Dent Dig* 1977; **8**: 77–84.
154. Simonsen RJ. Pit and fissure sealant: review of the literature. *Pediatr Dent* 2002; **24**: 393–414.
155. Smales RJ, Gao W, Ho FT. In vitro evaluation of sealing pits and fissures with newer glass-ionomer cements developed for the ART technique. *J Clin Pediatr Dent* 1997; **21**: 321–3.
156. Soncini JA, Maserejian NN, Trachtenberg F, Tavares M, Hayes C. The longevity of amalgam versus compomer/composite restorations in posterior primary and permanent teeth: findings from the New England Children's Amalgam Trial. *J Am Dent Assoc* 2007; **138**: 763–72.
157. Sonmez D, Duruturk L. Success rate of calcium hydroxide pulpotomy in primary molars restored with amalgam and stainless steel crowns. *Br Dent J* 2010; **208**: E18, discussion 408–9.
158. Splieth CH, Bünger B, Pine C. Barriers for dental treatment of primary teeth in East and West Germany. *Int J Paediatr Dent* 2009; **19**: 84–90.
159. Splieth CH, Ekstrand KR, Alkilzy M, Clarkson J, Meyer-Lueckel H, Martignon S, Paris S, Pitts NB, Ricketts DN, van Loveren C. Sealants in dentistry: outcomes of the ORCA Saturday Afternoon Symposium 2007. *Caries Res* 2010; **44**: 3–13.
160. Strand GV, Nordbø H, Tveit AB, Espelid I, Wikstrand K, Eide GE. A 3-year clinical study of tunnel restorations. *Eur J Oral Sci* 1996; **104**: 384–9.
161. Strand GV, Nordbø H, Leirskar J, von der Fehr FR, Eide GE. Tunnel restorations placed in routine practice and observed for 24 to 54 months. *Quintessence Int* 2000; **31**: 453–60.
162. Takahashi N, Nyvad B. Caries ecology revisited: microbial dynamics and the caries process. *Caries Res* 2008; **42**: 409–18.
163. Taifour D, Frencken JE, Beiruti N, van 't Hof MA, Truin GJ. Effectiveness of glass-ionomer (ART) and amalgam restorations in the deciduous dentition – results after 3 years. *Caries Res* 2002; **36**: 437–44.
164. Thomas RZ, Ruben JL, ten Bosch JJ, Fidler V, Huysmans MC. Approximal secondary caries lesion progression, a 20-week in situ study. *Caries Res* 2007; **41**: 399–405.
165. Thylstrup A, Bille J, Qvist V. Radiographic and observed tissue changes in approximal carious lesions at the time of operative treatment. *Caries Res* 1986; **20**: 75–84.
166. Tjäderhane L, Nascimento FD, Breschi L, Mazzoni A, Tersariol ILS, Geraldeli S, Tezvergil-Mutluay A, Carrilho M, Carvalho RM, Tay FR, Pashley DH. Strategies to prevent hydrolytic degradation of the hybrid layer – a review. *Dent Mater* 2013; **29**: 999–1011.
167. Topaloglu-Ak A, Eden E, Frencken JE. Perceived dental anxiety among schoolchildren treated through three caries removal approaches. *J Appl Oral Sci* 2007; **15**: 235.
168. Trairatvorakul C, Itsaraviriyakul S, Wiboonchan W. Effect of glass-ionomer cement on the progression of proximal caries. *J Dent Res* 2011; **90**: 99–103.
169. Tyas MJ, Anusavice KJ, Frencken JE, Mount GJ. Minimal intervention dentistry – a review. *Int Dent J* 2000; **50**: 1–12.
170. Van Amerongen JP, Penning C, Kidd EAM, ten Cate JM. An in vitro assessment of the extent of caries under small occlusal cavities. *Caries Res* 1992; **26**: 89–93.
171. Van Bochove JA, van Amerongen WE. The influence of restorative treatment approaches and the use of local anaesthesia on the children's discomfort. *Eur Arch Ped Dent* 2006; **7**: 11–16.
172. Van der Zee V, van Amerongen WE. Short communication: influence of preformed metal crowns (Hall technique) on the occlusal vertical dimension in the primary dentition. *Eur Arch Paediatr Dent* 2010; **11**: 225–7.
173. Van't Hof MA, Frencken JE, van Palenstein Helderman WH, Holmgren CJ. The ART approach for managing dental caries: a meta-analysis. *Int Dent J* 2006; **56**: 345–51.
174. Vidnes-Kopperud S, Tveit AB, Espelid I. Changes in the treatment concept for approximal caries from 1983 to 2009 in Norway. *Caries Res* 2011; **45**: 113–20.
175. Waggoner WF, Siegal M. Pit and fissure sealant application: updating the technique. *J Am Dent Assoc* 1996; **127**: 351–61, quiz 391–2.
176. Welbury R, Raadal M, Lygidakis NA. EAPD guidelines for the use of pit and fissure sealants. *Eur J Paediatr Dent* 2004; **5**: 179–84.
177. Wilson NHF, Wilson MA, Wastell DG, Smith GA. Performance of Occlusin in butt-joint and bevel-edged preparations: five-year results. *Dent Mater* 1991; **7**: 92–8.
178. Yengopal V, Mickenautsch S, Bezerra AC, Leal SC. Caries-preventive effect of glass ionomer and resin-based fissure sealants on permanent teeth: a meta analysis. *J Oral Sci* 2009; **51**: 373–82.

20

Caries 'removal' and the pulpo-dentinal complex

E.A.M. Kidd, L. Bjørndal, and O. Fejerskov

Introduction

When Black wrote his textbook of *Operative Dentistry* in 1908 he based it on his observations and understanding of the disease processes at that time. One conclusion was [11]:

> *The complete divorcement of dental practice from studies of the pathology of dental caries, that existed in the past, is an anomaly in science that should not continue. It has the apparent tendency to make dentists mechanics only.*

Over the past century something has gone strangely wrong, probably because in many dental schools the science of cariology and the technicalities of operative dentistry have been taught and researched separately from each other. Generations of students have passed through operative technique courses and phantom-head exercises restoring natural caries-free teeth or, even worse, plastic counterfeits. This use of plastic may be essential if natural teeth are not available, but it is less than ideal because it encourages a

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

template, mechanical approach to a subject that should be taught biologically.

When caries-free natural or plastic teeth are used, the eventual appearance of caries lesions in patients is a considerable inconvenience, ruining stereotyped preconceptions of outline forms, appropriate depths, widths, and angles taught in classical phantom-head courses. Indeed, the students' transition to the clinic can be very traumatic. They *must not* now produce the stereotyped outline demanded in a phantom head. For instance, a flat floor would never be produced following caries removal, and even to attempt this could result in exposure. Appropriate caries removal dictates the shape of the cavity, hence this chapter will assemble the biological evidence behind caries removal. An understanding of the pathology of dental caries (presented in Chapter 5) should underpin clinical management.

In 1967 Massler elegantly distilled current scientific knowledge on this subject. He stressed [46]:

> *It is somewhat disturbing to the biologically oriented clinical teacher to witness the overly focused attention of some dentists upon the operative and restorative phases of dentistry, the 'drilling and filling' of teeth, to the neglect of the disease process which causes the lesion (cariology) and the preoperative treatment of the wounded tooth-bone.*

These words are the reincarnation of G.V. Black's plea, written some 60 years earlier than Massler.

Another 25 years later these thoughts were clinically implemented as shown in Fig. 13.6. Within 3 weeks it was possible after one session to teach such patients with open, painful cavities to brush and clean the cavities to the extent that pain relief was obtained. Note the change in color of the dentin obtained just by cleaning the cavity – no removal of carious dentin had been performed. This concept was then systematized in an attempt to arrest root surface lesions [51] – see Fig. 13.4. The outcome was the same. Thus, it was concluded that by merely brushing the biofilm partly away it was possible to convert active, ongoing caries lesions into arrested lesions – and eliminate the pain reaction. In other words, the statements from Black and Massler were correct.

In this chapter we are going to bring these concepts even further in an attempt to apply a biological approach to restorative treatment in the future.

The pulpo-dentinal complex and caries

In the following we summarize essential points from Chapter 5 about caries progression in dentin and the reaction of the pulpo-dentinal complex.

- Lesions, whether in enamel or dentin, surface intact or cavitated, can be arrested by plaque control alone provided the lesion can be accessed for cleaning.
- Dentin lesions beneath demineralized, but uncavitated, enamel are a result of the biofilm metabolism on the tooth surface. The surface is accessible to cleaning, and this is why these lesions can be arrested. They never justify operative intervention.
- Similarly, the root surface lesion can be arrested at any stage, although cementum and dentin are invaded by microorganisms very early in the process. Arrested dentinal lesions, whether in the crown or root, are 'infected' without this resulting in further lesion progression.
- Dentin is a vital tissue containing odontoblast processes, and dentin and pulp must be considered together.
- Dentin mounts a cellular driven defence to the pH fluctuations in the biofilm, resulting in tubular and peritubular mineralization and tertiary dentin at the pulp-dentin border.
- In slowly progressing lesions, these odontoblastic reactions gradually 'occlude' the tubules and seal off the pathways between the oral environment and the pulp.
- Inflammatory reactions in the pulp may occur even when demineralization is confined to enamel.
- In rapidly progressing dentin lesions, the odontoblasts may be destroyed and this results in open tubular pathways in the dentin.
- When the bacterial invasion penetrates the tertiary dentin there will eventually be a severely inflamed pulp followed by necrosis.

Pulpitis and its clinical diagnosis

Clinical symptoms relate poorly to pulp pathology, which is a problem to the clinician who needs to know whether the pulp is likely to survive. A clinical diagnosis of reversible or irreversible pulpitis is used to predict whether the pulp is likely to survive. In *reversible pulpitis* the pain evoked by a hot, cold, or sweet stimulus is of short duration, disappearing when the stimulus is removed. The clinician hopes to preserve a healthy vital pulp. In *irreversible pulpitis* the pain persists for minutes or hours after removal of the stimulus. The pulp is likely so damaged that it must be removed.

Why are pulpo-dentinal reactions important to the choice of operative management?

It is the pulpo-dentinal complex, with a certain inflammatory reaction, that the clinician interferes with when instituting operative treatment. Should a classical operative approach that focuses on removing all 'infected' dentin prior to restoration be the treatment of choice? For more than a century dentists have been taught that 'all' infected, softened dentin should be removed—the cavity even washed with antimicrobials—to eliminate microorganisms. But is this possible, is it necessary, or might it actually be contraindicated because it could irreparably damage the pulp? Why is it possible to arrest cavitated root-surface caries lesions without removing the dentin invaded by numerous bacteria? In order to answer these questions we have to examine the literature in order to seek evidence for the various views.

From the present understanding of the pathophysiology of the caries process as outlined in Chapters 3, 5, 9, and 18, logical clinical management should follow: that is, arrest ongoing carious lesions and evaluate the symptoms from the pulp before a decision about a possible operative intervention is made. There is evidence to show it is not necessary to remove all infected soft dentin mechanically in order to arrest further lesion progression. Indeed, this vigorous excavation may further compromise the survival of the tooth.

The infected dentin concept and its clinical consequence

It is the biofilm metabolism that drives the caries dissolution. Hence, the biofilm should be interfered with (mechanically disturbed/removed) as far as possible to arrest any lesion. Microorganisms invade along the gap between the demineralized enamel and the dentin once a cavity is created (Fig. 20.1), but this does not imply that all of the infected dentin should, or even can be removed. The simple answer is that it is neither necessary nor possible to do this.

As emphasized in Chapter 5 (see the schematic illustration in Fig. 5.73), softening due to dentin demineralization precedes the organisms responsible for it [17, 18, 40, 52]. However, microorganisms may invade any open tubule in dentin exposed to the oral environment without necessarily demineralizing the tissue. Microorganisms will remain even if all soft dentin is removed. These organisms remain viable beneath restorations without apparently causing any detrimental effect. Little evidence has been produced to support the concept of removing 'infected dentin.' Maybe the appreciation of dental caries as an infectious disease [31, 54] led the profession to think that all infected tissues should be eliminated. We came from the period where microorganisms were immediately associated with disease and hence should be eliminated. Just think of the focal infection concepts. What has emerged in recent years, as we will see as the chapter unfolds, is that organisms 'sealed' in a cavity by a filling are deprived of nutrients and respond to this stress to the extent that, if they are now sampled, they no longer represent the acid-producing, cariogenic bacteria.

Figure 20.2 shows the clinical appearance of a cavitated occlusal lesion where the patient is not able to clean the biofilm out of the cavity. A restoration is needed. The figure shows and describes the clinical appearances as the lesion is opened for restoration. How much soft, demineralized dentin should be removed prior to sealing this cavity? For many years the operative tradition was as follows: remove softened (Fig. 20.3), infected carious dentin with a bur or excavator until the dentin is hard to touch; extend the removal of enamel and dentin to obtain a cavity suitable for insertion of the restorative material of choice; apply some agent (e.g., calcium hydroxide, zinc oxide eugenol, or glass-ionomer cement) to protect the pulpo-dentinal complex from any toxic effects of restorative materials, microorganisms penetrating due to leakage of the tooth–restoration interface, and thermal fluctuations.

Some dental schools teach that the enamel–dentin junction should be rendered hard and free of any brown stain. Other schools teach students to remove everything at the enamel–dentin junction to the hard substrate and ignore the brown stain. However, the degree of discoloration alone is a subjective and rather unreliable guide to gauge the level of dentin infection: a few bacteria remain whatever restorative approach is adopted and practiced (there are more microorganisms living on and within us than we are composed of in terms of the number of mammalian cells in tissues and organs of the body!). Thus, it seems logical to leave stain as the more conservative approach [34], unless the line of stain would compromise the appearance of the completed tooth-colored restoration.

Over the pulpal surface, only dentin that can be gently removed with an excavator should be eliminated, provided that the tooth is symptomless and responds as vital to pulp testing. Vigorous hand excavation over the pulpal surface of a deep cavity is contraindicated because it is very easy to expose the pulp. Soft, heavily infected dentin is usually wet (Fig. 20.3e), but it is impossible to know the depth of the dentin remaining between the base of the cavity and the pulp. The experienced clinician makes an educated guess and the student is in tiger country! Slow excavation close to the pulp represents a risk of pulp exposure. Sometimes, particularly when an old restoration has been removed, the demineralized dentin may appear darkly stained, dry, and friable (Fig. 20.4). This dentin has been shown to be 'lightly' infected [34] and it may represent residual caries that a previous dentist left during cavity preparation. It does not require vigorous excavation, but excavation is now unlikely to cause exposure because tertiary dentin will be present.

The subjective clinical assessment of carious dentin led Fusayama to develop a caries dye (acid red in propylene glycol) [17–19] to differentiate clinically 'infected' from 'affected' dentin [14, 26, 36]. He reported that the more superficial zone of infected dentin was an irreversibly damaged, bacterially infected layer that would never remineralize. The deepest affected dentin has been claimed to harden as a result of remineralization [15] (see Fig. 5.73). Fusayama suggested that the dye-staining front coincided with the bacterial invasion of the dentin. However, several studies have reported that the dye does not discretely discriminate the bacterially infected from softened affected tissues [2, 13, 70]. Consequently, its injudicious use may lead to overpreparation.

Others have recommended the chemical removal of carious (infected) dentin [4] based on the philosophy that

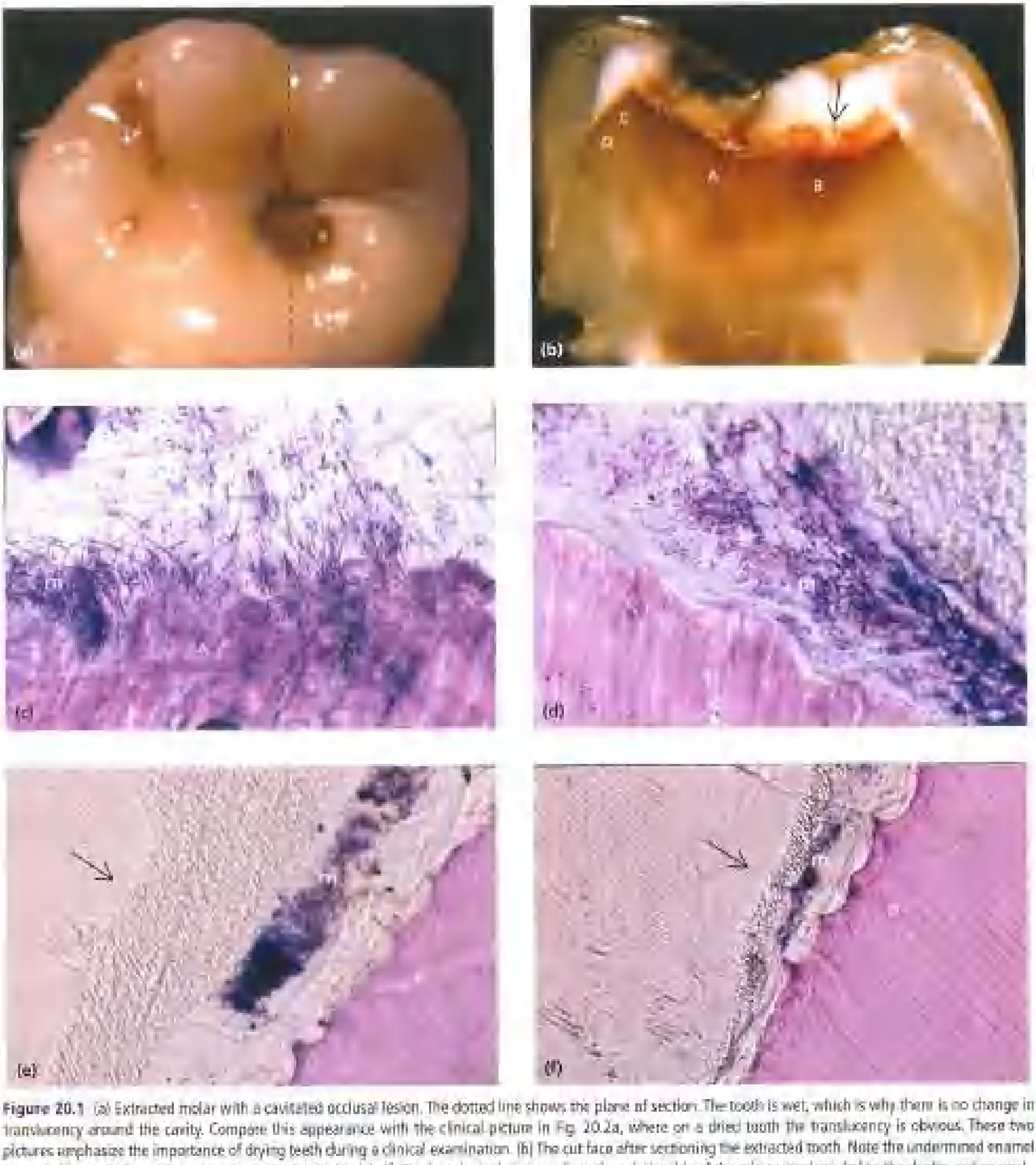


Figure 20.1 (a) Extracted molar with a cavitated occlusal lesion. The dotted line shows the plane of section. The tooth is wet, which is why there is no change in translucency around the cavity. Compare this appearance with the clinical picture in Fig. 20.2a, where on a dried tooth the translucency is obvious. These two pictures emphasize the importance of drying teeth during a clinical examination. (b) The cut face after sectioning the extracted tooth. Note the undermined enamel (arrow). Sites A, B, C, and D are histologically detailed in (c)–(f). The histological pictures show the relationship of the microorganisms (m) to the dentin and enamel–dentin junction. (c) Site A. The microorganisms penetrate the dentinal tubules superficially in the center of the cavity. (d) Site B. Microbial growth along the enamel–dentin junction gap, but not into dentin tubules. (e, f) Sites C and D. The microbial accumulation and size of the gap decrease towards the periphery of the open cavity. Arrows show a pattern of demineralized rod structure. Modified from [6]. Reproduced with permission of George Warman Publications.

sodium hypochlorite, which is a nonspecific proteolytic agent, can remove partly demineralized dentin. This concept has been further developed, and a gel is presently marketed that can be applied in the carious cavity and left for a while to dissolve the dentin matrix components, which contain partly degraded collagen. Again, the question is does this part of the dentin need to be removed? It would be unfortunate if dentists started to apply this on any dentin lesion (e.g., root-surface lesions) that are accessible to arrest by plaque control alone. Not only would this be unnecessary

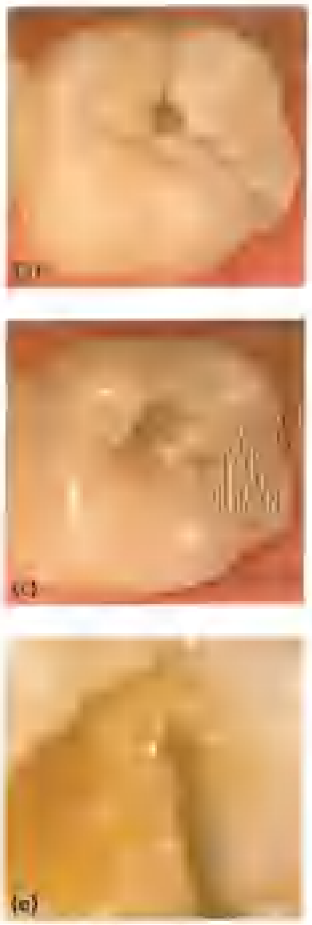


Figure 20.2 The cavitated coronal lesion with accumulations of microorganisms, and with a change in enamel translucency around the cavity (a) demonstrating that enamel demineralization at this stage develops along enamel–dentin junction and creates a retrograde pattern of enamel demineralization (b, c). The clinical removal of overhanging and undermined enamel is here guided by the retrograde pattern of enamel demineralization (d). The opening of the closed ecosystem along the enamel–dentin junction reveals a brown discolored demineralized dentin related to the exposed central and oldest part of the lesion, whereas the peripheral and outermost area has a more light yellow discoloration. A probe penetrates with easy fragment loss of the tissue, which is very soft and oozing moisture (d–e). Note the gap is visible in the clinic between the enamel and the dentin due to extensive dentin demineralization (e, f). Clinically recorded by Bjørndal in 2006.

Figure 20.3 The current clinical practice of mechanical excavation combines a peripheral dentin excavation, carried out using a round bur (a, b), with elimination of the centrally infected tissue using an excavator (c, d). The probe is used to assess clinical consistency, and here, dentin that is hard to touch has not yet been obtained (e). Note that the deeper and soft carious dentin is a fragmented tissue (f). An excavation close to the pulp represents a risk, because cracks along the fragments may lead to pulp exposure. Clinically recorded by Bjørndal in 2006.

with the knowledge about how to arrest such lesions [51], but it would result in an increased need for restorations.

Since there is still argument about the need to attempt to remove infected dentin, it now seems logical to look at the evidence on the consequences of leaving infected dentin.

Studies placing fissure sealants over carious dentin

Many years ago the consequences of simply sealing over carious dentin were investigated. Studies reported between 1975 and 1992 [20, 23, 24, 28, 29, 47–49, 58]. All but one were prospective, and in many there were unsealed, control lesions. Caries activity was assessed in a number of ways, including clinical observation, lesion depth measurement, radiographic lesion depth measurement, and microbiological sampling. Observation periods varied from 2 weeks to 5 years. The disparity of methodologies militates against a systematic review of the studies, but some uniform themes emerge. Sealed lesions appeared to arrest both clinically and radiographically. Investigations of the fate of the sealed bacteria showed a decrease in microorganisms with time or their complete elimination. However, lesions progressed where sealants were lost and in unsealed, control teeth.

One study [58] is an interesting outlier. This work was a retrospective examination of sealed teeth where radiographs showed radiolucency in dentin beneath a sealant that was clinically intact. This methodology precluded microbiological sampling before the sealant was placed, which is unfortunate because there can be no comparison

Figure 20.4 An old restoration has been removed and stained, soft, friable, dry dentin is present beneath. This does not require vigorous excavation, although exposure is unlikely because reactionary (tertiary) dentin will be present. The cervical margin must be made hard prior to placing a new restoration to ensure a good bond and seal.

of microbial counts before and after sealing. Nevertheless, when these teeth were entered for microbiological sampling, dentin was often soft and wet and microorganisms were found in 50% of teeth. So it seems that the sealing procedures had not been properly conducted.

Stepwise excavation studies

In stepwise excavation, first described by Bodecker in 1938 [12], only part of the soft, dentin caries is removed at the first visit. The cavity is temporarily restored and reopened after a period of weeks. Further excavation is now carried out prior to a definitive restoration. The objective of the exercise is to arrest lesion progression and allow the formation of tertiary dentin before final excavation, making pulpal exposure less likely. Thus, it is a biologically based principle to enhance the tissue's own capability of stimulating repair processes. This procedure has been investigated scientifically for more than 30 years. These studies have involved baseline investigations of carious dentin and then a reanalysis after a period of sealing it in the tooth. This work is important evidence of the consequences of sealing infected dentin into teeth (Fig. 20.6a–d).

Between 1961 and 2001 more than 20 studies of stepwise excavation, involving both deciduous and permanent teeth, were reported [32]. The varied experimental protocols can be summarized as follows. In the majority of studies only deep lesions were included (Fig. 20.6). All studies state that there was no irreversible pulpitis pretreatment, but one included teeth with slight 'pretreatment pain' [10]. Cavity walls were made hard, before incomplete caries removal was carried out over the pulp. This avoided exposure but left soft, wet dentin on the part of the dentin covering the pulp (i.e., the pulpal floor). The amount of demineralized dentin removed at the initial excavation varied from access to caries only, to removing the bulk of it. Most had no control where excavation continued to hard dentin. Calcium hydroxide has usually been placed over remaining dentin prior to restoration, but glass-ionomer cement and composite resin have also been applied directly to soft, infected dentin. The time to reentry for further excavation varied from 25 days to 2 years. At the reentry appointment a number of criteria were used to indicate caries activity, including clinical assessment of dentin hardness, wetness and color, radiographic appearance, and microbiology, with samples being taken before and after sealing.

With such varying methodologies, a systematic review of the results is not possible, but some themes emerge. The clinical success of incomplete caries removal appeared high. Exposure was usually avoided using the stepwise technique, and symptoms rarely arose between excavations. Pain was relieved shortly after the first excavation procedure. Where control lesions were excavated to hard dentin, these were often exposed.

On reentry, several studies [7–9, 30, 35, 39, 40, 59] reported the dentin was altered, being drier, harder, and darker (Fig. 20.5). Microbiological monitoring indicated substantial reductions in cultivable flora. In a few teeth no microorganisms could be cultivated, but in most some microorganisms were present. A likely explanation for this was that the nutrients available for the growth of these bacteria after a restoration is placed were very different from those available above and within the cavity. The major source of nutrients after restoration to support bacterial persistence and growth are the proteins, including glycoproteins, passing through the dentinal tubules from the dental pulp. Several studies [7, 42, 55] suggest the cultivable flora is altered on reentry to a 'less cariogenic flora' dominated by *Streptococcus oralis* and *Actinomyces naeslundii*, two species able to liberate and utilise the sugars from glycoproteins present in the tubules. This shift in microbial composition is in full accordance with the concept of the ecological plaque hypotheses presented in Chapter 7.

A randomized clinical trial [38] carried out on deciduous teeth is of particular interest. Complete caries removal was carried out in the control group guided by a caries dye; the remaining dentin would be minimally

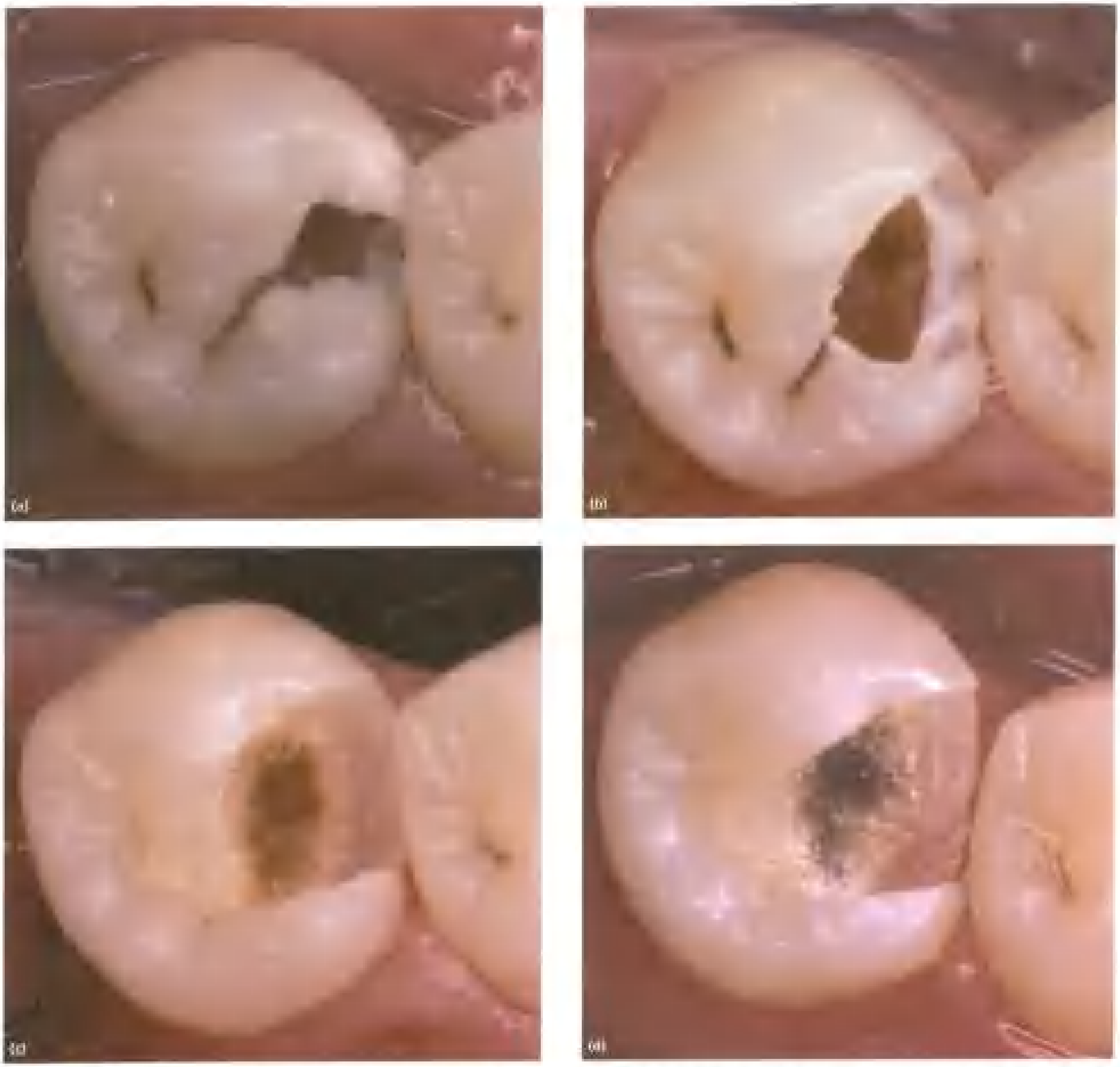


Figure 20.5 Deep caries lesion in a lower premolar during sequences of caries excavation (a–d). Undermined enamel along the enamel-dentin junction can be noted as a white zone around the cavity (a). During removal of the undermined enamel a clear pattern of demineralized enamel (b) is noted along the enamel–dentin junction. In the first excavation procedure the superficial and central part of demineralized dentin is removed, including the peripheral parts of the lesion. The exposed soft dentin is light brown (c). Following temporary filling and a treatment interval of 6 months, and before final excavation, the central exposed dentin is dark brown (d). From [5]. Reproduced with permission of the *Danish Dental Journal*.

infected. The experimental group had minimal caries removal, and thus heavily infected dentin would have been sealed in the teeth. Despite these differences, microbiology carried out on reentry 3–6 months later showed the dentin to be similarly and minimally infected in both groups. A comparable clinical trial in permanent teeth [43] compared microbiological samples following complete caries removal with samples following incomplete caries removal and restoration. Results showed the amount of bacteria detected after complete caries removal was higher than the bacterial load remaining after partial caries removal and restoration. These studies clearly indicate the numbers of bacteria reduce following placement of a restoration that minimizes exposure to the oral environment. This is irrespective of the amount of demineralized, infected dentin removed.

Figure 20.6 A deep lesion treated with stepwise excavation in a lower second molar (a). Note remnants of the roots of the first molar indicating a very rapid caries progression. The second molar was permanently restored with a composite inlay. After 1 year pulp vitality was confirmed, and a new radiograph showed no apical radiolucency (b). A 4-year recall confirmed the vitality of the pulp as well as the absence of apical radiolucency (c). However, complete arrest of caries activity has not been achieved: a new proximal lesion has progressed in the third molar. Modified from [5]. Reproduced with permission of the *Danish Dental Journal*.

Randomized controlled clinical trials on stepwise excavation outcome

Randomized controlled clinical trials are required to assess any deleterious consequences of incomplete caries removal. These trials should have well-defined inclusion criteria and a sufficient (large) number of patients should be enrolled. Ideally, patients should be allocated into control or experimental groups at random using a concealed allocation procedure such as computer-generated numbers. The follow-up should be conducted by an examiner who is not aware of the patient's group to eliminate bias.

Only four trials [10, 37, 41, 53] were included in a recent systematic review [57]. Two of these [41, 53] included deciduous teeth. The lesions were deep and without symptoms of irreversible pulpitis. For all studies, complete caries removal was carried out in the control group, whereas only partial caries removal was carried out in the experimental group, usually avoiding exposure. The time interval between the first and second excavations varied between 4 and 24 weeks, but this has not been done in a systematic manner. Thus, we can say nothing about the clinical relevance of this time dimension.

Table 20.1 gives results with respect to exposures. In each study there were significant differences in exposures between complete and partial caries removal. At the first visit between 22% and 53% of pulps were exposed by complete caries removal. In stepwise groups there were only exposures of the pulps at the first visit in one of four studies and only in very few of the teeth. On reentry, further caries removal resulted in some exposures in all studies. It should be noted that teeth with carious exposures require root canal treatment. In the study by Bjørndal *et al.* [10], where patients with some degree of pretreatment pain were enrolled, there was a higher risk of pulp exposure at 1 year follow-up and a lower degree of pulp survival among cases with pretreatment pain. Taken together, the trials show that the stepwise approach reduces the need for root canal treatment, but does not obviate it.

Table 20.1 Exposure rates in randomized clinical trials of stepwise excavation.

	Control		Stepwise			
			Stage 1		Reentry	
Magnusson and Sundell [41]	29/55	53%	0/55	0%	8/55	14.5%
Leksell *et al.* [37]	28/70	40%	0/64	0%	10/57	17.5%
Orhan *et al.* [53]	12/55	22%	0/49	0%	4/49	8.2%
Bjørndal *et al.* [10]	43/149	28.9%	4/143	2.8%	21/139	15%

Numbers and percentages of exposures, relative to total number of teeth, in four clinical studies. It is apparent that the stepwise approach is saving significantly more teeth from exposure, and hence root canal treatment, than excavating in one session only.

Do we need to reenter?

The final excavation allows the dentist to be sure that there is no exposure and removes the remaining softened dentin. The logic here is that the dissolution process may continue, albeit slowly, in this infected tissue. So the final excavation – it is claimed – is needed to ensure the survival of the restoration.

However, perhaps there is no need to reenter, and indeed this is the base of the indirect pulp capping technique [15, 25, 56], although most of the demineralized tissue is removed in this procedure (Fig. 20.7) [22]. In stepwise excavation, on the other hand, soft, wet dentin is left in place. Is it now necessary to reenter? After all, 'sealing' a cavity should significantly slow down or even stop the caries process. The persistence of microorganisms may be irrelevant.

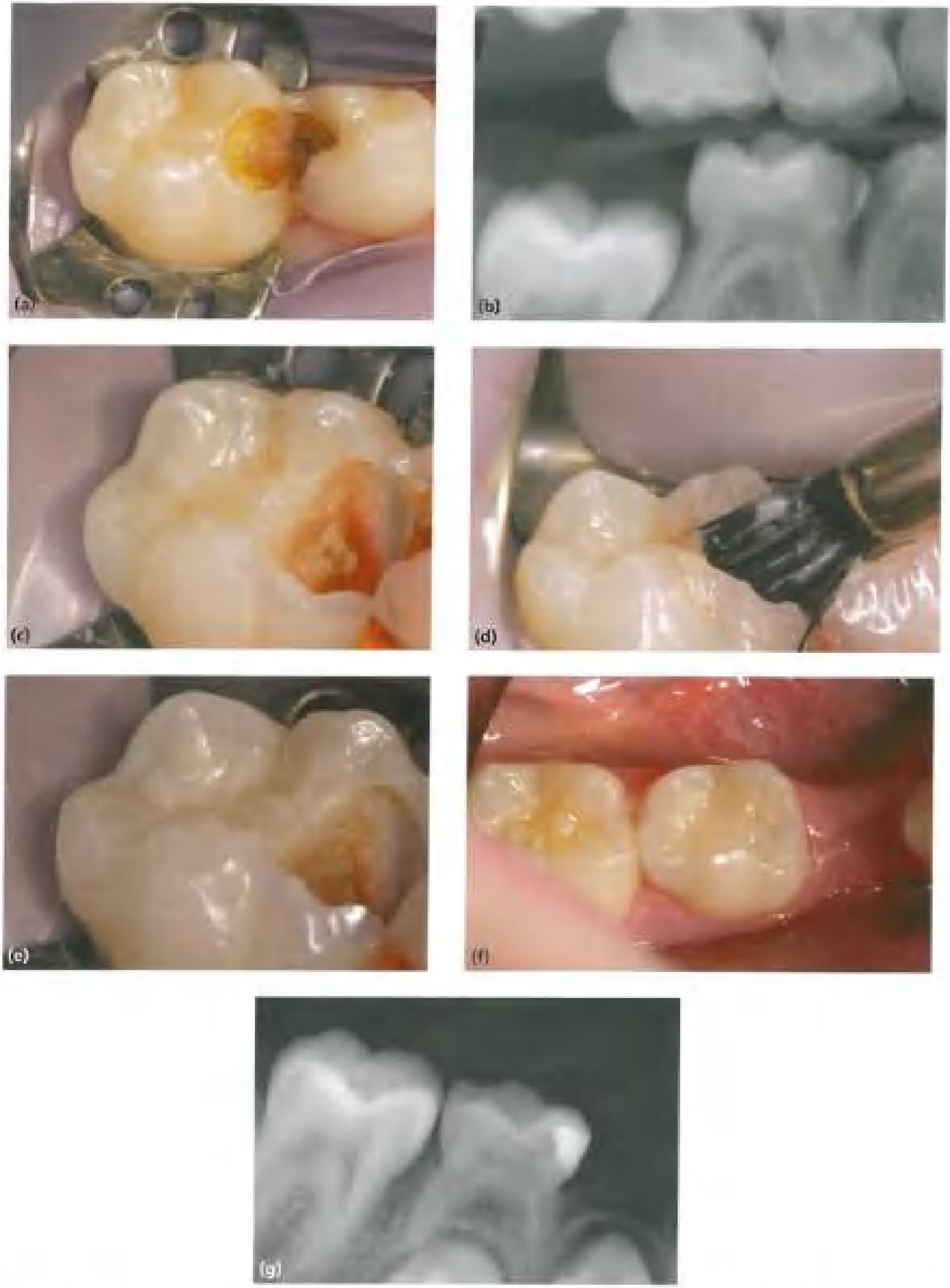


Figure 20.7 Indirect pulp capping. (a) Deep carious second lower deciduous molar before indirect pulp treatment. (b) Same tooth on bitewing. (c) After excavation of the dentin–enamel junction. The biomass is still present in the center of the cavity. (d) Removing biomass with a rotating prophy brush and fluoride toothpaste only. (e) After removing the biomass. Next the cavity was dried, a resin-modified glass–ionomer liner (Vitrebond/3 M Espe) was applied, and the cavity was restored with a compomer (Dyract/Dentsply Caulk). (f) Clinical result after 2 years and 4 months. (g) Radiographic result after 2 years and 4 months. Courtesy of Rene Gruythuysen and BSL, Springer Media, Houten, The Netherlands.

Perhaps they are just opportunistic squatters adapted to the new environment in which they find themselves.

The microbiological studies discussed above show the dentin is now minimally infected. Outcomes for pulp survival are poor following pulp capping or pulpotomy in teeth with carious exposures [1, 3, 10]. Thus, it is tempting to suggest reentry is *not* required and might even be detrimental, particularly in children's dentitions! The need to subject a child to a second operative procedure in a deciduous tooth that will exfoliate seems unacceptable in view of the evidence. There is a need for better and more systematic research on this topic, particularly the long-term follow-up of pulp vitality and restoration longevity. However, these studies should be on permanent teeth and logically must also be carried out *in vivo*, as no *in situ* or laboratory model can simulate the relevant pulp–dentin response.

The choice of treatment in the control group in further studies of stepwise excavation deserves comment. Table 20.1 shows a high prevalence of exposures when complete caries removal is chosen as the control. Bearing in mind the poor prognosis for the preservation of a vital pulp in these teeth, is it now ethical to plan studies including a complete caries removal group? Maltz *et al.* [45] considered this and designed a study comparing partial caries removal with the stepwise approach; there was no complete caries removal group.

This randomized clinical trial [44, 45] on permanent teeth with deep lesions compared partial caries removal – where teeth were permanently restored with glass–ionomer cement and then composite – with a stepwise approach. In the stepwise group, after initial caries removal, temporary restorations (calcium hydroxide and then zinc oxide and eugenol) were placed prior to reentry. One-year follow up showed a high success rate (98% partial caries removal; 91% stepwise group) for both groups. However, the 3-year follow-up showed a significant difference between the groups favoring the partial caries removal and permanent restoration group (91% success compared with 69% of the stepwise group). The failures were due to several patients in the stepwise group not attending for the final excavation and the temporary cavity seal was lost in these cases. There are important clinical implications here. Partial caries removal and permanent restoration caused very few adverse events from leaving soft, demineralized dentin on the pulpal wall. However, if the operator chooses a stepwise approach it seems unwise to place a temporary restoration that may be lost should the patient not return for subsequent excavation.

What happens if we do not remove caries at all but seal it in the tooth permanently?

Two randomized controlled trials have used this unconventional approach. They are completely different and must be considered separately. The first [50] was carried out on permanent teeth with occlusal lesions halfway through dentin on radiograph. This was a split-mouth study, which means control and experimental teeth were in the same patient. There was complete caries removal in control teeth, which were restored with amalgam. The experimental teeth were managed by beveling the enamel at the entrance to the lesion, but no demineralized dentin was removed; the enamel–dentin junction was not even made caries free. These teeth were restored with sealed composite restorations and teeth were followed annually for 10 years. Some 50% of patients were still attending review after this time. In these patients, lesion progression was arrested and there were no more clinical failures in the sealed group than in the control, completely excavated teeth restored with amalgam. There is no way of knowing what happened in the remaining half of the sample.

The second study was equally unconventional and carried out in deciduous teeth [27]. In the control group, conventional caries removal was followed by the practitioners' usual treatment (in most cases a glass–ionomer cement restoration). In the experimental group, there was no caries removal and no tooth preparation. A stainless steel crown ('Hall crown', see Fig. 19.41) was cemented with glass–ionomer cement. This was also a split-mouth study. There are now 5-year results [27] showing more major failure (defined as irreversible pulpitis, loss of vitality, abscess, tooth unrestorable) in the control group (17%) compared with 3% in the Hall crown group. The poor performance of the control group is likely to be due to the practioners' use of glass–ionomer cement restorations. Such restorations have shown poor survival clinically [14]. What is more remarkable is the excellent performance of the Hall crowns where infected dentin was sealed in the teeth.

Further consideration of deciduous teeth

The caries process is the same whether teeth are deciduous or permanent. However, deciduous teeth are temporary; only in the mouth 6–9 years, their owners are small and immature, and they rely on parents for care. Frightening the child can have serious consequences for subsequent care, and pain in children is particularly worrying for parents as well.

Up to this point caries removal in deciduous teeth has been discussed in relation to what should be removed before restoring the tooth. There is, however, another possibility, and that is to open the teeth for cleaning and not place a restoration. This approach is called nonrestorative cavity treatment [21] (see 'Inactivation of lesions without caries removal' section in Chapter 19 and Fig. 19.39).

This has many advantages from a cariological point of view. The grinding of the teeth facilitates brushing to disturb the biofilm, and with regular disturbance and fluoride toothpaste the lesions will arrest. The technique is gentle, not requiring local anesthesia; it does not frighten the child.

However, of particular importance is that it puts the responsibility for caries control where it has to lie: with the parent. It is not a case of 'let me fill your tooth to solve the problem'; it is 'here is how you can solve this problem.' It could even be said that filling the tooth is less advantageous as it rewards the very behavior that caused the problem in the first place.

This approach is funded in the dental services in Holland, but it must be emphasized that the whole package as described in Chapter 19, is required. It is not allowed just to sliced the teeth and not instruct the parent in the proper brushing. Unfortunately, some pediatric dentists are very unhappy with the concept, which they think is abrogating responsibility to the point of being unethical. Arguments rage but will only be settled with appropriately designed clinical trials. We can only contend that, from a cariological perspective, the approach makes biological and sociological sense.

Conclusion on caries removal and the pulpo-dentinal complex

Based on the discussions presented herein, there appears to be little logic in the practice of 'complete' caries removal, particularly in symptomless vital teeth with deep lesions. Biologically, it would appear to be potentially damaging to even attempt to remove all infected dentin. It is not even possible to achieve this. The evidence shows that, provided either the cavity is sufficiently accessible to regular plaque removal or a restoration is placed that 'seals' the cavity, infected and partially softened dentin may be left where its exposure might expose the pulp. It does not prejudice pulpal health, and the caries process does not continue. These statements appear logical and predictable, when seen in the light of the knowledge about the nature of dental caries as presented throughout this textbook. In some situations partial or even no caries removal is preferable to complete excavation, for instance, in a deciduous tooth that will be exfoliated within a few years, a tooth in a frail elder person, or in a very nervous patient where the minimal intervention itself is a triumph.

These arguments will have a strong bearing on the future of restorative dentistry. Clinical studies now exist which are intriguing. We must rethink the most appropriate way of controlling dental caries and its lesion progression. *Many dentists have been performing a variety of often unnecessary operative procedures which all too often have added to loss of teeth with time* [16]. We would suggest that on the basis of evidence it is no longer acceptable to risk pulp exposure by immediately performing complete caries removal on *a vital, symptomless tooth* with a deep lesion. The evidence indicates that it is now more than ever required that the dentist makes a careful examination and consideration about what is best for the survival *of this particular tooth*. This necessitates both clinical competence and a thorough knowledge about pathology and pathophysiology of the caries lesion.

References

1. Al-Hiyasat AS, Barrieshi-Nusair KM, Al-Omari MA. The radiographic outcomes of direct pulp-capping procedures performed by dental students: a retrospective study. *J Am Dent Assoc* 2006; 137: 1699–705.
2. Anderson MH, Loesche WJ, Charbeneau GT. Bacteriologic study of a basic fuchsin caries-disclosing dye. *J Prosth Dent* 1985; 54: 51–5.
3. Barthel CR, Rosenkranz B, Leuenberg A, Roulet JF. Pulp capping of carious exposures: treatment outcome after 5 and 10 years: a retrospective study. *J Endod* 2000; 26: 525–8.
4. Beeley JA, Yip HK, Stevenson AG. Chemomechanical caries removal: a review of the techniques and latest developments. *Br Dent J* 2000; 188: 427–30.
5. Bjørndal L. Behandling af profunde cariesläsioner med gradvis ekskavering. En praktikerbaseret undersøgelse. *Tandlægebladet* 1999; 103: 498–506 (English summary).
6. Bjørndal L, Kidd EAM. The treatment of deep dentine caries lesions. *Dental Update* 2005; 32: 402–13.
7. Bjørndal L, Larsen T. Changes in the cultivable flora in deep carious lesions following a stepwise excavation procedure. *Caries Res* 2000; 34: 502–8.
8. Bjørndal L, Thylstrup A. A practice-based study on stepwise excavation of deep carious lesions in permanent teeth: a 1-year follow-up study. *Community Dent Oral Epidemiol* 1998; 26: 122–8.
9. Bjørndal L, Larsen T, Thylstrup A. A clinical and microbiological study of deep carious lesions during stepwise excavation using long treatment intervals. *Caries Res* 1997; 31: 411–17.
10. Bjørndal L, Reit C, Bruun G, Markvart M, Kjældgaard M, Näsman P, Thordrup M, Dige I, Nyvad B, Fransson H, Lager A, Ericson D, Petersson K, Olsson J, Santimano EM, Wennström A, Winkel P, Gluud C. Treatment of deep caries lesions in adults: randomized clinical trials comparing stepwise vs. direct complete excavation, and direct pulp capping vs. partial pulpotomy. *Eur J Oral Sci* 2010; 118: 290–7.
11. Black GV. *Operative dentistry. Vol. 1, Pathology of the hard tissues of the teeth*. Chicago, IL: Medico-Dental Publishing Co.; 1908.
12. Bodecker CF. Histologic evidence of the benefits of temporary fillings and successful pulp capping of deciduous teeth. *J Am Dent Assoc* 1938; 25: 777–86.
13. Boston DW, Graver HT. Histological study of an acid red caries-disclosing dye. *Op Dent* 1989; 14: 186–92.
14. Chadwick BL, Evans DJ. Restoration of class II cavities in primary molar teeth with conventional and resin modified glass ionomer cements: a systematic review of the literature. *Eur Arch Paediatr Dent* 2007; 8: 14–21.
15. Eidelman E, Finn SB, Koulourides T. Remineralization of carious dentin treated with calcium hydroxide. *J Child Dent* 1965; 32: 218–25.
16. Elderton RJ. Preventive (evidence-based) approach to quality general dental care. *Med Princ Pract* 2003; 12 (Suppl 1): 12–21.
17. Fusayama T. Two layers of carious dentin: diagnosis and treatment. *Op Dent* 1979; 4: 63–70.
18. Fusayama T. Clinical guide for removing caries using a caries-detecting solution. *Quintessence Int* 1988; 19: 397–401.
19. Fusayama T, Terashima S. Differentiation of two layers of carious dentin by staining. *J Dent Res* 1972; 51: 866.
20. Going RE, Loesche WJ, Grainger DA, Syed SA. The viability of microorganisms in carious lesions five years after covering with a fissure sealant. *J Am Dent Assoc* 1978; 97: 455–62.
21. Gruythuysen RJ. Non-restorative cavity treatment. Managing rather than masking caries activity. *Ned Tijdschr Tandheelkd* 2010; 117: 173–80.
22. Gruythuysen RJ, van Strijp AJ, Wu MK. Long-term survival of indirect pulp treatment in primary and permanent teeth with clinically diagnosed deep carious lesions. *J Endod* 2010; 36: 1490–3.
23. Handelman SL, Washburn F, Wopperer P. Two-year report of sealant effect on bacteria in dental caries. *J Am Dent Assoc* 1976; 93: 967–70.

24. Handelman SL, Leverett DH, Solomon ES, Brenner CM. Radiographic evaluation of the sealing of occlusal caries. *Community Dent Oral Epidemiol* 1981; **9**: 256–9.
25. Hilton TJ, Summitt JB. Pulpal considerations. In: Summitt JB, Robbins JW, Schwartz RS, eds. *Fundamentals of operative dentistry: a contemporary approach*. Chicago, IL: Quintessence, 2006: 103.
26. Hosoda H, Fusayama T. A tooth substance saving restorative technique. *Int Dent J* 1984; **34**: 1–12.
27. Innes NP, Evans DJ, Stirrups DR. Sealing caries in primary molars: a randomized control trial, 5-year results. *J Dent Res* 2011; **90**: 1405–10.
28. Jensen OE, Handelman SL. Effect of an autopolymerizing sealant on viability of microflora in occlusal dental caries. *Scand J Dent Res* 1980; **88**: 382–8.
29. Jeronimus DJ, Till MJ, Sveen OB. Reduced viability of microorganisms under dental sealants. *J Dent Child* 1975; **42**: 275–80.
30. Kerkhove BC, Herman SC, Klein AI, McDonald RE. A clinical and television densitometric evaluation of the indirect pulp capping technique. *J Dent Child* 1967; **34**: 192–201.
31. Keyes PH. The infectious and transmissible nature of experimental dental caries. Findings and implications. *Arch Oral Biol* 1960; **1**: 304–20.
32. Kidd EAM. Clinical threshold for carious tissue removal. *Dent Clin N Amer* 2010; **54**: 541–9.
33. Kidd EAM, Joyston-Bechal S, Beighton D. The use of a caries detector dye during cavity preparation: a microbiological assessment. *Br Dent J* 1993; **174**: 245–8.
34. Kidd EAM, Ricketts DJ, Beighton D. Criteria for caries removal at the enamel–dentin junction: a clinical and microbiological study. *Br Dent J* 1996; **180**: 287–91.
35. Kreulen CM, de Soet JJ, Weerheijm KL, van Amerongen WE. In vivo cariostatic effect of resin modified glass ionomer cement and amalgam on dentine. *Caries Res* 1997; **31**: 384–9.
36. Kuboki Y, Liu CF, Fusayama T. Mechanism of differential staining in carious dentin. *J Dent Res* 1983; **62**: 713–14.
37. Leksell E, Ridell K, Cvek M, Mejàre I. Pulp exposure after stepwise versus direct complete excavation of deep carious lesion in young posterior permanent teeth. *Endod Dent Traumatol* 1996; **12**: 192–6.
38. Lula ECO, Monteiro-Neto V, Alves CMC, Ribeiro CCC. Microbiological analysis after complete or partial caries removal of carious dentin in primary teeth: a randomized controlled clinical trial. *Caries Res* 2009; **43**: 354–8.
39. Lula ECO, Almeida LJS, Alves CMC, Monteiro-Neto V, Ribeiro CCC. Partial caries removal in primary teeth: association of clinical parameters with microbiological status. *Caries Res* 2011; **45**: 275–80.
40. MacGregor AB, Marsland EA, Batty I. Experimental studies of dental caries. The relation of bacterial invasion to softening of the dentin. *Br Dent J* 1956; **101**: 230–5.
41. Magnusson BO, Sundell SO. Stepwise excavation of deep carious lesions in primary molars. *J Int Assoc Dent Child* 1977; **8**: 36–40.
42. Maltz M, de Oliveira EF, Fontanella V, Bianchi R. A clinical, microbiologic, and radiographic study of deep caries lesions after incomplete caries removal. *Quintessence Int* 2002; **33**: 151–9.
43. Maltz M, Henz SL, de Oliveira EF, Jardim JJ, de Paula LM, Yamaguti PM, Moura MS, Garcia E, Nascimento A, Oliveira A, Mestrinho HD. Conventional caries removal and sealed caries in permanent teeth: a microbiological evaluation. *J Dent* 2012; **40**: 776–82.
44. Maltz M, Garcia R, Jardim JJ, de Paula LM, Yamaguti PM, Moura MS, Garcia F, Nascimento C, Oliveira A, Mestrinho HD. Randomized trial of partial vs stepwise caries removal: 3-year follow-up. *J Dent Res* 2012; **91**: 1026–31.
45. Maltz M, Jardim JJ, Mestrinho HD, Yamaguti PM, Podestá K, Moura MS, de Paula LM. Partial removal of carious dentine: a multicenter randomized controlled trial and 18-month follow-up results. *Caries Res* 2013; **47**: 103–9.
46. Massler M. Pulpal reactions to dental caries. *Int Dent J* 1967; **17**: 441–60.
47. Mertz-Fairhurst EJ, Schuster GS, Williams JE, Fairhurst CW. Clinical progress of sealed and unsealed caries. Depth changes and bacterial counts. *J Prosthet Dent* 1979; **42**: 521–6.
48. Mertz-Fairhurst EJ, Schuster GS, Williams JE, Fairhurst CW. Clinical progress of sealed and unsealed caries. Standardized radiographs and clinical observations. *J Prosthet Dent* 1979; **42**: 633–7.
49. Mertz-Fairhurst EJ, Schuster GS, Fairhurst CW. Arresting caries by sealants: results of a clinical study. *J Am Dent Assoc* 1986; **112**: 194–8.
50. Mertz-Fairhurst EJ, Curtis JW, Ergle JW, Rueggeberg FA. Ultraconservative and cariostatic sealed restorations: results at year 10. *J Am Dent Assoc* 1998; **129**: 55–66.
51. Nyvad B, Fejerskov O. Active root-caries converted into inactive caries as a response to oral hygiene. *Scand J Dent Res* 1986; **94**: 281–4.
52. Ogawa K, Yamashita Y, Ichijo T, Fusayama T. The ultrastructure and hardness of the transparent layer of human carious dentin. *J Dent Res* 1983; **62**: 7–10.
53. Orhan AI, Oz FT, Orhan K. Pulp exposure and outcomes after 1- or 2-visit indirect pulp therapy vs complete caries removal in primary and permanent molars. *Ped Dent* 2010; **32**: 347–55.
54. Orland FJ, Blayney JR, Harrison RW, Reyniers JA, Trexler PC, Wagner M, Gordon HA, Luckey TD. Use of germ free animal technique in the study of experimental dental caries. *J Dent Res* 1954; **33**: 147–74.
55. Paddick JS, Brailsford SR, Kidd EAM, Beighton D. Phenotypic and genotypic selection of microbiota surviving under dental restorations. *Appl Environ Microbiol* 2005; **71**: 2467–72.
56. Prader F. Conservative treatment of the floor of the carious cavity – carious dentine near the pulp. *Int Dent J* 1958; **8**: 627–38.
57. Ricketts D, Lamont T, Innes NPT, Kidd E, Clarkson JE. Caries management in adults and children. *Cochrane Database of Systematic Reviews* 2013; (3): CD003808.
58. Weerheijm KL, Kreulen CM, de Soet JJ, van Amerongen WE, de Graaff J. Sealing of occlusal caries lesions: an alternative for curative treatment? *J Dent Child* 1992; **59**: 263–8.
59. Weerheijm KL, Kreulen CM, de Soet JJ, Groen HJ, van Amerongen WE. Bacterial counts in carious dentin under restorations: 2 year in vivo effects. *Caries Res* 1999; **33**: 130–4.

21

Longevity of restorations: 'the death spiral'

V. Qvist

Introduction

From a cariological point of view the most important reason for placing restorations is to aid plaque control, and plaque control may be difficult or impossible if a caries lesion has progressed to the stage of a cavitated lesion (see Chapters 19 and 20 for further discussion of the role of operative treatment in caries control). Restorations are also undertaken for other reasons, such as trauma, wear, erosion, and aesthetic demands. Over the last decades, dental health has improved, and the number of restorations placed has declined in the industrialized part of the world, despite the fact that the number of teeth present has increased. However, millions of restorations are still inserted and replaced every year in deciduous and permanent teeth, placing an enormous burden on the resources of the national health-care systems.

Surveys on the reasons for the placement and replacement of restorations have been conducted in various countries. The data indicate that initial restorations,

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

due to primary caries, account for 75–85% of all restorative caries treatment in primary and permanent teeth in children and adolescents [23, 27, 28, 56, 65, 67]. However, replacement of existing restorations accounts for 60–70% of the restorative interventions carried out in clinical practice on adults in Scandinavia, UK, and USA [24, 27, 28, 54, 55, 65, 67, 79].

Evidence also suggests that the so-called permanent restorations are not permanent in the true sense of the term. Restorations have a limited lifetime, and once a permanent tooth is restored the filling is likely to be replaced several times in the patient's lifetime in a 'restorative cycle' that eventually may lead to destruction of the tooth – 'the death spiral' [8, 19].

Clinical assessment of restorations

It has been demonstrated that the treatment decisions concerning placement, repair, and replacement of restorations made by clinicians are subject to a great deal of variation [2, 20, 29–32, 58]. In clinical dental practice, decisions are often made subjectively with a lack of standardization, as there are no or few valid criteria to decide whether a restoration requires retreatment such as repair or replacement. It is difficult to distinguish between objective and subjective factors in the decision-making process, and it is possible that the subjective influence has a greater impact on longevity of restorations than the clinical properties and biocompatibility of the restorative materials. For example, the clinician may have the opinion that mercury in dental amalgam may be harmful to the patient and, therefore, advocate replacement of well-functioning amalgam restorations even in patients who attend with no complaints; another example is where the same marginal discoloration may be interpreted as caries adjacent to a composite resin restoration but not next to a glass-ionomer restoration due to different expectations of the cariostatic potential of the restorative materials.

The criteria used for the evaluation of restoration failure vary widely among dentists and may not be explicit [36, 41]. It is often difficult, therefore, to determine whether a restoration was replaced because it actually failed or because a clinician subjectively deemed it to have failed. For example, one clinician may decide to replace an old corroded and 'ditched' amalgam whereas another may repair or polish it [30, 32].

The first standardized method for evaluating the clinical performance of restorations was developed in the 1960s by a Dane, Gunnar Ryge, through the United States Public Health Service (USPHS) [11, 12]. The USPHS system, still widely used today with modifications, bases the evaluation of restorations on three clinical judgments: clinically ideal, clinically acceptable, and clinically unacceptable. These judgments are applied to characteristics generally associated with the deterioration process for a given type of restorative material, and each of these characteristics is discussed separately.

Tables 21.1 and 21.2 describe a new and updated modification of the USPHS system, which may be applied for detailed as well as overall clinical assessment of the majority of dental restorations. The modification is based on present knowledge of demands on restorations and knowledge of actual clinical manifestations of caries in relation to restorations, also designated secondary or recurrent caries. The use of the assessment system is exemplified in Figs 21.1, 21.2, 21.3, and 21.4. The examples emphasize the importance of considering alternatives to replacement of restorations, such as repair of localized defects, finishing of restorations with superficial staining, smoothing and sealing restorations with marginal discrepancies and staining, and the mere monitoring of defects to examine their progression and sequelae. These simple measures may significantly increase the longevity of restorations and save tooth substance, which is inevitably lost when restorations are replaced [7, 47, 52, 60]. Furthermore, the examples point out the patient's right to participate in decisions where several different treatments are considered professionally justifiable.

Assessment of restoration longevity

The longevity of restorations may be registered in prospective or retrospective longitudinal studies, or it may be assessed in cross-sectional surveys, based on retrospective data from dental records, provided records are available to document the complete treatment performed over many years.

The classical longitudinal randomized controlled trial (RCT) comes close to the ideal test conditions and meets the demands for evidence-based dentistry [10, 66].

The RCT study design has the following characteristics:

- randomized allocation to test and control groups;
- 'blinding' of patient as well as therapist if possible;
- limited number of restorations of each material or method;
- selection of suitable patients and treatments;
- treatments and controls performed by one or few calibrated and skilled clinicians;
- optimal clinical conditions;
- standardized control intervals;
- detailed assessments of the quality of the restorations according to well-defined criteria.

In general, the results show what can be obtained with the tested materials and methods under optimal conditions. In other words, they provide us with the 'gold standard' with which we can compare our everyday results. This is essential for the continuing development of materials and methods. However, it is unrealistic to expect RCT investigations to exceed 10 years, although the requirement for restoration longevity in the permanent dentition

Table 21.1 Clinical assessment of restorations.[a]

Assessment	Explanation	Intervention
Optimal	The restoration protects the tooth and the surrounding tissues and meets aesthetic demands	None
Acceptable	The restoration exhibits one or more features that deviate from ideal functional and aesthetic conditions, but it protects the tooth and the surrounding tissues	None or Observe or Implement preventive measures or Repair sooner or later
Not acceptable	Aesthetics are obviously compromised or the restoration does not protect the tooth and/or the surrounding tissues. Damage is likely to occur	Observe or Implement preventive measures or Repair sooner or later or Replace sooner or later
Not acceptable	The restoration does not protect the tooth and/or the surrounding tissues. Damage is occurring	Repair immediately or Replace immediately

[a] Modified from [11, 12].

Table 21.2 Criteria for clinical assessment of restorations.[a]

Category	Assessment	Criteria
Secondary/recurrent caries	Optimal	No evidence of caries contiguous with the margin of the restoration or beyond the restoration
	Acceptable	Evidence of superficial and/or inactive caries, no operative treatment necessary Preventive measure may be indicated
	Not acceptable	Evidence of deep and/or active caries with cavitation Preventive measures or operative treatment indicated
Color match/surface discoloration (tooth-colored restorations)	Optimal	The restoration matches the color, shade, and translucency of adjacent tooth tissues
	Acceptable	Slight mismatch in color, shade, or translucency
	Not acceptable	Obvious mismatch outside the normal range of tooth color, shades, or translucency
Marginal discoloration	Optimal	No discoloration at the junction of the tooth tissues and the restoration
	Acceptable	Slight superficial or localized marginal staining
	Not acceptable	Obvious deep or extended marginal staining
Marginal integrity	Optimal	No evidence of discrepancies or crevice at the junction of the tooth tissue and the restoration
	Acceptable	Minor or localized marginal discrepancies or crevice
	Not acceptable	Obvious deep or extended marginal discrepancies or crevice and/or mobile or missing restoration
Fracture of restoration or tooth	Optimal	No evidence of surface cracks or fracture of restoration. No evidence of dentinal cracks
	Acceptable	Superficial cracks or minor fractures of restoration or tooth tissues
	Not acceptable	Major fracture of restoration or tooth tissues. Restoration is missing completely or partially, or contact is faulty, or occlusion is affected
Morphology/wear of restoration	Optimal	Restoration restores missing tooth tissues, function, and aesthetics
	Acceptable	Morphology compromises plaque removal or aesthetic demands; occlusal or proximal contact is faulty
	Not acceptable	Morphology prevents plaque removal, allows food impaction, overeruption, or tooth drifting, or does not meet aesthetic demands
Pulpal complications	Optimal	No dentinal hypersensitivity or pulp pain
	Acceptable	Transient hypersensitivity or pulp pain of minor intensity
	Not acceptable	Frequent or sustained hypersensitivity or moderate/intense pulp pain

[a] Modified from [11, 12].

may be many times longer to obtain lifelong durability. The reliability of the results may also be contested because the results are based on a few dentists' handling of materials and methods as well as the characteristics of a selected group of patients, and may be challenged by patient dropouts. When restorative treatment in the primary dentition is studied, another inevitable problem is the high percentage of observations lost at follow-up because of exfoliation of teeth. This makes the presentation and comparison of absolute failure rates questionable. Furthermore, control groups are not always included in longitudinal studies, and the clinical performance of the restorations, therefore, cannot be directly compared with that of another material used for a similar purpose. The results of such studies tend to be overoptimistic – especially if manufacturers have directly supported the research.

Figure 21.1 Detailed assessment of occluso-distal, class II amalgam restoration in the lower second molar. The 28-year-old male patient complains about occasional pain from the region. Fracture and loss of distal part of restoration. Probably minor fracture of disto-lingual cusp, too. Plaque-covered active caries in the cavity. Gingivitis in adjacent gingiva. *Overall assessment and intervention.* Damage is occurring in the tooth and the surrounding tissues. The restoration is not acceptable. Replace restoration immediately.

Figure 21.2 Detailed assessment of occluso-distal, class II amalgam restoration in the first upper premolar: (a) clinical photograph; (b) plaster model. Minor fracture of buccal part of marginal ridge. No evidence of plaque or caries in the cavity. No evidence of gingivitis in adjacent papilla. No complaints of pain or food impaction. *Overall assessment and intervention.* There is no damage of tooth or surrounding tissues. The restoration is acceptable. No intervention needed.

Figure 21.3 Detailed assessment of 2-year-old, distal, class III composite resin restoration in the upper lateral (a). Fracture of disto-incisal corner of the tooth beneath otherwise optimal restoration. *Overall assessment and intervention.* The restoration is not acceptable. Repair or replace restoration sooner or later. However, the 46-year-old female patient did not want the restoration to be repaired! She attended 4 years later with the same unrepaired but now worn restoration, which she still did not want to be repaired. (b) Illustration that restoration of the incisal tooth fracture would require reduction of the incisal edge of the lower canine to protect the class IV restoration against fracture and/or loss during occlusion/articulation.

Figure 21.4 Detailed assessment of 12-year-old, mesial, class III composite resin restoration in the upper canine. Obvious deep and extended marginal staining along the periphery of the restoration. No evidence of secondary or recurrent caries. *Overall assessment and intervention.* The restoration is objectively acceptable. However, the patient may find the restoration not acceptable and in that case it has to be replaced sooner or later.

Contrary to the RCT studies, the practice-based longitudinal and cross-sectional studies normally have the following characteristics:

- large number of restorations performed without randomization or blinding;
- inclusion of all patients in need of treatment;
- large number of clinicians with varying clinical experience and skills;
- no calibration of clinicians to minimize discrepancy in decision-making;
- routine daily clinical treatment conditions;
- individual follow-ups;
- simple assessments of restorations, focusing on the need of repair or replacement.

The lack of randomization and uniform, fixed criteria for decisions to place and replace restorations complicate the studies and the interpretation of the results. Nevertheless, if the clinicians, the patients, and the treatments are representative for the actual population and the dental health service, the results from practice-based longitudinal and cross-sectional studies are of great value because they reflect current dental practice, including the considerable variation in dentists' clinical decision-making. In fact, they show what can be expected in daily routine clinical use, although it is likely that the age data in cross-sectional surveys is lacking for 30–40% of the restorations, which probably includes the oldest of the failed restorations [10, 66].

When considering the disparities in the two study designs and their consequences for the results, it is understandable that measurements of restoration longevity are usually shorter in practice-based studies than in RCT studies. It is important, therefore, to realize that reliable comparisons of the absolute failure rates of different types of restorations presuppose the same study design, although the relative failure rates may be rather independent of the type of study.

The amalgam debate and its consequences for restoration longevity

Until the 1990s amalgam was the worldwide, all-round material of choice for posterior restorations in primary and permanent teeth. However, changes have occurred for several reasons. The development of alternative tooth-colored restorative materials and the controversy over the potential side effects of amalgam have had an influence on the selection of restorative materials. The dramatic reduction in caries over the last decades, along with the increased affluence and welfare systems in the industrialized world, has called for treatment with materials other than amalgam. With a reduced need for operative treatment of caries, the costs for the individual restorations may be relatively less important for the patient and for public dental health-care services as well. Over the past decades, the environmental and health authorities in Scandinavia and a number of other countries have, furthermore, placed increasing pressure on dentists to reduce the use of dental amalgam. The intention is to protect the environment, and hence the population, from the heavy-metal mercury, and perhaps it is also a response to the ongoing debate on the possible injurious effects of amalgam. This has been a debate that has continued in the media in defiance of the fact that health authorities on a worldwide basis confirm that the overwhelming weight of scientific evidence supports the safety and efficacy of dental amalgam [57, 73].

The result has been a marked phasing out in the use of dental amalgam in developed countries, particularly for fillings in primary teeth, but also for fillings in permanent teeth, as illustrated in Fig. 21.5. From 1992, the altered treatment patterns have been followed up by recommendations and even requirements from health authorities in some countries not to use amalgam in children below 6 years (Germany), not to use amalgam in children and adolescents (Finland, Norway, and Sweden), and to limit the use of amalgam to specific posterior restorations in permanent teeth, where an amalgam restoration is supposed to have a significant increased longevity compared with a tooth-coloured restoration (Denmark). Dentists and authorities have focused directly and indirectly on the primary dentition, because children may potentially be more vulnerable to toxic exposure and because the demands on the clinical properties of the materials and the longevity of the fillings are less here than in the permanent dentition [6, 17]. Although the maximal lifespan for a restoration in a primary tooth is around 8 years, the restorations are usually needed to serve for only 5–6 years with a median of 2.5 years [69].

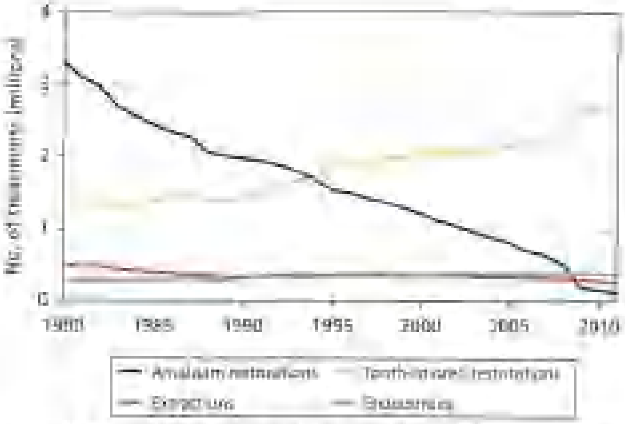


Figure 21.5 Annual number of amalgam restorations, tooth-colored restorations, endodontic treatments, and extractions performed in adults in general dental practice in Denmark from 1980 to 2011. Data from [13].

Alterations in dental restorative treatment patterns affect the measurements of longevity, especially in cross-sectional studies. As only the age of the failed and replaced fillings are recorded, the estimated longevity of improved and newly introduced materials, such as the whole range of tooth-colored materials, will be encumbered with uncertainty and probably be too short. On the other hand, data on restorative materials or techniques on the decline, such as amalgam, will be relatively too long.

Longevity of restorations in the primary dentition

In the few cross-sectional surveys that include primary teeth the median longevity of failed and replaced amalgam fillings is only 2–3 years, and this period is even shorter for tooth-colored fillings [23, 27, 28, 56, 65, 67]. These measurements, however, may be misleadingly short because the majority of restorations inserted in primary teeth will be well functioning until the time for exfoliation and because data on the 20–30% failed restorations are truncated, owing to the shedding of the teeth [39]. The surveys further indicate that the most frequent reasons for retreatment of restored primary teeth are primary caries in unrestored parts of the teeth and secondary or recurrent caries in relation to the fillings, although many restorations also fail because of bulk fracture and loss of retention.

Longitudinal studies of posterior restorations in primary teeth have been reviewed by Hickel *et al.* [35]. The review includes 57 studies with an observation period of at least 2 years, published from 1971 to 2003. The range and median values obtained for annual failure rates for class I/II restorations in different restorative materials and for stainless steel crowns are given in Fig. 21.6 together with the number of studies incorporated in the calculations. The great disparity in the results for restorations in a given type of material (i.e., the large ranges) is caused by variations in the detailed study design, inclusion criteria, observation period, statement of results, and so on. The disparity and the skewed distribution of the results compromise the reliability of comparisons among different materials and different studies. A way to overcome this problem is to focus on the median failure rates from all studies on a treatment, and by so doing it becomes obvious that posterior restorations in amalgam, composite resin, compomer, and resin-modified glass–ionomer have the lowest annual failure rates, and thus an increased longevity compared with conventional glass–ionomer restorations and stainless steel crowns.

Over the last decade, a multicenter project has been carried out in Denmark aiming to provide a realistic basis for estimation of the consequences for the Danish Public Dental Health Service (PDHS) of using amalgam and alternative restorative materials for restorations in the primary dentition [69–73]. It comprises three longitudinal, prospective, and randomized studies, with a design that otherwise resembled the design described above for practice-based longitudinal and cross-sectional studies. An additional study, where the clinicians freely selected which restorative material to use, completed the project. The studies include more than 4000 restorations in amalgam, conventional glass–ionomer, resin-modified glass–ionomer, and compomer made in the primary teeth of around 2500 children and adolescents by 32 PDHS-clinicians in everyday practice. The requirements for additional treatment of the restored primary teeth before exfoliation, as well as the need for operative caries treatment of some 2300 adjacent unrestored surfaces in primary and permanent teeth in contact with the restorations, have been assessed.

In accordance with other studies, high frequencies of bulk fractures and loss of retention of class II and even class I conventional glass–ionomer restorations were recorded in the first study in the project [35, 69]. The better fracture toughness and wear resistance of resin-modified glass–ionomer and polyacid-modified composite resin, so-called compomer, compared with conventional glass–ionomer were reflected in the findings from the studies of Qvist and coworkers [70–72] and Hickel *et al.* [35]. The frequencies of retreatments of primary teeth filled with the newer tooth-colored resin-modified glass–ionomer and compomer materials were around 20% for class II restorations, almost the same as for teeth restored with amalgam, but only half that of conventional glass–ionomer restored teeth. Endodontic complication was a major reason for failures of restorations in all restorative materials. This appeared to be a consequence of the inclusion of pulp-capped and pulpotomized teeth in the project. The other major reasons for failure were fracture of the restoration, loss of retention, and degradation and wear. It should be noted that primary and secondary or recurrent caries seldom resulted in replacement of restorations, and

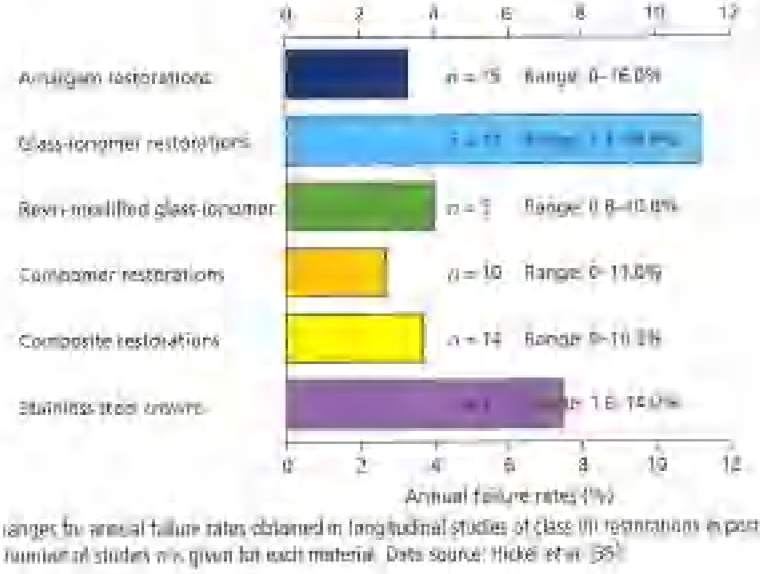


Figure 21.6 Median values and ranges for annual failure rates obtained in longitudinal studies of class I/II restorations in posterior primary teeth using different types of restorative materials. The number of studies (*n*) is given for each material. Data source: Hickel *et al.* [35].

this finding is in contrast to the results from cross-sectional surveys [23, 27, 28, 56, 65, 67]. The reasons may be the generally low caries activity in the population studied, along with the numerous class II restorations in the Danish project, as class II restorations in primary teeth seldom fail due to primary or secondary caries, but often due to fracture of restoration or tooth.

The type of restoration influenced the frequencies of retreatments, with far the highest occurrence for class II restorations. This is important, as approximately 80% of all restorations in the primary dentition are class II restorations, while only 15% are class I and 5% class III and V restorations [69, 70]. The median survival times for class II restorations in resin-modified glass–ionomer and compomer were similar to that of amalgam and exceeded 6–6.5 years, while 50% of the corresponding conventional glass–ionomer restorations failed during the first 3 years (Fig. 21.7). However, the individual clinicians obtained their best results (i.e. their highest survival rates) with different types of restorative materials (Fig. 21.8). Detailed analyses further showed that newer versions of the same conventional glass–ionomer and compomer did not increase the longevity of the restorations in spite of promising laboratory findings [63, 73, 81]. So, it may take some years after the launching of a new material until clinical results have proved if it was an improvement or deterioration compared with earlier versions of the same material.

Another important aspect of different restorative materials is their effect on caries development on adjacent proximal surfaces. In this project it was shown that the fluoride-containing and fluoride-releasing conventional glass–ionomers, resin-modified glass–ionomers, and compomers reduced the development of primary caries on adjacent proximal surfaces and curtailed the progression of existing caries lesions compared with amalgam (Fig. 21.9) [69, 73].

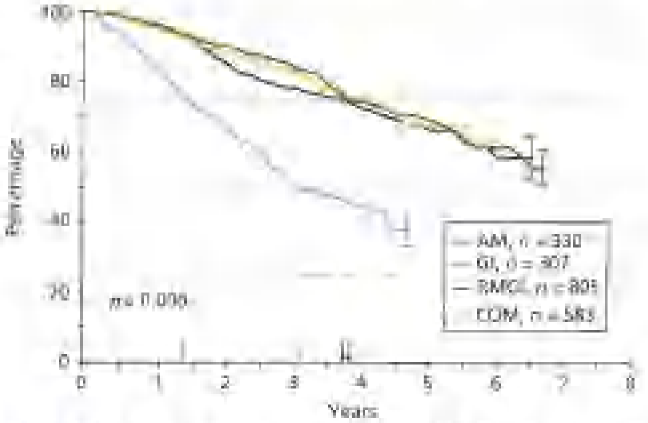
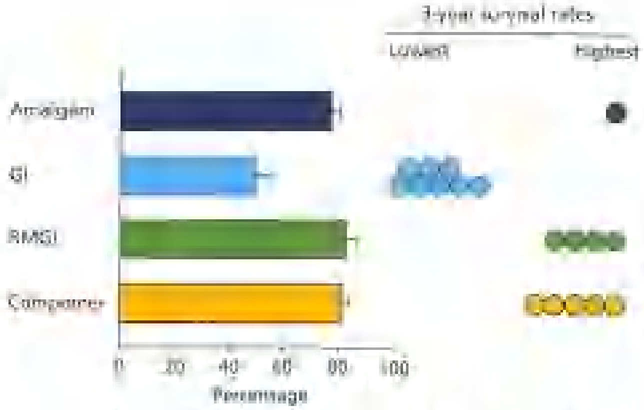


Figure 21.7 Cumulative survival distribution of 2025 class II restorations in primary teeth performed in amalgam (AM), conventional glass–ionomer (GI), resin-modified glass–ionomer (RMGI), and compomer (COM). The curves are drawn as long as at least 10 restorations remained in function. The points at which the curves cross the horizontal quartile lines are indicated by arrows on the abscissa. It appears that the median or 50% longevity for GI restorations was around 3 years, while more than 75% of the AM, RMGI, and COM restorations would still be in function at that time, provided that the teeth have not been exfoliated before then. The difference is highly significant (p = 0.000). The vertical bars represent standard errors of the survival rates [72].



Dentists with ≥ 15 class II restorations in each material

Figure 21.8 Bar graph showing 3-year survival rates (mean, standard error) for class II restorations in primary teeth made in amalgam, conventional glass–ionomer (GI), resin-modified glass–ionomer (RMGI), and compomer by eight dentists with at least 15 restorations in each type of material. The figure also illustrates that GI resulted in the lowest 3-year survival rate for all eight dentists, while one dentist received the highest 3-year survival rate with amalgam, four with RMGI, and five with compomer, and two dentists got equally superior results with RMGI and compomer [69–71].

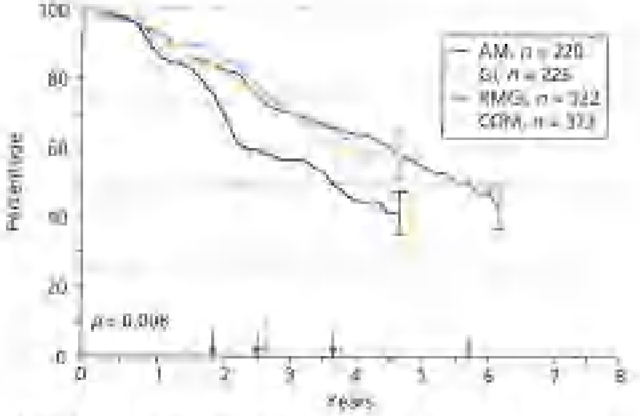


Figure 21.9 Cumulative survival distribution of 1341 unrestored approximal surfaces adjacent to class II restorations in primary teeth performed in amalgam (AM), conventional glass–ionomer (GI), resin-modified glass–ionomer (RMGI), and compomer (COM). The curves are drawn as long as at least 10 surfaces remained unrestored and under observation. The points at which the curves cross the horizontal quartile lines are indicated with arrows on the abscissa. It appears that the median or 50% longevity for surfaces in contact with AM restorations was around 3.5 years, compared with 4.5 years and 5.5 years for surfaces in contact with COM and RMGI respectively. The GI curve followed the RMGI curve, but the surfaces could only be followed for 4.5 years owing to short longevity of GI restorations. The difference is highly significant (p = 0.008). The vertical bars represent standard errors of the survival rates [73].

In 2003, the Danish Health Authorities effectuated a ban against the use of amalgam for restorations in primary teeth. This legislation had been pending for a long time. The results from the project were important documentation in this context. The complete series of studies demonstrated that tooth-colored fluoride-containing and -releasing materials are realistic alternatives to amalgam with the same or even enhanced longevity of the restorations and a cariostatic influence on adjacent proximal surfaces, which reduce the need for operative treatments.

Longevity of restorations in the permanent dentition

Another survey, by Manhart *et al.* [46], reviewed a large number of longitudinal studies of posterior restorations in permanent teeth performed since 1990 with an observation period of at least 2 years. The longevity of class I/II direct and indirect restorations is illustrated in Fig. 21.10 by the range and median values of the annual failure rates for different types of restorations. The results from different studies on the same restorative material diverge as much as the corresponding results from studies in primary teeth (Fig. 21.6). However, it is notable that the relative longevity of restorations in various materials resembles that for the same types of restorations in primary teeth, although the longevity generally is increased in the permanent dentition. So, the median annual failure rates for posterior restorations in permanent versus primary teeth were 1.5% versus 3.3% for amalgam, 2.0% versus 3.7% for direct composite resin, and 8.8% versus 11.2% for conventional glass–ionomer (Figs 21.6 and 21.10). With these failure rates, it will, in theory, be around 67 years until all posterior amalgam restorations in permanent teeth had failed compared to 50 years for composite resin restorations and 11 years for glass–ionomer restorations. Although these calculations appear fairly unrealistic, they indicate the significance of differences in annual failure rates, and give a measure of comparison between materials.

On the basis of the failure rates shown in Fig. 21.10 it may be concluded that indirect composite restorations are not superior to direct composite restorations, and that computer-aided design/machining (CAD/CAM) and laboratory-manufactured ceramic inlays/onlays have a longevity that approaches that for cast gold and metal-ceramic restorations. Furthermore, it is evident that conventional glass–ionomer is not appropriate for either class I/II or tunnel restorations in permanent teeth because of early failures due to wear and bulk fracture of the stress-bearing class I/II restorations and fracture of the marginal ridge and recurrent caries of the tunnel restorations.

During the last decades, numerous cross-sectional surveys on restorative treatment behaviors in the permanent dentition have been carried out [24, 27, 28, 34, 55, 65, 67, 79]. In accordance with longitudinal studies, the surveys clearly point out that resin restorations have a shorter longevity than amalgam restorations in general practice, irrespective of the type of the restoration and the type of failure (Figs 21.11 and 21.12). However, there has been a gradual increase in the longevity of especially class I and II resin restorations, for which the median age of replaced restorations has doubled from around 3 years in a Danish survey from 1990 [67] to around 6 years in a recent Norwegian survey (Fig. 21.11) [54]. The increment reflects the development of particular resin materials for stress-bearing restorations with better wear resistance and higher fracture toughness

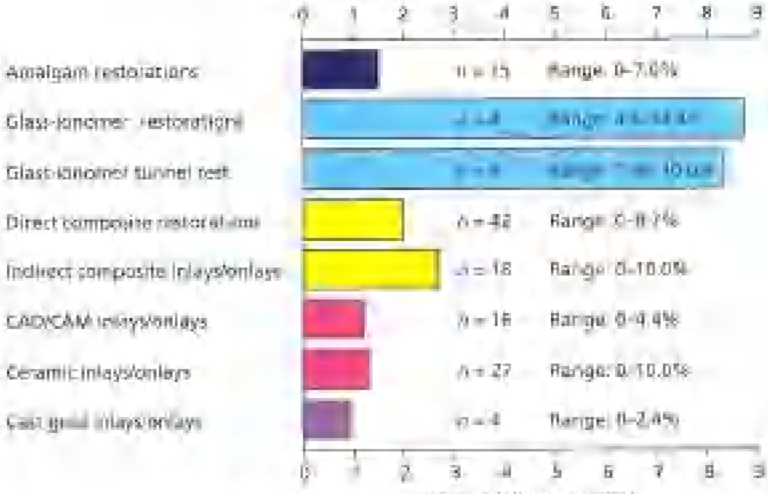


Figure 21.10 Median values and ranges for annual failure rates obtained in longitudinal studies of class I/II restorations in posterior permanent teeth using different types of restorative materials. The number of studies (n) is given for each material. Data source: Manhart *et al.* [46].

along with new bonding agents, which have enhanced the marginal adaptation of the restorations. Still, however, secondary or recurrent caries and fracture of restorations are major reasons for replacement of direct as well as indirect posterior resin restorations, while occlusal and interproximal wear has diminished significantly. The clinical diagnosis secondary or recurrent caries was the most common reason for replacement of amalgam and even glass–ionomer restorations in all cavity types in the Norwegian survey [55].

Most practice-based cross-sectional surveys have recorded the age of restorations at the time they were replaced, whereas few studies have recorded the age of restorations in situ; that is, the age of restorations that have not failed [38]. It appears that the age distributions are similar for failed and acceptable restorations in situ, supporting the relevance of using median age of failed restorations as a criterion for restoration performance in practice-based studies, even though patient treatment records often do not extend back to the date of restoration placement. There is no doubt, however, that analyses of cumulative survival distributions based on data from long-term longitudinal studies remain the optimal method of calculating longevity of groups of dental restorations [39, 59].

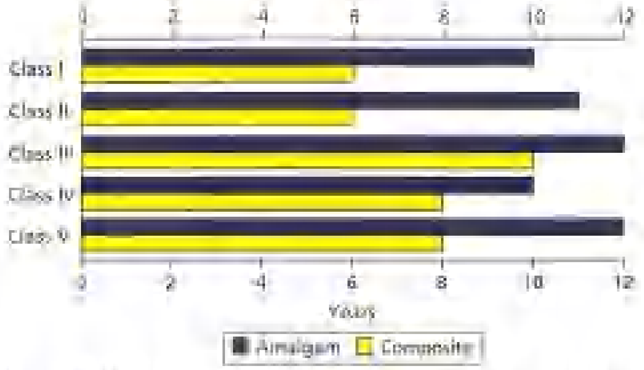


Figure 21.11 Bar graph showing median recorded age of failed amalgam and composite resin restorations in adults in relation to type of restoration. Data source: Mjör *et al.* [54].

Longevity of fissure sealants

Knowledge of caries progression rates has led to considerable modification of restorative intervention thresholds and further management of the caries disease. Today, 'minimal invasive dentistry' is widely used aiming to arrest caries progression and postpone the first placement of a traditional restoration [76]. One option is sealing of the occlusal pit and fissures with a resin-based material or glass–ionomer cement. The results of glass–ionomer sealant studies have so far been divergent, and it is not clear if the fluoride release from such sealants has any additional beneficial effects in caries prevention [1, 44]. Resin-based sealants are today mostly used on indication; that is, in order to either prevent development of carious lesions or therapeutically arresting the progression of initial carious lesions with no cavitation [5, 34, 78]. Another few studies have aimed to investigate the possibility of sealing dentinal carious lesions in occlusal surfaces [3]. The results indicate that all carious lesions may be arrested provided that the sealant is tight [4, 33, 49, 74]. The longevity of sealants is therefore of great importance. In the permanent dentition a recent meta-analysis including 98 clinical reports and 12 field trial reports calculated the 2–3 year retention rates for light-polymerizing resin-based sealants with and without fluoride release to 75–80%, while the similar figures for glass–ionomer sealants were 10–15% [44].

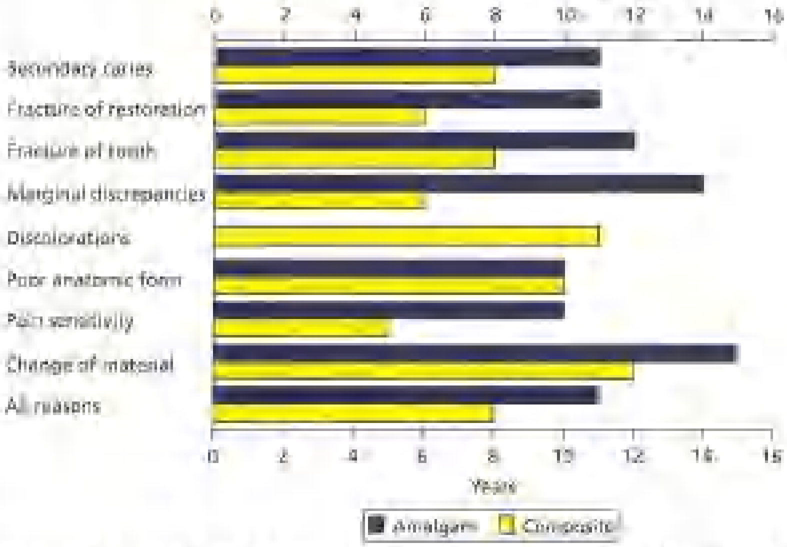


Figure 21.12 Bar graph showing median recorded age of failed amalgam and composite resin restorations in adults in relation to type of failure. Data source: Mjör *et al.* [55].

In the primary dentition the retention rate may be slightly decreased [5]. Previous studies have further shown that children of a high baseline caries-risk status showed lower retention rates and higher occlusal caries prevalence following sealant loss compared with those of moderate- and low-risk status [61], that demineralized and cavitated surfaces may decrease sealant longevity because microleakage occurs more frequently around sealed carious lesions than sealed sound surfaces [34], and that the more posterior the teeth were placed, the higher was the rate of retreatments [64].

Figure 21.13 illustrates the inferior longevity of resin-based sealants compared with resin-based restorations from an ongoing, randomized, clinical and radiographic study of sealing versus restoring manifest occlusal enamel and dentin caries lesions in children and adolescents. All 521 lesions included in the study were in need of operative treatment according to current treatment guidelines [74]. The 4-year cumulative survival rates were around 90% for the restorations, but just 60% for the sealants. However, repairs and replacements accounted for half of the retreatments during the first 4 years, and less than 20% of the sealed lesions were replaced with a restoration because of caries progression. The results, therefore, support the view that a sealing may postpone the first placement of a traditional restoration for several years.

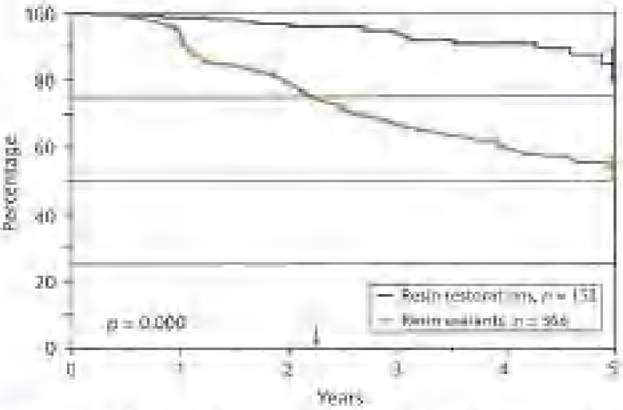


Figure 21.13 Cumulative survival distribution of 153 resin restorations and 368 resin sealants placed in teeth with manifest occlusal enamel and dentin caries lesions in children and adolescents. The 4-year survival rates were around 90% for the restorations, but just 60% for the sealants ($p = 0.000$). The vertical bars represent standard errors of the survival rates [74].

Longevity of atraumatic restorative treatment restorations

Another minimally invasive treatment modality is atraumatic restorative treatment (ART) (see Chapter 19). ART is a one-session approach where cavity opening and removal of soft demineralized carious tissue is done with hand instruments, usually without anesthesia. The cavity is sealed by manual application of an adhesive, usually a high-viscosity conventional glass–ionomer, and this same material is used to simultaneously seal any remaining pits and fissures. The method was developed some 25 years ago for preserving decayed teeth in people of all ages in both developing countries and disadvantaged countries, where resources such as electricity, piped water, and finance are scarce. Nowadays, ART restorations are also widely used in clinics, especially for caries treatment of primary teeth and anxious people [26]. Clinical examples of 3- and 4-year old ART restorations in primary teeth are shown in Fig. 21.14.

ART restorations fail for the same reasons as restorations produced using other techniques and materials. Just as with conventional glass–ionomer restorations, most ART restorations fail because of mechanical failures, particularly fractures and lack of retention. The highest frequency is for multiple-surfaced restorations, and there is a high operator effect. Alternative materials with higher fracture resistance, such as resin-modified glass–ionomer, compomer, and composite

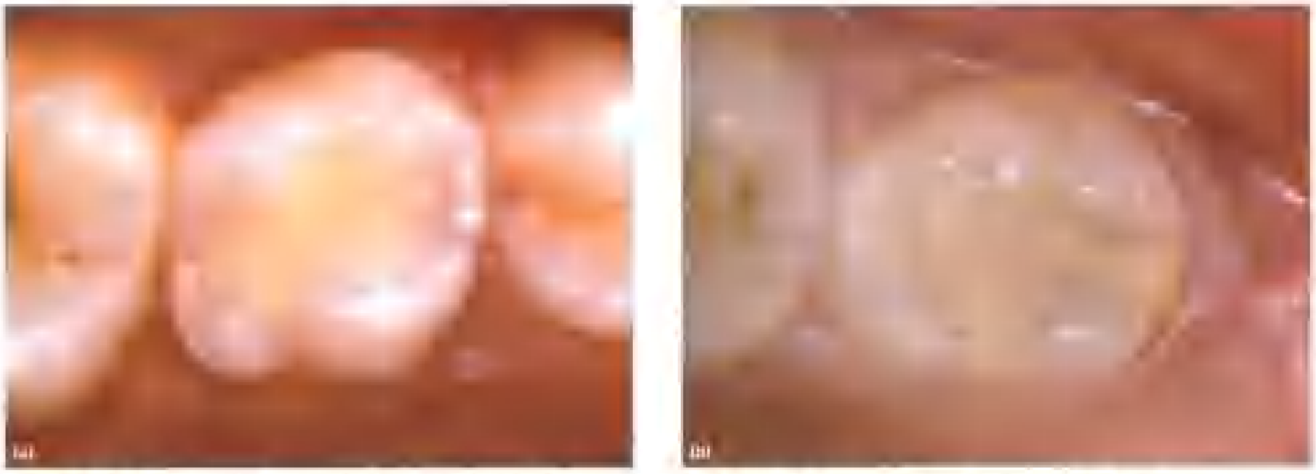


Figure 21.14 Examples of ART restorations: (a) 3-year-old occlusal restoration in the upper second primary molar and (b) 4-year-old occluso–distal restoration in the lower second primary molar. Courtesy of Dr J. Frencken.

resin have therefore also been tried for ART restorations in a few recent studies, but so far the results are inconclusive [25]. It is important to note that recurrent caries is a relatively rare cause of failure of single-surface ART restorations in primary and permanent teeth. This was initially surprising to those who feared the hand excavation would result in incomplete caries removal. However, an excavator removes demineralized dentin efficiently, and incomplete caries removal is moreover of little consequence provided the restoration gives a good seal (see Chapter 20).

Most often ART restorations have been assessed using special ART criteria developed to ensure easy but reliable restoration assessment in the field, but also modified USPHS criteria and Fédération Dentaire Internationale (FDI) criteria have been used. The choice of criteria may have a tremendous effect on the outcomes, as shown in a recent study, where a difference of around 30% in failures of single-surface restorations in permanent teeth was observed over a 10-year period using ART and USPHS criteria, with the USPHS criteria leading to the highest success rate [82]. The fact that retreatment of ART restorations is not always possible during the follow-up period complicates comparisons of failure frequencies and survival rates of ART restorations with that of traditional restorations. There is also a risk that the results are affected by bias [37]. Nevertheless, it is remarkable that a systematic review from 2012 indicates that ART restorations with high-viscosity glass-ionomer during the first years of function have the same failure rate as amalgam restorations placed with conventional rotary instruments in tooth cavities of the same size in primary as well as permanent teeth [50]. When considering the longevity of ART restorations, it becomes most relevant to confine the analyses to ART restorations exclusively. In a recent meta-analysis including 27 studies from 18 countries published until 2010, the 2-year mean survival percentages for *single-* and *multiple-surfaced* restorations in primary teeth were 93% and 62% respectively, and the corresponding 2-year figures for restorations in permanent teeth were 93% and 41% [15].

Let us consider some points of relevance in these results. First, notice the analysis included *27 studies from 18 countries*. Bearing in mind the ART technique has only been described for 25 years, this is remarkable. Those involved throughout the world should be congratulated for assessing and publishing the success or otherwise of the technique. Also, notice the survival of ART restorations in single surfaces in primary and permanent teeth is high, and only the survival of ART restorations in multiple-surface cavities needs to be improved due to material and/or operator-related effects. It is hardly surprising that the skill of the operator is found to be of relevance to the longevity of the restorations, but this means that these techniques must be most carefully taught before applying ART in the field or clinic.

Factors influencing restoration longevity

A number of factors affect the longevity of restorations. These include the type and size of the restoration, the type and brand of the restorative material, along with the restorative technique applied and the quality of the restoration at the time of insertion, together with the dentition, the age of the patient, oral hygiene, the caries activity, and to what extent the patient maintains regular recall appointments in the same dental practice [16, 35, 45, 46]. Moreover, the age of restorations at replacement is dependent on the criteria for failure, which vary markedly in general practice. This is especially the case for secondary or recurrent caries, because it is clinically difficult to differentiate between discolored marginal discrepancies and active caries lesions [40, 53, 62]. The reader should note that in Chapter 19 it is suggested that a cavitated carious lesion, at the margin of the restoration, that cannot be cleaned, is the indication for repairing or replacing a restoration.

The type of failure influences the longevity in another way, too (Fig. 21.13). Most failures occur some time after the restorations have been inserted. They are a result of:

- gradual development of secondary or recurrent caries;
- physical defects, such as discoloration of the restoration;
- degradation, such as marginal breakdown, 'ditching' or 'chipping';
- continuous detrimental damage to the pulp due to bacterial leakage.

Other failures occur during the first few years after the restoration is placed, such as:

- bulk fracture due to inadequate dimensions of the restoration or because the occlusion/articulation has not been adjusted properly;
- loss of restoration due to lack of retention of the restorative material;
- pulp complications due to preparation damage, chemical injuries from restorative materials in deep cavities or even pulp capping, regardless of whether a perforation is properly treated or overlooked.

In the above-mentioned Danish project, multivariate survival analyses were used to find the factors that significantly affect restoration failures in the primary dentition [69–71]. Figure 21.15 summarizes the results of the analyses for the important class II restorations for all types of failures and for the three most frequent types, which were bulk fracture, loss of retention, and endodontic complications. It is evident that numerous factors related to the patient as well as to the treatment, the materials and methods, and the clinician are all decisive for the success of restorative treatments. For example, the risk of failure diminished with increasing age of the child, it was lower for first-time than for replacement restorations, and lower for restorations placed in

Variable	Failures at all	Fracture restoration	Loss of retention	Endodontic complications
Restorative material	★			
Restorative method	★	★		
First time restoration/replacement	★	★		
Location of restoration-jaw	★			
Location of restoration-tooth				
Location of restoration-surface				★
Base material				
Endodontic treatment of tooth	★			★
Treatment problems				
Age of children	★	★		★
Caries experience at 5 years				
Clinician	★	★	★	★

★ $p < 0.05$.

Figure 21.15 Variables of significance for overall survival of restorations in the primary dentition and for occurrence of the three most frequent types of failure; i.e. bulk fracture of restoration, loss of retention, and endodontic complications. Based on Qvist and coworkers [69, 71].

teeth with sound pulps compared with endodontically treated teeth. Furthermore, conventional glass-ionomer showed a higher risk of failure than amalgam and resin-modified glass-ionomer and compomer, and cavity conditioning further reduced the failure rates for compomer restorations. The significance of the variation among clinicians was highlighted in the statistical results of the Danish project and has also been shown in a few other investigations on the outcome of dental restorative treatments in primary as well as permanent teeth [16, 35, 46]. The analyses showed that clinicians using various materials achieve the highest survival rate with one particular material, which may differ from clinician to clinician. Often, the clinicians will not be aware of such differences. Hopefully, computer-aided evaluations of longevity results will be a valuable tool in the near future. These may help the individual clinician select optimal restorative materials and methods for their specific patient population. They may also help to diminish their specific restorative shortcomings.

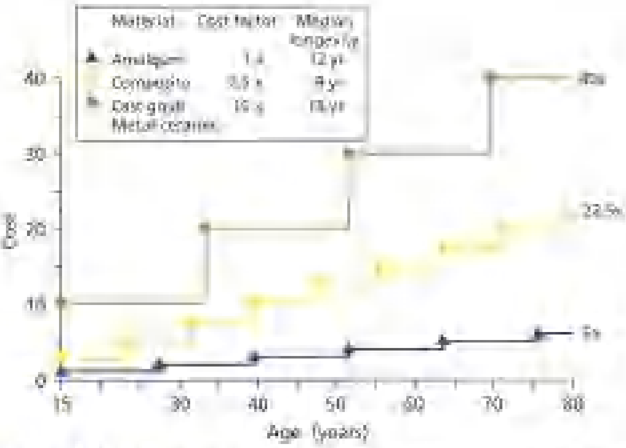


Figure 21.16 Cumulative cost of restorative treatment using amalgam, composite resin, or cast gold/ceramic for class II restorations over a 65-year period. The calculations are based on actual Danish costs (1× for amalgam, 2.5× for composite, and 8× for gold/metal-ceramic restorations) and today's expectations as to their median longevity: 8 years for composite, 12 years for amalgam, and 18 years for gold/metal-ceramic class II restorations.

Consequences of restoration longevity for dental health and cost

The cost of restorative therapy, using various materials, differs not only when the tooth is restored, but also over time due to differences in longevity [14, 42, 51, 77]. Figure 21.16 illustrates the long-term costs for two- and three-surfaced posterior restorations made in contemporary composite resin, amalgam, and gold/metal-ceramic. The costs are based on updated expectations of the median longevities and actual Danish cost for restorations in the different materials. Over a 65-year period – from 15 to 80 years of age – the cumulative cost of composite restorations would be about 3.5 times that of amalgam restorations, while similar gold/metal-ceramic restorations would cost about 6.5 times more than amalgam restorations.

However, the calculations are unrealistic in the way that they presuppose new restorations to be performed of the same size as the restorations they replace. Successive direct and indirect restorations tend to enlarge the cavity, leading to an increased risk of subsequent tooth fracture and other types of failures [8, 43]. Therefore, replacement restorations are likely to be larger, more complex, and sometimes more expensive than the initial restorations. Consequently, they often have a shorter longevity as they can have an injurious effect on the

Figure 21.17 Illustration of the detrimental long-term consequences for the dental health of the restorative cycle – 'the death spiral.' Over the years, the initially sound first lower premolar (a) has been restored with a localized (b) and then an extended occlusal amalgam restoration (c), a two-surfaced (d) and a three-surfaced occluso-proximal amalgam restoration (e), and because of gingival caries (f) or abrasion (g) a facial composite (h) and amalgam restoration (i), a cast gold crown (j), and eventually a bridge has been made (k) after extraction of the premolar (l).

pulp, occasionally leading to endodontic treatment, involving further expenses. Restorative treatments may, furthermore, involve a risk of iatrogenic damage on adjacent tooth surfaces, which itself will compromise dental health as it often results in caries development and progression [48, 68].

The possible detrimental long-term consequences for the dental health of the 'restorative cycle' or 'the death spiral' are illustrated in the first premolar in the lower jaw in Fig. 21.17.

Concluding remarks

Restorations may be needed to replace lost and defective tissues (see Chapter 20). However, restorations per se will not 'treat away' caries [18]. They have a limited lifetime and most restorations fail due to clinically diagnosed secondary or recurrent caries. The longevity, side effects, aesthetics, and economics of dental restorations are the most important parameters for dentists and patients in the choice of restorative materials [9, 21, 22, 80]. Measurements of the longevity of restorations reflect all conditions that affect the restoration from the day of insertion until failure occurs. The longevity of restorations and the cost of placing/replacing restorations are two decisive factors determining the long-term expenses of restorative therapy.

Once a permanent tooth is restored, the filling is likely to be replaced several times in the patient's life, and repeated replacements of restorations may compromise the survival of the tooth itself, and thus the dental health of the patient. It is important, therefore, to ensure that a tooth surface is not restored until it is obvious that arrestment of the disease is unlikely. Furthermore, it is important to consider all possibilities to prolong the durability of restorations through optimal choice and use of restorative materials, prevention of recurrent disease, and improved clinical diagnostics of restoration quality, including minor corrections and repair to postpone replacements.

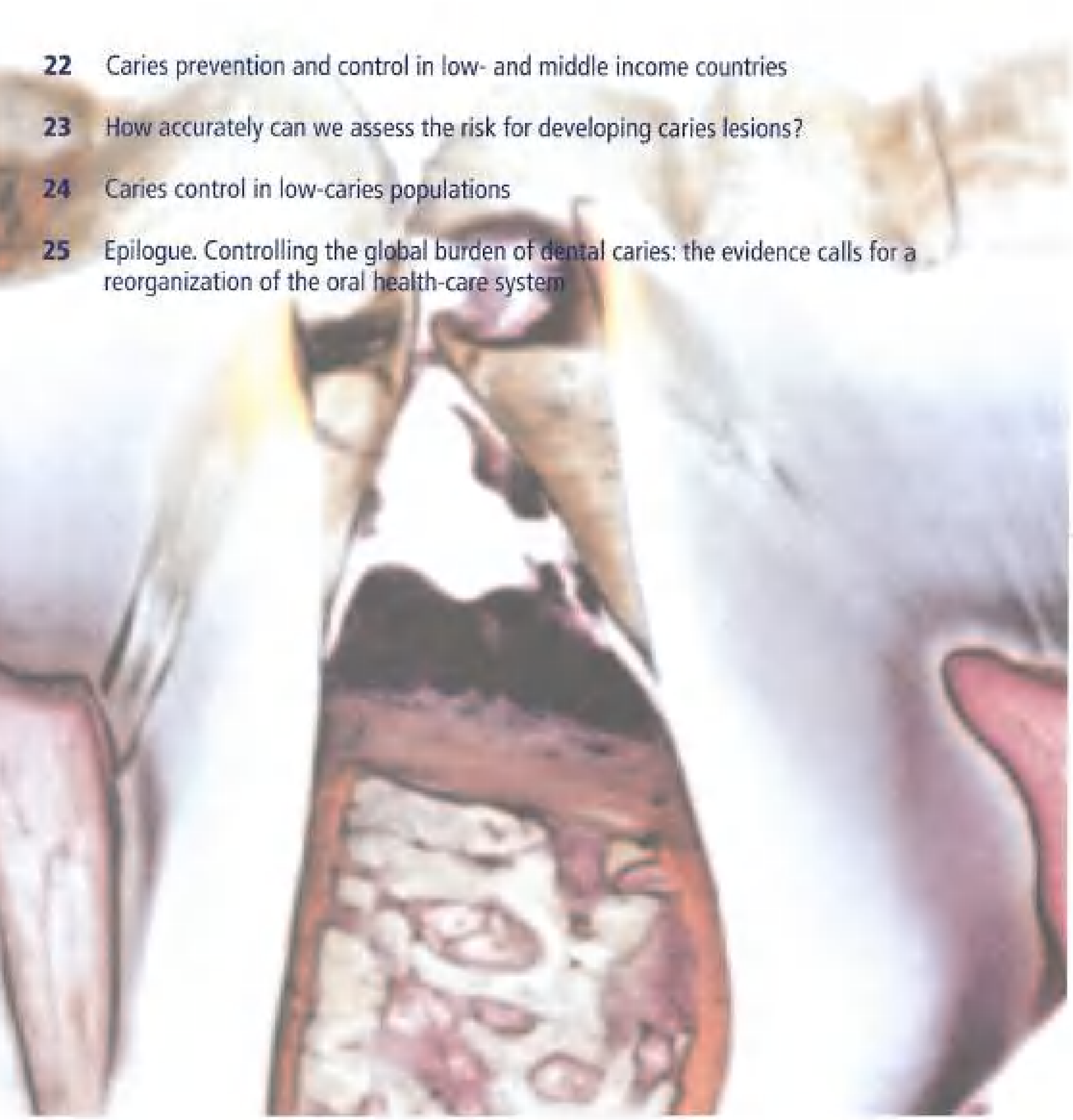
References

1. Ahovuo-Saloranta A, Hiiri A, Nordblad A, Mäkelä M, Worthington HV. Pit and fissure sealants for preventing dental decay in the permanent teeth of children and adolescents. *Cochrane Database Syst Rev* 2008; (4): CD001830.
2. Bader JD, Shugars DA. Variation in dentists' clinical decisions. *J Public Health Dent* 1995; 55: 181–8.
3. Bakhshandeh A. *Quantification and management of manifest occlusal caries lesions in adults. A methodological and a clinical study*. PhD thesis. Copenhagen: University of Copenhagen, 2011.
4. Bakhshandeh A, Qvist V, Ekstrand KR. Sealing occlusal caries lesions in adults referred for restorative treatment: 2–3 years of follow-up. *Clin Oral Investig* 2012; 16: 521–9.
5. Beauchamp J, Caufield PW, Crall JJ, Donly K, Feigal R, Gooch B, Ismail A, Kohn W, Siegal M, Simonsen R. Evidence-based clinical recommendations for the use of pit-and-fissure sealants. A report of the American Dental Association Council on Scientific Affairs. *J Am Dent Assoc* 2008; 139: 257–68.
6. Bellinger DC, Trachtenberg F, Barregard L, Tavares M, Cernichiari E, Daniel D, McKinlay S. Neuropsychological and renal effects of dental amalgam in children: a randomized clinical trial. *J Am Med Assoc* 2006; 295: 1775–83.
7. Blum IR, Mjör IA, Schriever A, Heidemann D, Wilson NFH. Defective direct composite restorations – replace or repair? A survey of teaching in Scandinavian dental schools. *Swed Dent J* 2003; 27: 99–104.
8. Brantley CF, Bader JD, Shugars DA, Nesbit SP. Does the cycle of rerestoration lead to larger restorations? *J Am Dent Assoc* 1995; 126: 1407–13.
9. Burke FJ. Amalgam to tooth-coloured materials – implications for clinical practice and dental education: governmental restrictions and amalgam-usage survey results. *J Dent* 2004; 32: 343–50.
10. Chadwick BL, Dummer PMH, Dunstan F, Gilmour ASM, Jones RJ, Phillips CJ, Rees J, Richmond S, Stevens J, Treasure ET. *The longevity of dental restorations: a systematic review*. York: NHS Centre for Reviews and Dissemination, University of York, 2001.
11. Cvar JF, Ryge G. *Criteria for the clinical evaluation of dental restorative materials*. USPHS Publication No. 790-244. San Francisco, CA: US Government Printing Office, 1971.
12. Cvar JF, Ryge G. Reprint of Criteria for the clinical evaluation of dental restorative materials. 1971. *Clin Oral Investig* 2005; 9: 215–32.
13. Danish National Health Insurance. Database on dental services, patients in Denmark from 1980 to 2011.
14. Da Silva RP, Meneghim MC, Correr AB, Pereira AC, Ambrosano GM, Mialhe FL. Variations in caries diagnoses and treatment recommendations and their impacts on the costs of oral health care. *Community Dent Health* 2012; 29: 25–8.
15. De Amorim RG, Leal SC, Frencken JE. Survival of atraumatic restorative treatment (ART) sealants and restorations: a meta-analysis. *Clin Oral Investig* 2012; 16: 429–41.
16. Demarco FF, Corrêa MB, Cenci MS, Moraes RR, Opdam NJ. Longevity of posterior composite restorations: not only a matter of materials. *Dent Mater* 2012; 28: 87–101.
17. DeRouen TA, Martin MD, Leroux BG, Townes BD, Woods JS, Leitão J, Castro-Caldas A, Luis H, Bernardo M, Rosenbaum G, Martins IP. Neurobehavioral effects of dental amalgam in children: a randomized clinical trial. *J Am Med Assoc* 2006; 295: 1784–92.
18. Elderton RJ. Preventive (evidence-based) approach to quality general dental care. *Med Princ Pract* 2003; 12: 12–21.
19. Elderton RJ, Nuttall NM. Variation among dentists in planning treatment. *Br Dent J* 1983; 154: 201–6.
20. Espelid I, Tveit AB, Mejàre I, Sundberg H, Hallonsten AL. Restorative treatment decisions on occlusal caries in Scandinavia. *Acta Odontol Scand* 2001; 59: 21–7.
21. Espelid I, Cairns J, Askildsen JE, Qvist V, Gaarden T, Tveit AB. Preferences over dental restorative materials among young patients and dental professionals. *Eur J Oral Sci* 2006; 114: 15–21.
22. Forss H, Widström E. Factors influencing the selection of restorative materials in dental care in Finland. *J Dent* 1996; 24: 257–62.
23. Forss H, Widström E. The post-amalgam era: a selection of materials and their longevity in the primary and young permanent dentitions. *Int J Paediatr Dent* 2003; 13: 158–64.
24. Forss H, Widström E. Reasons for restorative therapy and the longevity of restorations in adults. *Acta Odontol Scand* 2004; 62: 82–6.
25. Frencken JE. The ART approach using glass-ionomers in relation to global oral health care. *Dent Mater* 2010; 26: 1–6.
26. Frencken JE, Leal SC, Navarro MF. Twenty-five-year atraumatic restorative treatment (ART) approach: a comprehensive overview. *Clin Oral Investig* 2012; 16: 1337–46.
27. Friedl KH, Hiller KA, Schmalz G. Placement and replacement of amalgam restorations in Germany. *Oper Dent* 1994; 19: 228–32.
28. Friedl KH, Hiller KA, Schmalz G. Placement and replacement of composite restorations in Germany. *Oper Dent* 1995; 20: 34–8.
29. Gordan VV, Garvan CW, Heft MW, Fellows JL, Qvist V, Rindal DB, Gilbert GH. Restorative treatment thresholds for interproximal primary caries based on radiographic images: findings from the Dental Practice-Based Research Network. *Gen Dent* 2009; 57: 654–63.
30. Gordan VV, Garvan CW, Richman JS, Fellows JL, Rindal DB, Qvist V, Heft MW, Williams OD, Gilbert GH. How dentists diagnose and treat defective restorations: evidence from the Dental PBRN. *Oper Dent* 2009; 34: 664–73.
31. Gordan VV, Bader JD, Garvan CW, Richman JS, Qvist V, Fellows JL, Rindal DB, Gilbert GH. Restorative treatment thresholds for occlusal primary caries among dentists in the Dental Practice-Based Research Network. *J Am Dent Assoc* 2010; 141: 171–84.
32. Gordan VV, Riley JL III, Geraldeli S, Rindal DB, Qvist V, Fellows JL, Kellum HP, Gilbert GH. Repair or replacement of defective restorations by dentists in the Dental Practice-Based Research Network. *J Am Dent Assoc* 2012; 143: 593–601.
33. Handelman SL, Leverett DH, Solomon ES, Brenner CM. Use of adhesive sealants over occlusal carious lesions: radiographic evaluation. *Community Dent Oral Epidemiol* 1981; 9: 256–9.
34. Hevinga MA, Opdam NJ, Frencken JE, Bronkhorst EM, Truin GJ. Can caries fissures be sealed as adequately as sound fissures? *J Dent Res* 2008; 87: 495–8.
35. Hickel R, Kaaden C, Paschos E, Buerkle V, García-Godoy F, Manhart J. Longevity of occlusally-stressed restorations in posterior primary teeth. *Am J Dent* 2005; 18: 198–211.
36. Hickel R, Peschke A, Tyas M, Mjör I, Bayne S, Peters M, Hiller KA, Randall R, Vanherle G, Heintze SD. FDI World Dental Federation – clinical criteria for the evaluation of direct and indirect restorations. Update and clinical examples. *J Adhes Dent* 2010; 12: 259–72.
37. Hurst D. Low quality evidence suggests that failure rates for atraumatic restorative treatment and conventional amalgam are similar. *Evid Based Dent* 2012; 13: 46–7.

38. Jokstad A, Mjör IA, Qvist V. The age of restorations in situ. *Acta Odontol Scand* 1994; **52**: 234–42.
39. Joly A, Gerds TA, Qvist V, Commenges D, Keiding N. Estimating survival of dental fillings on the basis of interval-censored data and multi-state models. *Stat Med* 2012; **31**: 1139–49.
40. Kidd EAM, Joyston-Bechal S, Beighton D. Marginal staining and ditching as a predictor of secondary caries around amalgam restorations: a clinical and microbiological study. *J Dent Res* 1995; **74**: 1206–11.
41. Knibbs PJ. Methods of clinical evaluation of dental restorative materials. *J Oral Rehabil* 1997; **24**: 109–23.
42. Kolker JL, Damiano PC, Flach SD, Bentler SE, Armstrong SR, Caplan DJ, Kuthy RA, Warren JJ, Jones MP, Dawson DV. The cost-effectiveness of large amalgam and crown restorations over a 10-year period. *J Public Health Dent* 2006; **66**: 57–63.
43. Kuper NK, Opdam NJ, Bronkhorst EM, Huysmans MC. The influence of approximal restoration extension on the development of secondary caries. *J Dent* 2012; **40**: 241–7.
44. Kühnisch J, Mansmann U, Heinrich-Weltzien R, Hickel R. Longevity of materials for pit and fissure sealing – results from a meta-analysis. *Dent Mater* 2012; **28**: 298–303.
45. Letzel H, van't Hof MA, Marshall GW, Marshall SJ. The influence of the amalgam alloy on the survival of amalgam restorations: a secondary analysis of multiple controlled clinical trials. *J Dent Res* 1997; **76**: 1787–98.
46. Manhart J, Chen HY, Hamm G, Hickel R. Buonocore Memorial Lecture. Review of the clinical survival of direct and indirect restorations in posterior teeth of the permanent dentition. *Oper Dent* 2004; **29**: 481–508.
47. Martin J, Fernandez E, Estay J, Gordan VV, Mjör IA, Moncada G. Minimal invasive treatment for defective restorations: five-year results using sealants. *Oper Dent* 2012; **37**: 125–33.
48. Medeiros VAF, Seddon RP. Iatrogenic damage to approximal surfaces in contact with class II restorations. *J Dent* 2000; **28**: 103–10.
49. Mertz-Fairhurst EJ, Curtis JW Jr, Ergle JW, Rueggeberg FA, Adair SM. Ultraconservative and cariostatic sealed restorations: results at year 10. *J Am Dent Assoc* 1998; **129**: 55–66.
50. Mickenautsch S, Yengopal V. Failure rate of atraumatic restorative treatment using high viscosity glass-ionomer cement compared to that of conventional amalgam restorative treatment in primary and permanent teeth: a systematic review update – III. *J Min Interv Dent* 2012; **5**: 273–291.
51. Mjör IA. Long term cost of restorative therapy using different materials. *Scand J Dent Res* 1992; **100**: 60–5.
52. Mjör IA. Repair versus replacement of failed restorations. *Int Dent J* 1993; **43**: 466–72.
53. Mjör IA, Toffenetti F. Secondary caries: a literature review with case reports. *Quintessence Int* 2000; **31**: 165–79.
54. Mjör IA, Dahl JE, Moorhead JE. Age of restorations at replacement in permanent teeth in general dental practice. *Acta Odontol Scand* 2000; **58**: 97–101.
55. Mjör IA, Moorhead JE, Dahl JE. Reasons for replacement of restorations in permanent teeth in general dental practice. *Int Dent J* 2000; **50**: 360–6.
56. Mjör IA, Dahl JE, Moorhead JE. Placement and replacement of restorations in primary teeth. *Acta Odontol Scand* 2002; **60**: 25–8.
57. Mutter J. Is dental amalgam safe for humans? The opinion of the scientific committee of the European Commission. *J Occup Med Toxicol* 2011; **6**: 2–11.
58. Nuttall NM, Elderton RJ. The nature of restorative dental treatment decisions. *Br Dent J* 1983; **154**: 363–5.
59. Opdam NJ, Bronkhorst EM, Cenci MS, Huysmans MC, Wilson NH. Age of failed restorations: a deceptive longevity parameter. *J Dent* 2011; **39**: 225–30.
60. Opdam NJ, Bronkhorst EM, Loomans BA, Huysmans MC. Longevity of repaired restorations: a practice based study. *J Dent* 2012; **40**: 829–35.
61. Oulis CJ, Berdouses ED. Fissure sealant retention and caries development after resealing on first permanent molars of children with low, moderate and high caries risk. *Eur Arch Paediatr Dent* 2009; **10**: 211–7.
62. Özer L. The relationship between gap size, microbial accumulation and the structural features of natural caries in extracted teeth with class II amalgam restorations. PhD thesis. Copenhagen: University of Copenhagen; 1997.
63. Peutzfeldt A, García-Godoy F, Asmussen E. Surface hardness and wear of glass ionomers and compomers. *Am J Dent* 1997; **10**: 15–17.
64. Poulsen S, Laurberg L, Vaeth M, Jensen U, Haubek D. A field trial of resin-based and glass-ionomer fissure sealants: clinical and radiographic assessment of caries. *Community Dent Oral Epidemiol* 2006; **34**: 36–40.
65. Qvist J, Qvist V, Mjör IA. Placement and longevity of amalgam restorations in Denmark. *Acta Odontol Scand* 1990; **48**: 297–303.
66. Qvist V. Longevity of restorations in primary teeth. In: Hugoson A, Falk M, Johansson S, eds. *Consensus conference on caries in the primary dentition and its clinical management*. Stockholm: Förlagshuset Gothia; 2002: 69–83.
67. Qvist V, Qvist J, Mjör IA. Placement and longevity of tooth-colored restorations in Denmark. *Acta Odontol Scand* 1990; **48**: 305–11.
68. Qvist V, Johannessen L, Bruun M. Progression of approximal caries in relation to iatrogenic preparation damage. *J Dent Res* 1992; **71**: 1370–3.
69. Qvist V, Laurberg L, Poulsen A, Teglers PT. Eight-year study on conventional glass ionomer and amalgam restorations in primary teeth. *Acta Odontol Scand* 2004; **62**: 37–45.
70. Qvist V, Laurberg L, Poulsen A, Teglers PT. Class II restorations in primary teeth: 7-year study on three resin-modified glass ionomer cements and a compomer. *Eur J Oral Sci* 2004; **112**: 188–96.
71. Qvist V, Manscher E, Teglers PT. Resin-modified and conventional glass ionomer restorations in primary teeth: 8-year results. *J Dent* 2004; **32**: 285–94.
72. Qvist V, Poulsen A, Teglers PT, Mjör IA. The longevity of different restorations in primary teeth. *Int J Paediatr Dent* 2010; **20**: 1–7.
73. Qvist V, Poulsen A, Teglers PT, Mjör IA. Fluorides leaching from restorative materials and the effect on adjacent teeth. *Int Dent J* 2010; **60**: 156–60.
74. Qvist V, Andersen TB, Borum MK, Møller KD. Sealing or restoring manifest occlusal caries in young permanent teeth – 3.5 years results. *Eur Arch Paediatr Dent* 2011; **12**, abstr. no. O17-153).
75. SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks). *Safety of dental amalgam and alternative dental restoration materials for patients and users*. European Commission. 2008: 1–74. http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_016.pdf (accessed November 9, 2014).
76. Simonsen RJ. From prevention to therapy: minimal intervention with sealants and resin restorative materials. *J Dent* 2011; **39**: 27–33.
77. Sjögren P, Halling A. Long-term cost of direct class II molar restorations. *Swed Dent J* 2002; **26**: 107–14.
78. Splieth CH, Ekstrand KR, Alkilzy M, Clarkson J, Meyer-Lueckel H, Martignon S, Paris S, Pitts NB, Ricketts DN, van Loveren C. Sealants in dentistry: outcomes of the ORCA Saturday Afternoon Symposium 2007. *Caries Res* 2010; **44**: 3–13.
79. Sunnegårdh-Grönberg K, van Dijken JW, Funegård U, Lindberg A, Nilsson M. Selection of dental materials and longevity of replaced restorations in public dental health clinics in northern Sweden. *J Dent* 2009; **37**: 673–8.
80. Widström E, Birn H, Haugejorden O, Sundberg H. Fear of amalgam: dentists' experience in the Nordic countries. *Int Dent J* 1992; **42**: 65–70.
81. Xie D, Brantley WA, Culbertson BM, Wang G. Mechanical properties and microstructures of glass-ionomer cements. *Dent Mater* 2000; **16**: 129–38.
82. Zanata RL, Fagundes TC, Freitas MC, Lauris JR, Navarro MF. Ten-year survival of ART restorations in permanent posterior teeth. *Clin Oral Investig* 2011; **15**: 265–71.

Part VI

From chair-side to population caries control



22

Caries prevention and control in low- and middle-income countries

W. van Palenstein Helderman, C. Holmgren,
B. Monse, and H. Benzian

Introduction

This chapter looks at prevention and control of caries from a public health standpoint and focuses on the situation in low- and middle-income countries (LMICs).

There are three major reasons for having this chapter in the textbook:

1. Caries and many other (oral) health conditions show a significantly different disease burden in LMICs – and the vast majority of populations live in LMIC.
2. General socio-economic conditions, health systems, and available resources differ greatly between LMIC and high-income countries (HICs), which may make many approaches to prevention and control of caries applied in HICs unrealistic for the majority of LMICs and their resources.
3. Realistic approaches to prevention and management of caries are necessary for the settings of LMICs.

This chapter will examine in detail these aspects and reflect on how the widespread neglect of oral diseases and caries in LMICs can be overcome.

The previously used terminology of 'developed' versus 'developing' countries is no longer politically accepted due to a lack of clear criteria for this categorization. Today, the classification of countries developed by the World Bank has been widely adopted [91]. It groups countries into low-, lower-middle-, upper-middle-, and high-income tiers, based on their gross national income (GNI) per capita (Table 22.1). Low-income countries (LICs) comprise over 827 million people in the world, while middle-income countries (MICs) account for 5 billion of the world's 7 billion people [40].

However, it has been argued that using GNI as the only criterion to characterize a country is too narrow and limited. This classification is also not ideal in the context of the caries burden, because it does not take into account

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd

important social determinants of health and oral health and the resulting disparities within countries. In most HICs there are deprived and disadvantaged populations with living and health conditions similar to populations in LMICs. Conversely, in LMICs there are populations that are financially capable of purchasing whatever health care they might require. In fact, caries should be considered as a disease of inequalities as many studies have demonstrated (see Chapter 4) [17].

With this in mind, it is obvious that some of the approaches for prevention and control of caries described for LMICs may be equally relevant for deprived and disadvantaged populations in HICs suffering from inequalities in health and socio-economic status.

Over the last decades, renewed international focus on reducing poverty through major initiatives such as the Millennium Development Goals, coupled with solid socio-economic development in many countries around the world, has led to unprecedented improvements in living conditions for billions of people worldwide (Fig. 22.1). Thanks to these efforts, the number of people living in LICs has been reduced from 3.1 billion in 1990 to 0.82 billion in 2011, and the number of people living in MICs has increased from 1.4 billion to 5 billion.

Table 22.1 World Bank country grouping according to GNI per capita.

Country grouping	GNI per capita (US$, 2013)
Low income (LIC)	≤1035
Lower-middle income (lower-MIC)	1035–4085
Upper-middle income (upper-MIC)	4086–12615
High income (HIC)	≥12616

These dramatic societal transitions go hand in hand with major social and economic changes, as well as different exposure to health risks and changes in disease burden resulting from new lifestyles. While many populations experienced a significant decrease of communicable diseases, such as malaria, tuberculosis, HIV/AIDS, a large number of countries observed a marked increase in non-communicable diseases (NCDs), such as cardiovascular diseases, diabetes, obesity, or cancer [7]. These transitions also affect oral diseases, particularly caries.

Caries: a public health problem in low- and middle-income countries

Caries is the most common chronic disease worldwide (Chapter 4) and is a major public health problem for all countries [51], but particularly for LMICs, who cannot afford to spend amounts even remotely comparable to the US$110 billion spent by the USA on oral health care in 2012 [22]. Costly programs focusing only on oral diseases in parallel with other programs (vertical programming) are unrealistic options for LMICs, where resources are scarce and the impact of untreated caries is particularly high. The analysis of the underlying broader social determinants of health and associated risk factors that are characteristic for LMICs gives important insights in designing appropriate strategies to address the problem.

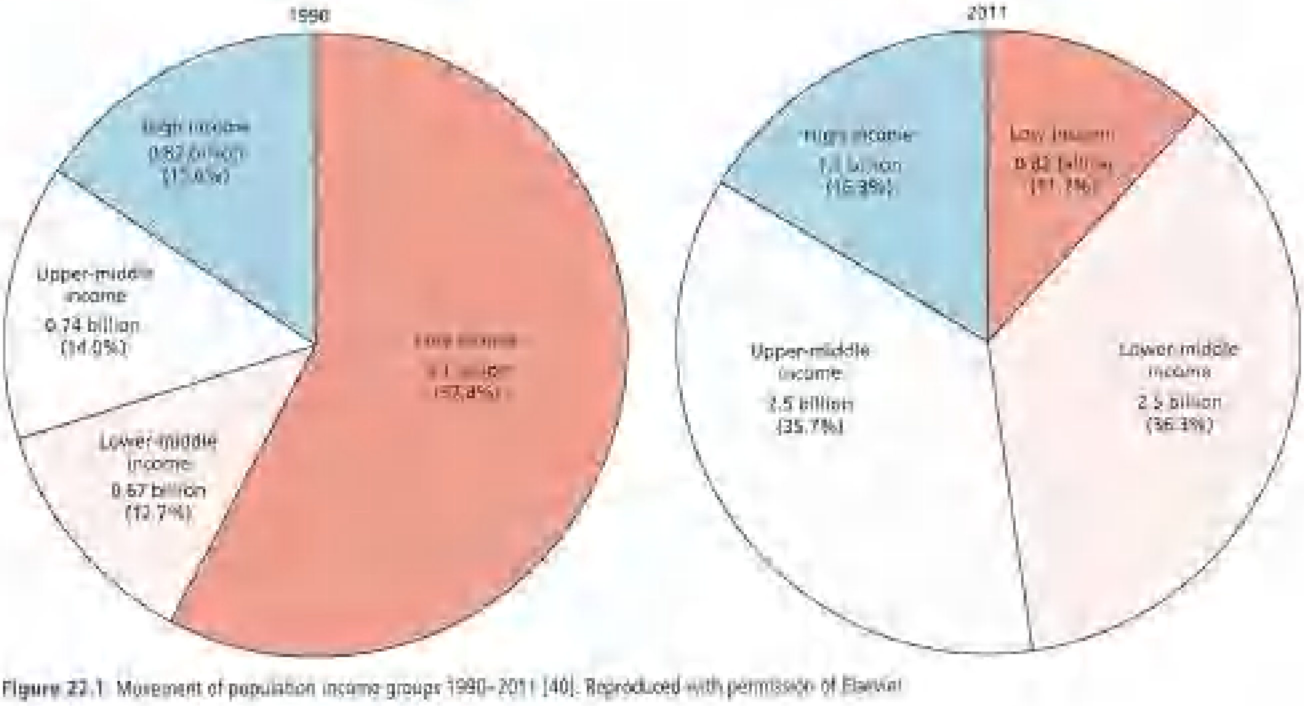


Figure 22.1 Movement of population income groups 1990–2011 [40]. Reproduced with permission of Elsevier.

Social determinants and risk factors of caries in low- and middle-income countries

The narrow concept of risk factors for oral diseases has been expanded to include social determinants, inspired by the landmark report of the World Health Organization (WHO) Commission on Social Determinants and Health [52] (see Chapter 4). A more comprehensive model has been proposed that explains the inequalities of the oral disease burden with intermediate determinants and the broader structural determinants of health (Fig. 22.2).

All LMICs are undergoing major demographic, economic, technological, social, and epidemiological transitions with concomitant changes in risk factor exposure, including higher consumption of tobacco, alcohol, salt, and sugar. Moreover, the speed of these changes, coupled with changes in diet and physical activity due to urbanization and occupation transitions affecting billions, are projected to result in major shifts in disease burdens [71]. For instance, tobacco use is growing fastest in LMICs, due to population growth and tobacco industry targeting. Similarly, there are considerable changes in the composition of average diets in these countries from diets high in complex less-cariogenic carbohydrates to diets that are high in fat, salt, and free sugars – a process labeled as the 'sweetening of the world's diet' [70]. The lifestyle transitions that include increasing sugar consumption in the absence of appropriate fluoride exposure remain an important risk factor. Moreover, there is consistent evidence about the relationship between the amount of sugar intake and the development of caries (irrespective of frequency of intake), with lower caries levels when free sugar intake is less than 10% of total energy consumption (calories). There may be further benefits if free sugar intake were to be reduced to less than 5% [61].

With a broader view of social determinants and risk factors for caries and oral health, it is obvious that all these transitions will result in change. While the general health and oral health of some populations will improve, even more will be exposed to new determinants and risks, resulting in different disease burdens. The resulting challenges for health systems are growing, as are pressures for policy makers to address them effectively [26].

Caries burden in low- and middle-income countries

The WHO's Oral Health Country/Area Profile Programme (CAPP) is the only authoritative source of international data on caries, but these data require cautious interpretation. Data for many countries are limited, neither updated nor representative and, owing to lack of calibration and standardization, are not comparable. Moreover, the recommended WHO caries diagnostic criteria have undergone subtle but significant changes over time. Such changes may account for substantial differences (up to 30%) in decayed, missing, filled teeth (DMFT) [50, 58]. Despite these limitations, some trends can be observed. For 12-year-olds, the lowest DMFT is found in LICs and the highest in upper-middle-income countries (UMICs), although there is a large variation between countries within each income category (Table 22.2).

The DMFT does not, however, give an indication of the level of care – although LICs might on average have lower DMFT, almost all caries remains untreated. As countries become wealthier the amount of care increases, but even in some HICs only about half the caries lesions in 12-year-olds have been restored (Fig. 22.3).

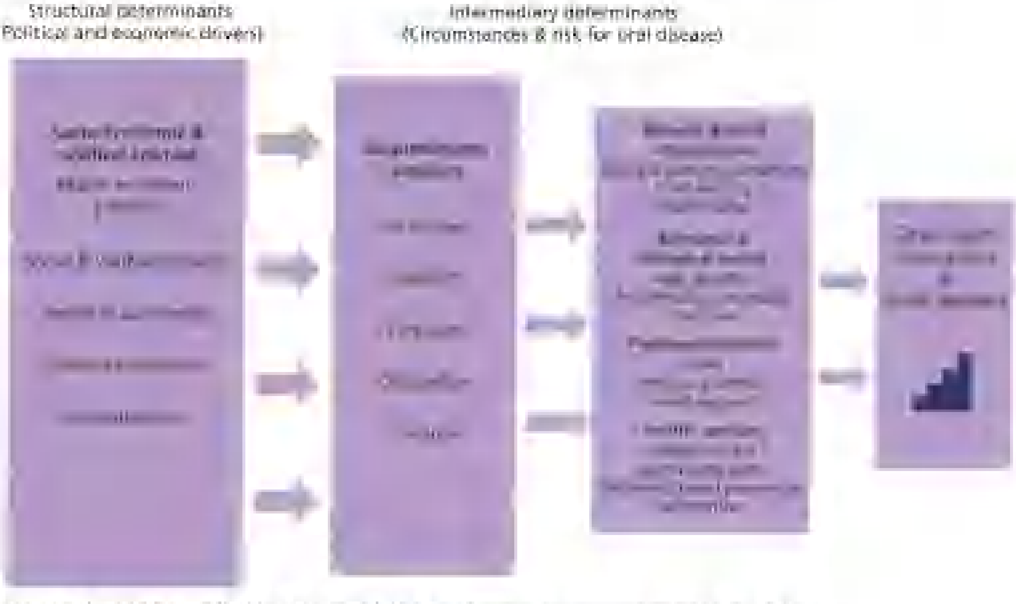


Figure 22.2 New conceptual model for oral health inequalities [80]. Reproduced with permission of John Wiley & Sons.

Table 22.2 Average caries experience expressed as DMFT in the permanent dentition of 12-year-olds in LICs, LMICs, UMICs, and HICs (data from 2000 onwards, WHO CAPP).

Country income classification	DMFT	Number
High income	1.61	43
Upper-middle income	2.19	29
Lower-middle income	1.77	18
Low income	0.86	9

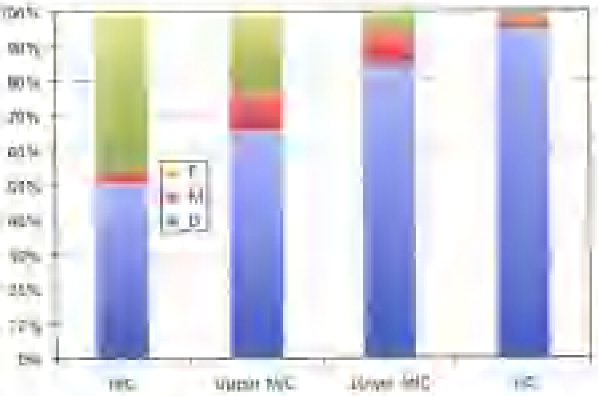


Figure 22.3 Proportion distribution of DMFT components in the permanent dentition of 12-year-olds in LICs, LMICs, UMICs, and HICs (data from 2000 onwards, WHO CAPP).

This also holds true for 35–44-year-olds in MICs such as in India, Pakistan, and Nigeria, where the care index (F/DMFT × 100) is less than 3% [20]. The global prevalence of untreated caries in the permanent dentition has been estimated at 35% [51]. Such a high prevalence leads to a high morbidity of pulpal involvement and odontogenic infection.

In order to complement DMFT data and to capture the epidemiology of pulpal involvement/odontogenic infection as a consequence of untreated caries, the PUFA index was developed (see later in this chapter).

Oral pain as a symptom of advanced caries has a high prevalence among all age groups and is following the social gradient of caries with higher prevalence associated with lower socio-economic status. However, there is only scattered and anecdotal information available regarding the prevalence of oral pain and the related impacts on quality of life, performance at work, or days missed in school [42, 54, 64].

Early childhood caries in low- and middle-income countries

Early childhood caries (ECC) is defined as the presence of one or more decayed, missing (due to caries), or filled tooth surfaces in the deciduous dentition of a child under the age of 6 years [2]. In LMICs, owing to the widespread absence of preventive measures and the lack of access to oral health care, ECC is highly prevalent and the caries experience is more than twice that of HICs [101]. In the Philippines, for instance, 6-year-old children suffer from very high levels of caries (prevalence 97%, mean dmft 8.4). Even more serious is the fact that 85% of the 6-year-olds have a mean of 3.4 teeth with pulpal involvement, a situation that has been labeled as a 'silent public health crisis' [58].

ECC is frequently considered to be an infectious disease transmitted from caretaker or siblings. This assumption has resulted in unrealistic recommendations to prevent caries, such as advice to reduce levels of infectious mutans streptococci in parents and siblings and to minimize transmission to the child. Although it has been shown that such measures potentially influence bacterial acquisition in the infant, they are inadequate and unrealistic recommendations (not only for LMICs) because a relationship with subsequent caries development has not been clarified [47]. The concept of caries as an infectious disease is outdated (see Chapter 7), and the WHO and others have recently reconfirmed their classification of caries as a chronic NCD [15].

Culturally determined nursing and rearing practices have a great impact on ECC and may differ from HIC contexts. For example, infants sharing a bed with their mother and having prolonged and frequent breastfeeding on demand at night are common practices in some areas, whereas the use of nursing bottles is less common in rural areas throughout South-East Asia and the Western Pacific [86].

The various cariogenic nursing and rearing practices that may exist in different cultures must be addressed through mother and childcare in the primary health-care (PHC) context. Reducing the risk factors (see Chapter 23), particularly reducing or removing sugar from nursing bottles and weaning food, combined with early supervised toothbrushing using fluoride toothpaste once the first teeth have erupted, are important measures to deal with the high prevalence of ECC in LMICs.

Health and oral health systems in low- and middle-income countries

A common characteristic of health systems in LMICs is that they function with varying limitations – financial and human resources, infrastructure, and facilities, as well as essential medications and supplies [53]. In the context of universal coverage and efforts to improve accessibility and use of health services, many LMICs have established – or are in the process of developing – social health insurance schemes, which usually provide coverage for essential services. Unfortunately, essential oral health-care services are often not included [76, 78].

Most LMICs have adopted the PHC approach in their national health-care systems [72]. More than 30 years after

Table 22.3 Essential activities in PHC [93].

Education concerning prevailing health problems and the methods of preventing and controlling them
Promotion of food supply and proper nutrition
Adequate supply of safe water and basic sanitation
Maternal and child health care, including family planning
Immunization against major infectious diseases
Prevention and control of locally endemic diseases
Appropriate treatment of common diseases and injuries
Provision of essential drugs

Reproduced with permission of the World Health Organization.

its introduction, the PHC approach is still at the center of efforts to provide universal coverage and health care for all.

PHC emphasizes prevention and control of common diseases at the lower levels of the health system rather than focusing on costly hospital-based care. In a PHC system, most essential health care is provided in health centers at the community level of the health-care pyramid (Table 22.3). This includes a range of health workers with different capacities and expertise. Ideally, PHC teams should provide an appropriate skill mix to address basic needs of the population.

Barriers to the integration of oral health care into primary health care

In most LMICs, oral health care is partially or not integrated in PHC. This may be because in the early days of PHC development and implementation there were no realistic concepts as to how oral health care could be included. Among the many contributing factors for this unfortunate situation is the traditional orientation of dentistry towards individual care with its focus on highly technical interventions rather than a community approach (Table 22.4).

This orientation has left a mark on the past and continues to the present. For the last 150 years the dental profession has emphasized its own independent identity in the medical field and guarded a clear separation from other medical specialties. Dentistry still focuses on the management of caries with a restorative approach – believing that caries can be controlled through technical perfection using the appropriate restorative materials [29] (see Chapters 13 and 25). The treatment philosophy of drilling, filling, and refilling builds on the paradigm that the caries process is irreversible and must be repaired once a caries lesion is detected (see Chapter 9). This ignores the fact that noncavitated caries lesions, or cavitated but cleansable lesions, can arrest or even regress through effective self-care and fluoride application (see Chapter 5).

There is ample evidence for the limited impact of conventional dentistry on the incidence, prevalence and distribution of oral disease in populations [65, 73]. The burden of oral diseases remains high and the conventional model of oral health care is seemingly ineffective but also too costly, because it is commonly delivered in private practice settings with a focus on treatment and technology [38]. This is even more relevant in LMICs, where resources for any kind of health care are limited. It has been estimated that the total costs of restoring caries cavities of the child population in Nepal with amalgam restorations would exceed the costs of the government's essential health-care package for children comprising immunizations, micronutrient supplementation, and essential public health interventions [101]. In view of the average LIC per capita government expenditure for health of just US$24 [97], it is obvious that a restorative approach to caries control is not realistic.

Table 22.4 Possible reasons why oral health care has not been included in PHC.

Oral diseases were not considered a public health problem
Health authorities had no idea how oral health care could contribute to PHC
Poor communication and disconnect between oral health and the broader medical arena
Lack of concepts and models on how to integrate oral health care services in PHC

Workforce planning for oral health care

Influenced by this restorative approach, health workforce planning in many LMICs has focused largely on increasing the number of dentists. Though there is no ideal dentist/population ratio, it is still widely used as the sole tool for oral health workforce planning (Box 22.1). However, health planners and managers are often lacking a broader public health perspective, resulting in a gross simplification of what is a complex planning exercise.

There are many regions in the world in desperate need of more oral health professionals, particularly in sub-Saharan Africa and South-East Asia (see Fig. 22.4), but the real challenge is not just the mere number of oral health professionals but the scope of care they provide, the appropriateness for the needs of the communities they serve, and the associated costs.

The approach of increasing the number of dentists in countries (e.g., in India, Nepal, Brazil, and Peru) by deregulating dental education and allowing a flourishing market of private dental education institutions has not contributed to improved access to oral health care [43]. At best, more dentists mean better access to oral health-care services for affluent urban population groups, but much less so for rural and deprived populations. At worst, the situation of dentist oversupply in urban areas combined with a lack of people

Syria: During one decade (1988–1998), government policies led to an increase of dentists from 1975 to 11 500 (dentist/population ratio of less than 1:1500). Even so, the 'care index' (F/DMFT × 100) only changed slightly and the caries levels remained unchanged [9].

Philippines: The dentist/population ratio is 1:3000, a ratio that approaches that of many HICs. However, the latest National Oral Health Survey revealed that virtually all caries in children remained untreated [58].

Box 22.1 Does the dentist-to-population ratio matter?

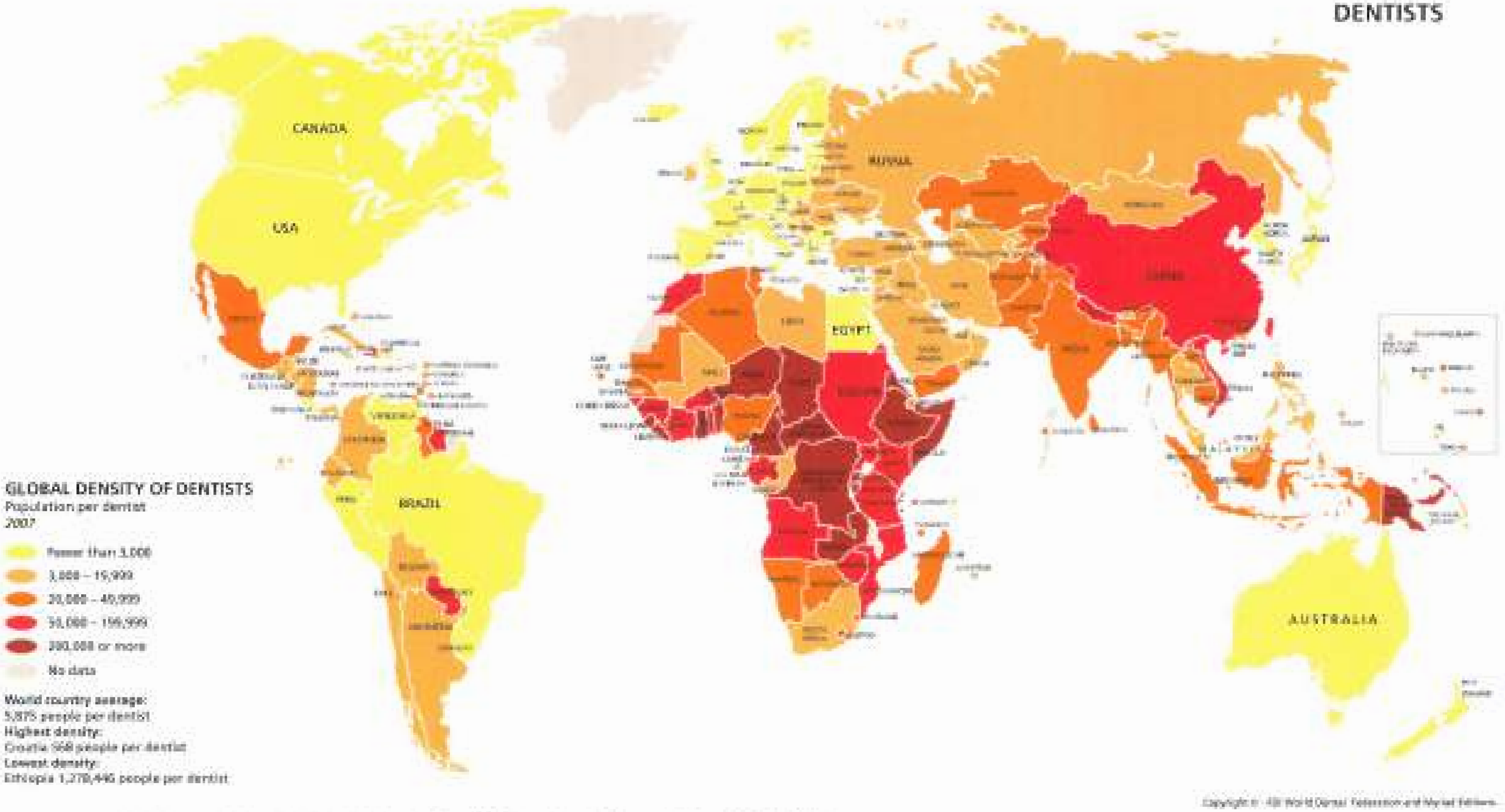


Figure 22.4 Global density of dentists in 2009. Adapted from [6]. Reproduced with permission of Myriad Editions.

who can afford such care results in overtreatment or dentists even forced to emigrate [65].

The focus on dentists as the only providers of oral health care contributes to the neglect of oral health in LMICs and ignores innovative concepts for a broader and interprofessional oral health workforce who would be more appropriate, realistic, and cost-effective.

In order to provide a more rational approach to oral health workforce planning, particularly in the context of universal coverage, the following questions should be asked and discussed at the national level prior to setting planning targets.

- What type of interventions will be delivered at which level of the health-care system?
- Who will pay for the services? Will social health insurance cover essential oral care? What resources are available to finance the services?
- To what extent are patient out-of-pocket payments acceptable for the poor segments of the population?
- How will nonessential oral health care be defined and managed?
- Who in the system will provide which health promotion activities?

The answers to these questions will help to define the skills and competencies required for different types of health-care workers at the different levels of the health-care system. Dentists who have received sophisticated technical training in dental care are used to a specific clinical environment. This is rarely available at the lower levels of PHC. Governments are thus compelled to invest in complex clinical facilities with all the implications concerning maintenance and supplies, even though other, more cost-effective solutions would have been possible. Moreover, such facilities are often used for private practice after public service duty hours or, if inadequately maintained, quickly become nonfunctional. The type of oral health-care providers required should be defined according to the government's strategy of care in order to improve oral health of the population. Experiences in Bangladesh, Indonesia, Nepal, Tanzania, Vietnam, and other countries have indicated that dentists are not needed in health-care centers at the lowest level of the health-care pyramid, but have an important role at the higher (referral) levels of the system, as well as in managing and training expanded oral health-care teams [83, 84].

Illegal oral care: symptom of a bigger problem

The problems of access to basic oral health care in LMICs force large parts of the population to rely on illegal oral health-care providers. Some of these are socially accepted and part of the cultural context. They range from traditional doctors, street 'dentists,' or quacks (Fig. 22.5) to providers who have at least some health training but overstep their scope of practice [12].

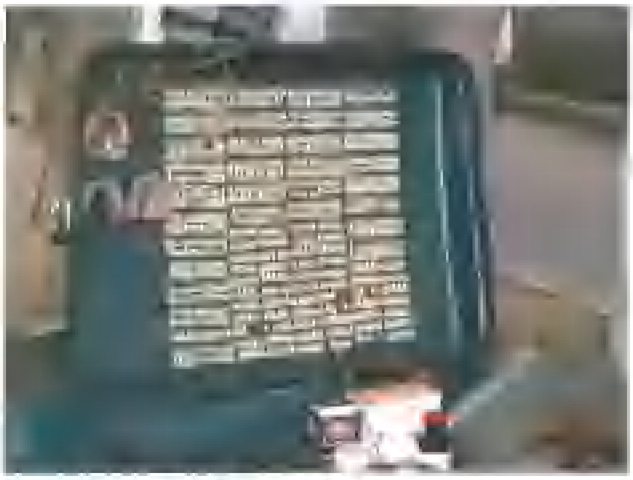


Figure 22.5 Street 'dentists' in India. Reproduced with permission of Matthew Logelin/Wikimedia Commons.

Although these providers fill a gap in service provision for poor populations, uncontrolled provision of oral health care is a serious public health problem, resulting in situations of low-quality care and risk for patients: for example, infection by cross-contamination through improperly sterilized instruments. It is a complex phenomenon going far beyond the legal context. It should be seen as a symptom of the failure of existing health delivery structures and societal deficits, such as low prioritization for formal oral health-care services, weak professional regulations, and inability to enforce existing laws. However, ethical challenges for the profession and society at large remain because these illegal providers may be the only ones available to provide relief from oral pain. In the context of global efforts for health systems strengthening and improving patient safety and the problem of illegal oral health care need further research [31].

Public health approaches to address caries in low- and middle-income countries

Caries is the result of complex multifactorial biological, physiological, behavioral, and social processes (see Chapters 2, 3, 5–9, and 13–15). Prevention and control of caries, therefore, has several entry points, both at the population and the individual levels. Interventions at the population and policy levels are highly cost-effective and should be priority choices in LMICs with limited resources. Focusing on one approach is less likely to succeed than a combined, multilevel approach [8].

Policy options to reduce risks to oral health and promote prevention

Governments have public policy options to influence exposure to risk factors and influence consumption as well as use of certain unhealthy products. This is based on the concept that achieving and maintaining good population health contributes to a nation's well-being, giving the government a clear mandate to provide an environment and living conditions conducive to health and to protect populations from certain risks [77]. The concept of social determinants of health and the common risk factor approach provide a sound basis for this expanded government action (see also Chapters 1 and 23).

There are many examples of successful legislation and regulations resulting in significant positive health impacts. Many countries observed sharp decreases in tobacco-related diseases after implementing advertising restrictions, smoking bans in public places, and increasing taxes using policy tools and templates developed by the WHO and other organizations [1].

The current international recognition of the growing burden of NCDs, of which 80% will occur in LMICs, provides opportunities for joint policy action between different sectors to address key modifiable common risk factors, such as reduction of sugar, salt, tobacco, and alcohol consumption. This integrates oral health into the NCD context [8]. The approach of the last decade to develop policies and strategies limited only to oral health has been superseded by a more holistic and integrated approach. Oral health strategies nowadays must be integrated and embedded within other contexts, such as broader NCD policies or planning for mother and child health [99].

Considering the detrimental effect of high sugar consumption, particularly of sugar-sweetened beverages, on incidence and prevalence of diabetes, obesity, and other NCDs on the one hand, and the clear dose–effect relation between sugar consumption and caries on the other hand, a joint policy approach to reducing overall sugar consumption in populations has the potential to be highly effective [18]. Innovative legislation to regulate advertising and marketing of unhealthy food and products, especially to children, are among the most promising and cost-effective approaches for governments [79]. Furthermore, available cost-effective preventive approaches, such as universal access to appropriate fluorides for the control of caries, need to be prioritized and strengthened through appropriate national planning.

However, sugar production is an important source of revenue for several LMICs [6] and a reduction in consumption might result in lower economic revenue. This could require adaptation of agricultural systems similar to the approach taken for tobacco-producing economies [89]. Table 22.5 shows selected policy options in the context of reducing dietary risk factors and promoting healthy nutrition.

The settings approach provides another entry point for the creation of healthier environments. Schools and workplaces are settings that allow for government control and restriction of unhealthy diets high in sugar, salt, and fat or for banning of tobacco on and around the premises [66, 92] (Box 22.2).

Table 22.5 Selected policy options for reducing dietary risk factors.

Regulating the labeling and advertising of unhealthy foods and sugar-sweetened beverages, especially to children
Regulating the amount of free and added sugars, fats, and salt in common food products, and ensure clear labeling
Promoting availability and affordability of healthy foods (especially fruit and vegetables) and non-sugar-sweetened beverages, especially in all public places such as schools and workplaces
Supporting measures that promote healthy eating and nutrition (e.g., healthy school and workplace meals, food provided at workplaces)
Raising taxes and duties for unhealthy foods and beverages and use the revenue to fund health promotion activities

The Philippine Department of Education, supported by the German Development Cooperation (GIZ), the Philippine nongovernmental organization Fit for School Inc., and other partners initiated the Essential Health Care Program (EHCP) in public elementary schools. The program is based on the Fit for School Approach and integrates evidence-based prevention measures for the most prevalent childhood diseases: soil-transmitted intestinal worm infections, hygiene-related diseases such as diarrhea and respiratory infections, and rampant caries. Toothbrushing as an essential caries-preventive measure is fully integrated into a package of affordable interventions implemented in the school setting and run by teachers: (1) daily group hand washing with soap, (2) daily group toothbrushing with fluoride toothpaste, and (3) biannual deworming according to WHO guidelines.

These interventions are complemented by the construction of group washing and sanitation facilities, and provision of clean water to schools without access to it. The EHCP is currently reaching more than 2.5 million children in the Philippines, Cambodia, Indonesia, and Lao PDR. The material costs average USD 50 per child per year, making the program highly affordable even in resource-poor settings.

Box 22.2 The Fit for School Approach

Evidence-based school health interventions in particular have a high potential for significant impact on preventable childhood diseases and have been emphasized as effective policy option especially for countries with weak health systems [57, 60].

Fluoride strategies as public health tools in low- and middle-income countries

The use of fluorides has been widely accepted as the most cost-effective and only realistic way of reducing the burden of caries (and is extensively described in Chapter 14). The WHO promotes 'automatic fluoridation' measures where fluoride exposure is less dependent on compliance (such as fluoridation of water, salt, or milk) since they are considered to be the most effective and equitable strategy for caries prevention and control [68]. The reality, however, is that even in HICs anything approaching universal coverage of such measures is rarely achieved. Rather than generally promoting automatic fluoridation measures, the complex conditions in a given setting should be taken into account for a more differentiated choice of fluoride interventions. This is particularly relevant in the context of LMICs, where only limited research has been conducted on the practicalities of fluoride interventions.

In order to assist public health decision-makers in selecting appropriate fluoride interventions, the Fluoride Intervention Template (FLINT) (see Table 22.6) has been developed. It is based on a system of prioritization where criteria and options for a comparison of interventions and setting characteristics are provided [100].

Water fluoridation

Water is often considered an ideal vehicle for fluoridation and has been stated to be one of the most successful public health interventions of the 20th century [21]. Yet, from a global perspective, only about 5% of the world's population are provided with artificially fluoridated water, mostly in HICs. No LICs and only a few MICs have artificial water fluoridation. Notable exceptions where a large proportion of the population is reached are Brazil and Malaysia, both countries that are amongst the wealthiest of MICs. Some of the challenges for implementation are presented in Table 22.7.

In addition to the practical and technical problems of water fluoridation, many countries are faced with arguments against 'compulsory mass medication' depriving the individual of the right to informed consent and choice. The cessation of water fluoridation in several European countries and elsewhere is often based on such ethical considerations.

Salt fluoridation

Adding fluoride to salt does not present the ethical drawbacks of water fluoridation, since the consumer has the option to purchase fluoridated or nonfluoridated salt. Challenges for salt fluoridation relate to practical and technical problems, the required quality control, and a generally weak evidence base (see Chapter 14). Only about 4% of the world's population have access to fluoridated salt, mainly in Latin American LMICs.

Milk fluoridation

The fluoridation of milk, particularly for school programs, has been proposed as an alternative vehicle. The evidence for the effectiveness of milk fluoridation remains equivocal (see Chapter 14). Other challenges include problems of distribution, the need for cold storage, and the widely prevalent lactose intolerance, particularly in Asian countries.

Professionally applied fluorides

This category includes fluoride gels, varnishes, foam, and rinses, which have been tested in a number of community or school-based prevention programs and need to be applied at regular intervals. However, the high cost of such professionally administered fluoride agents and the shortages of an appropriately skilled oral health workforce in LMICs are significant barriers for using these caries prevention methods in the private and public oral health-care services [48]. These approaches are thus largely unrealistic for population-wide caries prevention in LMICs.

Fluoride toothpaste

Fluoride toothpaste remains the most widespread and significant form of fluoride used globally (see Chapter 14). It is a safe population-based preventive measure with proven

Table 22.6 Criteria and guiding principles for the selection of a fluoride intervention according to the FLINT.

Criteria	Guiding principles
Equity	The fluoride intervention must promote equity, thus be accessible to the majority of the population regardless of geography, social class, gender, or age
Effectiveness	The fluoride intervention must have good evidence of effectiveness in preventing caries in all age groups (primary and permanent dentition)
Efficiency	The fluoride intervention must be cost-effective and affordable for the setting
Sustainability	The fluoride intervention must be financially, organizationally, and technically sustainable for at least 5 years
Safety	The fluoride intervention must cause no physical, social, psychological, or emotional harm
Compliance	The fluoride intervention's effectiveness does not require substantial cooperation or change in population behavior
Feasibility	The human capacity, technology, infrastructure, and financial resources are adequate to implement the fluoride intervention
Legislation	The required supportive laws and regulations for the introduction, quality assurance, impact monitoring, and sustainability of the fluoride intervention must be in place
Quality control	To ensure quality and safety of the fluoride intervention, standards and measures are required, including human resources trained to undertake monitoring and control
Surveillance	Epidemiological surveillance of a fluoride intervention using water, salt, or milk is necessary to ensure proper dosage for maximum protection with minimal side effects; furthermore, the oral health impacts of the intervention should be monitored
High fluoride areas	Naturally occurring drinking water levels of fluoride must be mapped prior to introducing a fluoride intervention involving water, salt, or milk (must not exceed 0.5 ppm)
Communication	Activities such as advocacy, facilitation, and education may be necessary for the initiation, implementation, and continued acceptance of fluoride interventions

Table 22.7 Possible challenges for implementing water fluoridation.

Requires access to public water supplies. Example: in Vietnam only 4% of the population have access to fluoridated water since 70% are not connected to a water supply [19]
In countries where public water supplies do not cover the majority of the population or are unreliable, water fluoridation can lead to increased inequalities with parts of the population benefitting and others, usually the more disadvantaged segments, who do not benefit. Example: Brazil [4]
Technical capacity for maintenance and quality assurance. Example: in Brazil just over half of samples contained the recommended fluoride levels, despite regular independent monitoring [74]
Supportive legislation required. Example: in South Africa legislation to fluoridate water in place since 2001, yet no artificially fluoridated water scheme exists in the country [48]

efficacy. Moreover, cleaning teeth and gums with a toothbrush or chewstick (miswak) is a widely accepted cultural norm, which makes the use of fluoridated toothpaste an easy choice for consumers (see Chapter 15). Exposure to fluoride toothpaste, however, depends on daily tooth cleaning, which involves a significant compliance element.

Considerations specific to the promotion of fluoride toothpaste in low- and middle-income countries

Affordability of fluoride toothpaste as an essential commodity

The WHO defines *affordable* toothpaste as 'one that is available at a price that allows people on low income to purchase it' [41]. What does this mean practically for the 1 billion people who still live on US$1 or less per day? Evidence shows that the number of workdays needed to pay for one annual dose of fluoride toothpaste per person at the lowest price available varies greatly for the 30% of the poorest population in different countries (Fig. 22.6) [34].

Ensuring a supply of affordable and effective fluoride toothpaste and promoting its use should be a key health policy option for LMICs. Affordability can be improved by reducing or removing taxes and duties for fluoride toothpastes, which can amount to 25% or more of the retail price [34]. Many LMICs promote essential preventive products, such as insecticide-treated mosquito nets, vaccines, contraceptives, or oral rehydration salts through exemption from taxes or through partial tax reduction. The WHO recommends this approach for fluoride toothpaste [68]. Options for policy and action for the promotion of affordable fluoride toothpaste are listed in Table 22.8. The affordability of toothpaste can also be improved by promoting the use of only a small amount (pea/rice/smear) at each brushing. Furthermore, public health recommendations should be as simple as possible; thus, only one type of toothpaste (1000–1500 ppm fluoride) is required for everyone. Supervising children is recommended to ensure their appropriate use (see Chapter 14).

The use of fluoride toothpaste in areas with high levels of natural fluoride in water

It is estimated that about 3% of the world population relies on drinking water containing levels of fluoride that are higher than the recommended 1.5 mg/L and most of them live in LMICs [3]. High systemic fluoride intake in these areas should be managed with appropriate measures such as alternative drinking water sources or de-fluoridation measures. The WHO, FDI World Dental Federation, and International Association for Dental Research clearly recommend that 'Fluoride toothpaste is safe to use irrespective of low, normal or high fluoride exposure from other sources' [98].

Ensuring the quality of fluoride toothpaste

Fluoride toothpaste should be considered an essential commodity for health and an important public health tool, and

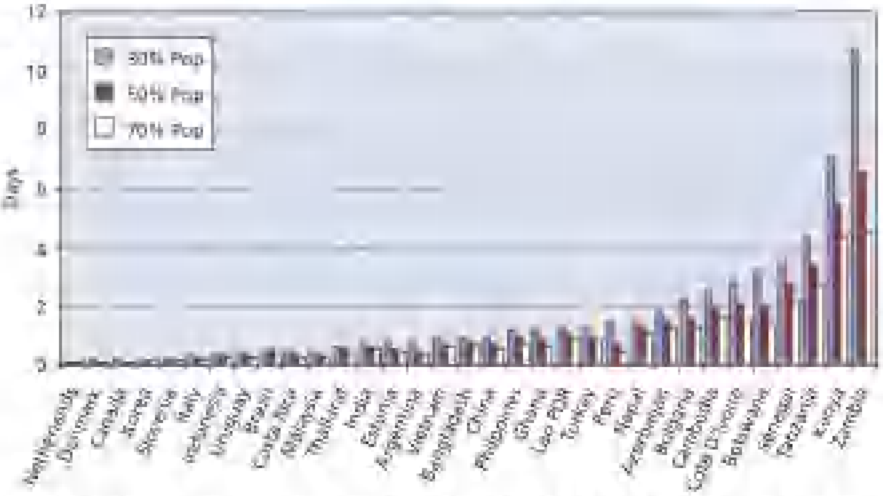


Figure 22.6 Number of days of household expenditure required to pay for one annual dosage of toothpaste at the lowest price by country and population group: the 30%, 50%, and 70% percentiles of the poorest sector of the population in a country are presented.

Table 22.8 Options for policy and action related to promotion of AFT

Make an inventory of available fluoride toothpastes in the country, the price by volume or weight, and the formulation
Test the toothpastes for levels of bioavailable and total fluoride through an independent laboratory using established standard analytical procedures
Encourage multinational toothpaste manufacturers to implement differential pricing for poorer countries and reduce the cost of toothpaste through inexpensive packaging and cheaper ingredients
Encourage generic and local production of affordable and effective fluoride toothpaste
Lobby for government policies and regional trade policies to reduce or eliminate taxation of effective fluoride toothpaste
Ensure compliance with ISO 11609 standards for labeling of fluoride dentifrices (e.g., fluoride type and concentration, production or expiry date, advice for adult supervision of toothbrushing by young children as well as instructions for using a small (rice/pea-sized) amount of paste by children and directions to avoid or limit rinsing after brushing)
Identify the toothpaste brands that have at least 80% of the fluoride in bioavailable form for the total length of the shelf life (3 years) and select the cheapest for utilization in the context of community-based toothbrushing programs

thus be subject to quality control. This requires not only technical capacity, but also political will and commitment to establish a supportive policy framework, including effective national drug and consumer product regulatory authorities.

The quality of fluoride toothpaste relates to the anticaries effectiveness and to consumer protection and information through correct labeling. For fluoride toothpaste to be effective, it must contain an appropriate concentration of bioavailable fluoride (see detail in Chapter 14). Sodium monofluorophosphate (MFP) toothpaste formulations using calcium-based abrasives are cheaper and, therefore, widely available in LMICs. The PO_3F_{2-} component is not stable [67] and, therefore, the levels of bioavailable fluoride in MFP/calcium-based toothpastes are lower than their total fluoride content [16, 25]. Other studies have reported on toothpastes losing bioavailable fluoride with aging and higher storage temperatures [5, 24, 35].

Unfortunately, the International Standards Organization (ISO) standard 11609:2010 for toothpaste only refers to the total fluoride content and does not address the important issue of fluoride bioavailability [39]. Practically, a toothpaste may thus be ISO compliant even if the bioavailable fluoride content is too low for an anticaries effect. Furthermore, the labeling practices for fluoride toothpastes in LMICs often do not conform with the ISO standard, so that expiry date, production date, and concentration or type of fluoride are not clearly indicated [16, 82]. The situation in LMICs is aggravated by a widespread influx of fake or counterfeit products containing low or no fluoride at all. The weak or nonexistent quality control systems are not able to ensure high-quality effective fluoride toothpaste for consumers in many countries.

Integrating basic oral health care into primary health care

The Basic Package of Oral Care

In the late 1990s the WHO commissioned the development of the Basic Package of Oral Care (BPOC). This conceptual policy document presented priorities in oral health care [30]. It was also an attempt to move away from a traditional, largely restorative approach delivered by dentists, and to focus instead on the philosophy of PHC. The concept was not intended as a universal recipe for integrating oral health care and PHC and thus did not present a strategy for implementation or other practical details. It was therefore suggested that small-scale demonstration projects should be established to determine the details of a BPOC and adapt the model to local resources before embarking on large-scale implementation [85].

The emphasis of the BPOC was on management of caries and its consequences, since caries at that time had been estimated to account for the majority of the global oral disease burden [62]. The starting point and first element of the BPOC was therefore oral health promotion and self-care through oral hygiene with affordable fluoride toothpaste (AFT).

The second element of the BPOC, oral urgent treatment (OUT), comprises on-demand care, including simple tooth extraction under local anesthesia, draining of abscesses, control of acute oral infection with appropriate drug therapy, first aid for maxillo-facial trauma, and recognition of oral conditions requiring patient referral for further care at the district or regional hospital dental clinic. However, untreated caries and its consequences are the most common reasons for people to seek oral health care in LMICs [26, 87].

The third component of the BPOC is atraumatic restorative treatment (ART), in order to provide a restorative treatment option that does not need a dedicated clinical environment or sophisticated equipment and that can be provided in resource-poor settings where running water and electricity might not be available (see Chapter 19).

Reviewing the Basic Package of Oral Care

More than a decade has passed since the publication of the BPOC manual. With the focus now on universal coverage and integration of services, a review of the strengths and weaknesses of the BPOC is warranted. Unfortunately, there have been few demonstration projects and even fewer well-documented evaluations. It is also obvious that individual elements of the package have been implemented rather than the complete package (see examples in Table 22.9).

While the evidence for ART restorations has grown and the dental community is increasingly accepting ART [37], there is little information as to its large-scale adoption in the PHC setting with the exception of Mexico [36]. Even though it might be possible to deliver ART in such settings,

Table 22.9 Examples of partial implementation of the BPOC

Nepal: advocacy for AFT resulted in a drastic increase of available fluoride toothpaste and a subsequent decrease in caries of 12–13-year-old Nepali schoolchildren [102, 103].
Cambodia: training of rural nurses to provide OUT and ART, including an evaluation showing the practical bottlenecks to effective implementation, such as lack of supplies, need for retraining and supervision, no proper integration in the health service system [25].
Burkina Faso, Madagascar, Lao, Peru, Tanzania: training of primary health care works in the provision of OUT – no formal evaluation of programs.

Table 22.10 Possible barriers to implementing the BPOC

A lack of political will of international health organizations, governments, and dental associations to promote the BPOC as a model of integrating basic oral care in PHC.
A failure to define how and where different components of the package can be implemented and integrated within existing health and educational structures.
A failure to emphasize the flexibility of the BPOC and the importance to adapt to local health/oral health priorities.
An overemphasis placed on certain components of the BPOC, namely the curative aspects of the package (ART and OUT) with little action on the preventive aspects of the BPOC (oral health promotion, AFT).
A reluctance of the dental profession to accept oral care provision by auxiliary personnel.
A failure to fully appreciate the cost/resources required for the different components of the package, including training and capacity building.
A lack of guidance on the development of supportive legal frameworks and policy contexts.

factors such as demand, patient expectations, cost, and availability of materials play an important role as to whether it is actually useful.

In many respects the BPOC has not had the impact that was expected from the outset. Possible reasons for this are presented in Table 22.10. In the context of developing a new and improved BPOC it is crucial to evaluate the impact of implementation examples in different settings.

The future for the Basic Package of Oral Care

In view of the limited impact of the BPOC over the past decade it could be questioned whether the continued promotion of the package in its current form for LMICs is still pertinent. The basic tenets of the BPOC are still valid, and the use of cost-effective packaged interventions for NCDs is considered to be an essential opportunity for strengthening health systems [40]. The advantages of packaging health interventions include cost-effectiveness, simplicity of implementation, and the ability to be integrated within other sectors of the health system.

In order to provide a relevant and updated model for integrating basic oral health care in PHC and social health insurance benefit packages, it will be necessary to place more emphasis on the realities of implementation. The original description of the BPOC limited itself to the philosophy of the approach and did not provide tools for practical implementation. However, such tools together with other aspects, such as policies and legal framework, training and capacity building, communication, monitoring, and performance management, as well as political commitment, are of great importance for success [32]. Given that countries' needs and resources differ, consideration should also be given to prioritize certain elements of the BPOC and to promote a stepwise implementation rather than the implementation of a complete package [11]. Links with other essential health service packages, such as the WHO *Package of Essential Non-Communicable Disease interventions* should also be explored [95] in order to foster integration. Finally, in order to overcome barriers of task delegation and workforce definition, an updated BPOC should focus on defining minimum competencies for certain services, rather than specify which type of health-care worker should be responsible for any given task.

Strengthening surveillance and research in low- and middle-income countries

Surveillance of oral diseases in LMICs is weak or nonexistent, and usually not integrated with routine NCD or other national disease surveillance [49, 69]. The lack of reliable and comparable oral health data affects prioritization of oral diseases and advocacy on all levels. Opportunities for integrating oral health data collection in ongoing international collaborative surveys, such as the Global School-based Student Health Survey, the Global Youth Tobacco Survey, the WHO STEP surveys, for NCDs exist but need to be promoted and applied more rigorously. Furthermore, the lack of applied research and rigorous evaluation of approaches, projects, and programs is a major challenge to developing effective and appropriate strategies for prevention and control of oral diseases.

Measuring caries matters for advocacy and planning

In order to position caries as a relevant problem for general and public health audiences, it is important to present its impact effectively. Two widely used measurements of disease burden used for prioritization in health policy and planning are disability-adjusted-life-years (DALY) and years-lived-with-disability (YLD). There are concerns that these measurements may result in an underestimation of the oral disease burden. The DMFT index, the most commonly used measurement for caries, is not easily compatible with the DALY/YLD framework. Caries is not a single entity; there are at least three main phases of the caries process: pre-cavity phase, cavity phase, and pulpal involvement, with each of them having different impacts in terms of pain, discomfort, functional limitations, and general health consequences. As outlined before (see Chapter 4) the decayed (D) component of the DMFT does not give detailed information about the stage of decay. The failure to differentiate the various stages of caries and their consequences for health and well-being may also contribute to underestimating the burden of caries in the DALY/YLD context. The problems of realistically comparing oral diseases with other health conditions do not help to prioritize oral health. This places oral health at a disadvantage in political decision processes [13].

The PUFA index to assess dimensions of untreated caries

For the last 70 years, caries data have been collected worldwide using the DMFT/dmft index (see Chapter 4). In order to assess and quantify the clinical consequences of untreated dental caries, visible pulpal involvement, ulceration caused by dislocated tooth fragments, fistula, and abscess have been included in a new caries index, the PUFA [56]. The PUFA index is designed to complement other dental caries indices that have no facility to record the clinical consequences of untreated dental caries (Fig. 22.7 and Table 22.11).

The PUFA/pufa score per person represents the number of teeth that meet the PUFA/pufa diagnostic criteria. The prevalence of PUFA/pufa is calculated as percentage of the population with a PUFA/pufa score of ≥ 1. The PUFA/pufa experience for a population is computed as the mean figure of the PUFA/pufa scores per person. PUFA and pufa are reported separately, and it is recommended that means for each of the components of the PUFA/pufa are reported.

Caries severity with advanced stages is generally higher in LMICs, which makes the use of the PUFA index even more relevant. Presenting caries data using the PUFA index provides health planners with relevant information complementary to the DMFT index. It gives additional information about the levels of untreated caries lesions, their severity, and possible associated health and quality of life consequences. Decisions about treatment need are inevitably linked to the resources and capacities of the health system setting. In most LMICs, the choices for interventions are limited and extraction of teeth with an open pulp is often the only realistic or available treatment. PUFA can help to prioritize treatment by allowing the selection of patients with high PUFA scores when resources are scarce, but it specifically does not give indications as to what type of intervention should be applied.

Since the introduction of the PUFA index, it has been successfully used in over a dozen surveys, including national oral health surveys, at times with high PUFA/pufa prevalence. Moreover, a high PUFA index could be associated with a higher risk of low body mass index and reduced quality of life [14, 46, 80]. Extraction of PUFA teeth resulted in rapid weight gain in severely underweight children in the Philippines [59].

Urgent need for health services research

The current evidence base related to approaches to prevent and control caries in LMICs is very limited. It should go beyond the evaluation of an intervention's efficacy through basic and applied research. It should also include an evaluation of intervention effectiveness under real-life conditions, preferably in the country where the intervention is to be applied (Fig. 22.8) [55, 73].

This requires the development and strengthening of local research capacities. An essential starting point is the inclusion of monitoring and evaluation activities in every program implementation [85]. Finally, and perhaps most importantly, research needs to be translated into information for policy, so that evidence-informed policies and practices can be implemented [27, 45].

Integration, advocacy, and a supportive policy context

There is growing recognition that isolated oral health programs using a vertical design are no longer justifiable in terms of resources required versus outcomes achieved. Building on the common risk factor approach and the concept of horizontal integration of oral disease prevention and control in the larger health service context, particularly the NCD strategies, will be the new dominating approach for the coming decades [10, 88]. This requires a fundamental change in dental education and professional practice complemented by a renewed focus on the needs of the billions of people not reached by current oral health-care approaches [33]. The supportive policy foundations for this advocacy and transformation process are already in place, including the WHO Oral Health Action Plan 2007, adopted by all ministers of health represented in the WHO [94]; the inclusion of oral health in the Political Declaration of the UN High-level Summit on Prevention and Control of NCDs [81]; and the inclusion of oral diseases in the Global Action Plan for Prevention and Control of NCDs 2013–2020 as action recommendations for member states [96].

However, the current status of oral health in LMICs and beyond should be primarily considered as a political neglect and should thus be addressed with coordinated political advocacy [13].

Conclusions and recommendations

The enormous burden of dental caries globally and the impacts on general health, well-being, and productivity are a major challenge for all health systems, but is even more daunting for LMICs. The analysis of the current technology-focused and dentist-centered approach revealed the neglect of the broader determinants and risk factors of oral health. There is a lack of integration in PHC, as well as a simplistic reduction of preventive interventions to effect behavior change through health education. Increasing only

Figure 22.7 (a, b) Pulpal involvement (P/p); opening of pulp chamber is visible or coronal tooth structures are destroyed by caries. (c, d) Ulceration (U/u); traumatic ulceration in the soft tissues (tongue and mucosa) caused by tooth or root fragments. (e, f) Fistula (F/f); a sinus tract releasing pus originating from an abscess and opening into the oral cavity. (g, h) Abscess (A/a), dento-alveolar abscess.

Table 22.11 Scoring criteria of the PUFA/pufa index.ᵃ

Letters	Description
P/p	Pulpal involvement is recorded when the opening of the pulp chamber is visible or the coronal tooth structures have been destroyed by the carious process and only roots or root fragments are left. No probing is performed to diagnose pulpal involvement
U/u	Ulceration due to trauma from sharp pieces of tooth is recorded when sharp edges of a dislocated tooth with pulpal involvement or root fragments have caused traumatic ulceration of the surrounding soft tissues (e.g., tongue or buccal mucosa)
F/f	Fistula is scored when a pus-releasing sinus tract related to a tooth with pulpal involvement is present
A/a	Abscess is scored when a pus-containing swelling related to a tooth with pulpal involvement is present

ᵃUpper case letters: permanent dentition; lower case letters: deciduous dentition.

the number of dentists in LMICs are likely to fail to improve oral health and will increase inequality. There is, therefore, a drastic need for reorientation, because more of the same will continue to fail in addressing the causes.

The available evidence for alternative approaches to prevention and control of caries in LMICs is not perfect, but is sufficient for translation into action. In summary, this requires:

- developing and adopting strategies to address the social determinants and common risk factors of caries, notably sugar consumption, through policies promoting healthy environments and healthy nutrition;
- implementing cost-effective population-wide prevention strategies through access to appropriate fluorides, focusing on measures to increase access to and use of fluoride toothpaste as an essential health commodity in LMICs;
- addressing the right to risk-free and affordable relief of oral pain even at the lower levels of PHC systems though the creation of workforce models and task-shifting that meet the needs of the entire population, but particularly those of the lower socio-economic and disadvantaged groups;
- developing concepts, practical implementation models, evaluation tools, and related national capacities for cost-effective 'best-buy' interventions to address caries and other priority oral diseases in LMICs;
- prioritization of schools as health-promoting settings where skills-based high-impact interventions can be implemented in a cost-effective way;
- an internationally coordinated oral health research and surveillance agenda with an emphasis on developing, evaluating, and promoting practical, effective, and affordable means to prevent and control the burden of caries in LMICs; and
- increased advocacy on all levels to emphasize the burden and consequences of oral diseases, particularly untreated dental caries, in order to prioritize interventions for prevention and control of oral diseases in LMICs.

This agenda of change should be based on a consensus of stakeholders and organizations active in prevention and control of oral diseases, supported by strong leadership and a sound evidence base. In this way, advocacy, communication, scientific support, capacity building, and technical assistance will go hand in hand in a concerted approach [13]. After all, the current state of neglect is largely the result of political neglect; therefore all efforts to improve prevention and control of caries and oral diseases in LMIC must start with changing political priorities.

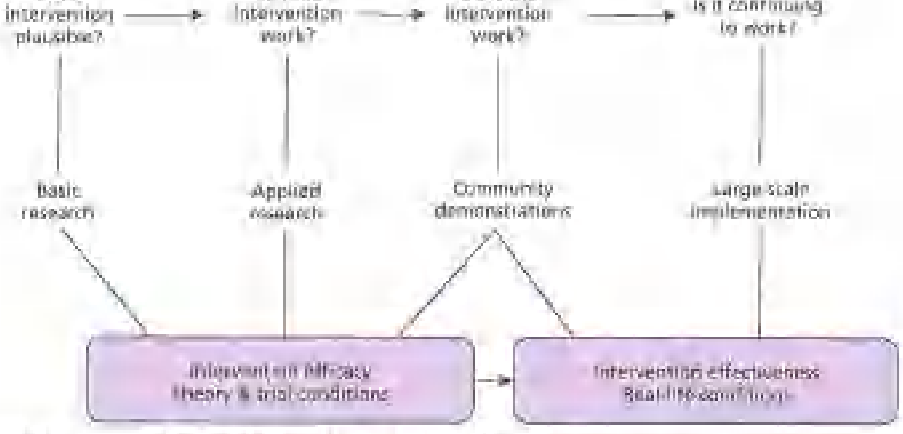


Figure 22.8 Relation between efficacy and effectiveness in different settings [55]. Modified from [73].

References

1. Adeyi O, Smith O, Robles S. *Public policy and the challenge of chronic noncommunicable diseases.* Washington: World Bank, 2007.
2. American Academy of Pediatric Dentistry; American Academy of Pediatrics. American Academy of Pediatric Dentistry Council on Clinical Affairs. Policy on early childhood caries (ECC): classifications, consequences, and preventive strategies. *Am Acad Ped Dent Ref Manual* 2011; 33 (6): 47–49.
3. Amini M, Mueller K, Abbaspour KC, Rosenberg T, Afyuni M, Møller KN, Sarr M, Johnson CA. Statistical modeling of global geogenic fluoride contamination in groundwaters. *Environ Sci Technol* 2008; 42: 3662–8.
4. Antunes JL, Narvai PC. Dental health policies in Brazil and their impact on health inequalities. *Rev Saude Publica* 2010; 44: 360–5.
5. Bardal PA, Olympio KP, de Silva Cardoso VE, de Magalhães Bastos JR, Buzalaf MA. Evaluation of total pH and soluble and total fluoride concentrations in dentifrices commercially available in Brazil. *Oral Health Prev Dent* 2008; 6: 241–8.
6. Beaglehole R, Benzian H, Crail J, Mackay J. *The Oral Health Atlas: mapping a neglected global health issue.* Geneva/Brighton: FDI World Dental Education Ltd/Myriad Editions, 2009.
7. Beaglehole R, Bonita R, Alleyne G, Horton R, Li L, Lincoln P et al. UN High-Level Meeting on Non-Communicable Diseases: addressing four questions. *Lancet* 2011; 378: 449–55.
8. Beaglehole R, Bonita R, Horton R, Adams C, Alleyne G, Asaria P et al. Priority actions for the non-communicable disease crisis. *Lancet* 2011; 377: 1438–47.
9. Beiruti N, van Palenstein Helderman W. Oral health in Syria. *Int Dent J* 2004; 54: 383–8.
10. Benzian H, Hobdell M. Seizing political opportunities for oral health. *J Am Dent Assoc* 2011; 142: 242–243.
11. Benzian H, Holmgren C. *Oral health for less than one dollar. The Essential Package of Oral Care (EPOC) – a proposal for integration of oral health in the health package of the Millennium Village Project.* Ferney-Voltaire: FDI World Dental Federation, 2008.
12. Benzian H, Jean J, van Palenstein Helderman W. Illegal oral care: more than a legal issue. *Int Dent J* 2010; 60: 399–406.
13. Benzian H, Hobdell M, Holmgren C, Yee R, Monse B, Barnard JT, van Palenstein Helderman W. Political priority of global oral health: an analysis of reasons for international neglect. *Int Dent J* 2011; 61: 124–30.
14. Benzian H, Monse B, Heinrich-Weltzien R, Hobdell M, Mulder J, van Palenstein Helderman W. Untreated severe dental decay: a neglected determinant of low body mass index in 12-year-old Filipino children. *BMC Public Health* 2011; 11: 558.
15. Benzian H, Bergman M, Cohen L, Hobdell M, Mackay J. The UN high-level meeting on prevention and control of non-communicable diseases and its significance for oral health worldwide. *J Pub Health Dent* 2012; 72: 91–3.
16. Benzian H, Holmgren C, Buijs M, van Loveren C, van der Weijden F, van Palenstein Helderman W. Total and free available fluoride in toothpastes in Brunei, Cambodia, Laos, the Netherlands and Suriname. *Int Dent J* 2012; 62: 213–21.
17. Bernabe E, Hobdell MH. Is income inequality related to childhood dental caries in rich countries? *J Am Dent Assoc* 2010; 141: 143–9.
18. Blakely T, Wilson N, Kaye-Blake B. Taxes on sugar-sweetened beverages to curb future obesity and diabetes epidemics. *PLoS Med* 2014; 11: e1001582.
19. British Fluoridation Society. *The extent of water fluoridation. One in a million – the facts about water fluoridation.* Manchester: British Fluoridation Society, 2004.
20. Brunton PA, Vrijhoef T, Wilson NH. Restorative care and economic wealth: a global perspective. *Int Dent J* 2003; 53: 97–9.
21. Centers for Disease Control and Prevention (CDC). Ten great public health achievements, United States 1900–1999. *MMWR Morb Mortal Wkly Rep* 1999; 48: 241–3.
22. Centers for Medicare & Medicaid Services. *National health expenditure highlights 2012.* Baltimore, MD: Centers for Medicare & Medicaid Services, 2012. http://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/NationalHealthExpendData/downloads/highlights.pdf (accessed November 2, 2014).
23. Chher T, Hak S, Courtel F, Durward C. Improving the provision of the Basic Package of Oral Care (BPOC) in Cambodia. *Int Dent J* 2009; 59: 47–52.
24. Conde NC, Rebelo MA, Cury JA. Evaluation of the fluoride stability of dentifrices sold in Manaus, AM, Brazil. *Pesqui Odontol Bras* 2003; 17: 247–53.
25. Cury JA, Oliveira MJ, Martins CC, Tenuta LM, Paiva SM. Available fluoride in toothpastes used by Brazilian children. *Braz Dent J* 2010; 21: 396–400.
26. Dye C, Mertens T, Hirnschall G, Mpanju-Shumbusho W, Newman RD, Raviglione MC, Savioli L, Nakatani H. WHO and the future of disease control programmes. *Lancet* 2013; 381: 413–18.
27. Ebrahim S, Pearce N, Smeeth L, Casas JP, Jaffar S, Piot P. Tackling non-communicable diseases in low- and middle-income countries: is the evidence from high-income countries all we need? *PLoS Med* 2013; 10: e1001377.
28. Ekanayake L, Weerasekare C, Ekanayake N. Needs and demands for dental care in patients attending the University Dental Hospital in Sri Lanka. *Int Dent J* 2001; 51: 67–72.
29. Fejerskov O, Escobar G, Jøssing M, Baelum V. A functional natural dentition for all – and for life? The oral healthcare system needs revision. *J Oral Rehabil* 2013; 40: 707–22.
30. Frencken JE, Holmgren C, van Palenstein Helderman W. Basic Package of Oral Care (BPOC). Nijmegen: WHO Collaborating Centre for Oral Health Care Planning and Future Scenarios, University of Nijmegen, 2002.
31. Frenk J, Chen L, Bhutta ZA, Cohen J, Crisp N, Evans T et al. Health professionals for a new century: transforming education to strengthen health systems in an interdependent world. *Lancet* 2010; 376: 1923–58.
32. Frieden TR. Six components necessary for effective public health program implementation. *Am J Public Health* 2014; 104: 17–22.
33. Glick M, Monteiro da Silva O, Seeberger GK, Xu T, Pucca G, Williams DM, Kess S, Eiselé JL, Séverin T. FDI Vision 2020: shaping the future of oral health. *Int Dent J* 2012; 62: 278–91.
34. Goldman A, Yee R, Holmgren C, Benzian H. Global affordability of fluoride toothpaste. *Global Health* 2008; 4: 7.
35. Hattab FN. The state of fluorides in toothpastes. *J Dent* 1989; 17: 47–54.
36. Hermosillo VH, Quintero LE, Guerrero ND, Suárez DD, Hernández MP, Holmgren CJ. The implementation and preliminary evaluation of an ART strategy in Mexico: a country example. *J Appl Oral Sci* 2009; 17 (Suppl): 114–22.
37. Holmgren CJ, Roux D, Doméjean S. Minimal intervention dentistry: part 5. Atraumatic restorative treatment (ART) – a minimum intervention and minimally invasive approach for the management of dental caries. *Br Dent J* 2013; 214: 11–18.
38. Holst D, Sheiham A, Petersen PE. Regulating entrepreneurial behaviour in oral health care services. In: Saltman RB, Busse R, Mossialos E, eds. *Regulating entrepreneurial behaviour in European health care systems.* Philadelphia: Open University Press, 2002.
39. International Organization for Standardization. *Dentistry – Dentifrices – Requirements, test methods and marking ISO 11609:2010.* Geneva: ISO, 2010.
40. Jamison DT, Summers LH, Alleyne G, Arrow KJ, Berkley S, Binagwaho A et al. Global health 2035: a world converging within a generation. *Lancet* 2013; 382: 1898–955.
41. Jones S, Burt BA, Petersen PE, Lennon MA. The effective use of fluorides in public health. *Bull World Health Organ* 2005; 83: 670–6.
42. Kakoei S, Parirokh M, Nakhaee N, Jamshidshirazi F, Rad M, Kakooei S. Prevalence of toothache and associated factors: a population-based study in southeast Iran. *Iran Endod J* 2013; 8: 123–8.
43. Kandelman D, Arpin S, Baez RJ, Baehni PC, Petersen PE. Oral health care systems in developing and developed countries. *Periodontol 2000* 2012; 60: 98–109.
44. Kroon J, Van Wyk PJ. A retrospective view on the viability of water fluoridation in South Africa to prevent dental caries. *Community Dent Oral Epidemiol* 2012; 40: 441–50.
45. Lavis JN, Posada FB, Haines A, Osei E. Use of research to inform public policymaking. *Lancet* 2004; 364: 1615–21.
46. Leal SC, Bronkhorst EM, Fan M, Frencken JE. Untreated cavitated dentine lesions: impact on children's quality of life. *Caries Res* 2012; 46: 102–6.

47. Leong PM, Gussy MG, Barrow SY, de Silva-Sanigorski A, Waters E. A systematic review of risk factors during first year of life for early childhood caries. *Int J Paediatr Dent* 2013; **23**: 235–50.
48. Lo EC, Tenuta LM, Fox CH. Use of professionally administered topical fluorides in Asia. *Adv Dent Res* 2012; **24**: 11–15.
49. Malvitz DM, Barker LK, Phipps KR. Development and status of the National Oral Health Surveillance System. *Prev Chronic Dis* 2009; **6**: A66.
50. Marcenes W, Freysleben GR, Peres MA. Contribution of changing diagnostic criteria toward reduction of caries between 1971 and 1997 in children attending the same school in Florianópolis, Brazil. *Community Dent Oral Epidemiol* 2001; **29**: 449–55.
51. Marcenes W, Kassebaum NJ, Bernabé E, Flaxman A, Naghavi M, Lopez A, Murray CJ. Global burden of oral conditions in 1990–2010: a systematic analysis. *J Dent Res* 2013; **92**: 592–7.
52. Marmot M, Bell R. Social determinants and dental health. *Adv Dent Res* 2011; **23**: 201–6.
53. Mills A. *Health systems in low- and middle-income countries*. Boston: Oxford University Press, 2011.
54. Miotto MH, Barcellos LA, Lopes ZV. Dental pain as a predictor of absenteeism among workers in a juice factory in southeastern Brazil. *Cien Saude Colet* 2013; **18**: 3183–90 (in Portuguese).
55. Monse B. The neglected state of oral health in the Philippines: effective action for change. PhD Thesis. Nijmegen: Radboud University, 2014.
56. Monse B, Heinrich-Weltzien R, Benzian H, Holmgren C, van Palenstein Helderman W. PUFA – an index of clinical consequences of untreated dental caries. *Community Dent Oral Epidemiol* 2010; **38**: 77–82.
57. Monse B, Naliponguit E, Belizario V, Benzian H, van Palenstein Helderman W. Essential health care package for children – the 'Fit for School' program in the Philippines. *Int Dent J* 2010; **60**: 85–93.
58. Monse B, Benzian H, Araojo J, Holmgren C, van Palenstein Helderman W, Naliponguit EC, Heinrich-Weltzien R. A silent public health crisis: untreated caries and dental infections among 6- and 12-year-old children in the Philippine National Oral Health Survey 2006. *Asia Pac J Public Health* 2012; doi: 10.1177/1010539512469250 [Epub ahead of print].
59. Monse B, Duijster D, Sheiham A, Grijalva-Eternod CS, van Palenstein Helderman W, Hobdell MH. The effects of extraction of pulpally involved primary teeth on weight, height and BMI in underweight Filipino children. A cluster randomized clinical trial. *BMC Public Health* 2012; **12**: 725.
60. Monse B, Benzian H, Naliponguit E, Belizario VJ, Schratz A, van Palenstein Helderman W. The Fit for School health outcome study – a longitudinal survey to assess health impacts of an integrated school health programme in the Philippines. *BMC Public Health* 2013; **13**: 256.
61. Moynihan PJ, Kelly SA. Effect on caries of restricting sugars intake: systematic review to inform WHO guidelines. *J Dent Res* 2014; **93**: 8–18.
62. Murray CJL, Lopez A. *The global burden of disease. A comprehensive assessment of mortality and disability from diseases, injuries and risk factors in 1990 and projected to 2020*. Cambridge, MA: Harvard University Press, 1996.
63. Nadanovsky P, Sheiham A. Relative contribution of dental services to the changes in caries levels of 12-year-old children in 18 industrialized countries in the 1970s and early 1980s. *Community Dent Oral Epidemiol* 1995; **23**: 331–9.
64. Naidoo S, Chikte UM, Sheiham A. Prevalence and impact of dental pain in 8–10-year-olds in the western Cape. *SADJ* 2001; **56**: 521–3.
65. Nair M, Webster P. Health professionals' migration in emerging market economies: patterns, causes and possible solutions. *J Public Health (Oxf)* 2013; **35**: 157–63.
66. Oxman AD, Lavis JN, Lewin S, Fretheim A. SUPPORT tools for evidence-informed health policymaking (STP) 10: taking equity into consideration when assessing the findings of a systematic review. *Health Res Policy Syst* 2009; **7** (Suppl 1): S10.
67. Pessan JP, Toumba KJ, Buzalaf MA. Topical use of fluorides for caries control. *Monogr Oral Sci* 2011; **22**: 115–32.
68. Petersen PE, Lennon MA. Effective use of fluorides for the prevention of dental caries in the 21st century: the WHO approach. *Community Dent Oral Epidemiol* 2004; **32**: 319–21.
69. Petersen PE, Bourgeois D, Bratthall D, Ogawa H. Oral health information systems – towards measuring progress in oral health promotion and disease prevention. *Bull World Health Organ* 2005; **83**: 686–93.
70. Popkin BM, Nielsen SJ. The sweetening of the world's diet. *Obes Res* 2003; **11**: 1325–32.
71. Popkin BM, Adair LS, Ng SW. Global nutrition transition and the pandemic of obesity in developing countries. *Nutr Rev* 2012; **70**: 3–21.
72. Rohde J, Cousens S, Chopra M, Tangcharoensathien V, Black R, Bhutta ZA, Lawn JE. 30 years after Alma-Ata: has primary health care worked in countries? *Lancet* 2008; **372**: 950–61.
73. Rose G. *The strategy of preventive medicine*. London: Oxford University Press, 1992.
74. Saliba NA, Moimaz SA, Garbin CA, Diniz DG. Dentistry in Brazil: its history and current trends. *J Dent Educ* 2009; **73**: 225–31.
75. Sheiham A. Impact of dental treatment on the incidence of dental caries in children and adults. *Community Dent Oral Epidemiol* 1997; **25**: 104–12.
76. Singh A, Purohit BM, Masih N, Kahndelwal PK. Risk factors for oral diseases among workers with and without dental insurance in a national social security scheme in India. *Int Dent J* 2014; **64**: 89–95.
77. Smith R, Beaglehole R, Woodward D, Drager N, eds. *Global public goods for health: from theory to policy*. Oxford: Oxford University Press, 2003: 304.
78. Söderlund N. Possible objectives and resulting entitlements of essential health care packages. *Health Policy* 1998; **45**: 195–208.
79. Toebes B, Gostin LO. Tackling the global NCD crisis: innovations in law and governance. *J Law Med Ethics* 2013; **41**: 16–27.
80. Turton M, Thomson WM, Foster Page LA, Saub RB, Razak IA. Validation of an oral health-related quality of life measure for Cambodian children. *Asia Pac J Public Health* 2013; doi: 10.1177/1010539513497786 [Epub ahead of print].
81. United Nations General Assembly. Political declaration of the high-level meeting of the General Assembly on the prevention and control of non-communicable diseases. Resolution A/66/L.1, 2011.
82. Van Loveren C, Moorer WR, Buijs MJ, van Palenstein Helderman WH. Total and free fluoride in toothpastes from some non-established market economy countries. *Caries Res* 2005; **39**: 224–30.
83. Van Palenstein Helderman W, Mikx F, Begum A, Adyatmaka A, Bajracharya M, Kikwilu E, Rugarabamu P. Integrating oral health into primary health care – experiences in Bangladesh, Indonesia, Nepal and Tanzania. *Int Dent J* 1999; **49**: 240–8.
84. Van Palenstein Helderman W, Mikx F, Truin GJ, Hoang TH, Pham HL. Workforce requirements for a primary oral health care system. *Int Dent J* 2000; **50**: 371–7.
85. Van Palenstein Helderman W, Lo E, Holmgren C. Guidance for the planning, implementation and evaluation of oral health care demonstration projects for under-served populations. *Int Dent J* 2003; **53**: 449–53.
86. Van Palenstein Helderman WH, Soe W, van't Hof MA. Risk factors of early childhood caries in a Southeast Asian population. *J Dent Res* 2006; **85**: 85–8.
87. Varenne B, Msellati P, Zoungrana C, Fournet F, Salem G. Reasons for attending dental-care services in Ouagadougou, Burkina Faso. *Bull World Health Organ* 2005; **83**: 650–5.
88. Watt RG. Strategies and approaches in oral disease prevention and health promotion. *Bull World Health Organ* 2005; **83**: 711–18.
89. Watt RG, Rouxel PL. Dental caries, sugars and food policy. *Arch Dis Child* 2012; **97**: 769–72.
90. Watt RG, Sheiham A. Integrating the common risk factor approach into a social determinants framework. *Community Dent Oral Epidemiol* 2012; **40**: 289–96.
91. World Bank. *How we classify countries*. http://data.worldbank.org/about/country-classifications (accessed November 11, 2014).
92. World Education Forum. Focusing resources on effective school health (FRESH): a FRESH start to improving the quality and equity of education. World Education Forum Dakar, Senegal, 2000.
93. WHO. *Alma-Ata: primary health care*. Geneva: World Health Organization, 1978.
94. WHO. Oral health: action plan for promotion and integrated disease prevention. *World Health Assembly Resolution WHA60.R17*. Geneva: World Health Organization, 2007.

95. WHO. *Package of essential noncommunicable (PEN) disease interventions for primary health care in low-resource settings*. Geneva: World Health Organization, 2010.
96. WHO. *Global action plan for the prevention and control of noncommunicable diseases 2013–2020*. Geneva: World Health Organization, 2013.
97. WHO. *World health statistics 2013*. Geneva: World Health Organization, 2013.
98. WHO, FDI World Dental Federation, International Association for Dental Research, Chinese Stomatological Association. Beijing declaration: achieving dental health through fluoride in China and South East Asia. Conference on dental health through fluoride in China and South East Asia. Beijing, September 18–19, 2007.
99. WHO SEARO. Strategy for oral health in South-East Asia 2013–2020 (SEA/NCD/90). New Delhi: World Health Organization Regional Office for South East Asia, 2013.
100. Yee R. Healthy choices, healthy smiles: appropriate and affordable fluorides in Nepal. PhD thesis. Nijmegen: Radboud University, 2008.
101. Yee R, Sheiham A. The burden of restorative dental treatment for children in Third World countries. *Int Dent J* 2002; **52**: 1–9.
102. Yee R, McDonald N, Walker D. An advocacy project to fluoridate toothpastes in Nepal. *Int Dent J* 2003; **53**: 220–30.
103. Yee R, McDonald N, van Palenstein Helderman WH. Gains in oral health and improved quality of life of 12–13-year old Nepali schoolchildren. *Int Dent J* 2006; **56**: 196–202.

23

How accurately can we assess the risk for developing caries lesions?

H. Hausen and V. Baelum

Introduction

The distribution of caries lesions is uneven among contemporary populations. Especially among children and adolescents in high income countries, the majority often has no or little experience of cavitated caries and most of the cavities occur among a minority of the population. The shape of a typical current distribution of caries experience is shown in Fig. 23.1, which presents the percentages of the 12-year-old residents of two Finnish cities, Jyväskylä and Kuopio, according to their D_3MFS counts (decayed, missing, and filled tooth surfaces). The polarization of the caries problem appears even more clearly from the Lorenz curves of Fig. 23.2, where the cumulative percentage of the same children has been plotted against the cumulative percentage of their D_3MFS counts. It can be seen that the worst-off quarter of the children accounted for 70% and 80% of all D_3MF surfaces in Kuopio and Jyväskylä respectively. For the interpretation of Lorenz curves, see Chapter 4.

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

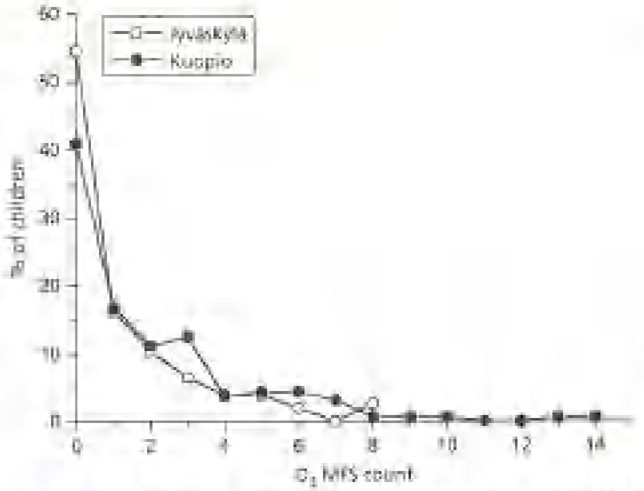


Figure 23.1 Percentage distribution of 12-year-olds according to D_3MFS counts in Kuopio ($n = 161$) and in Jyväskylä ($n = 154$) in 1998.

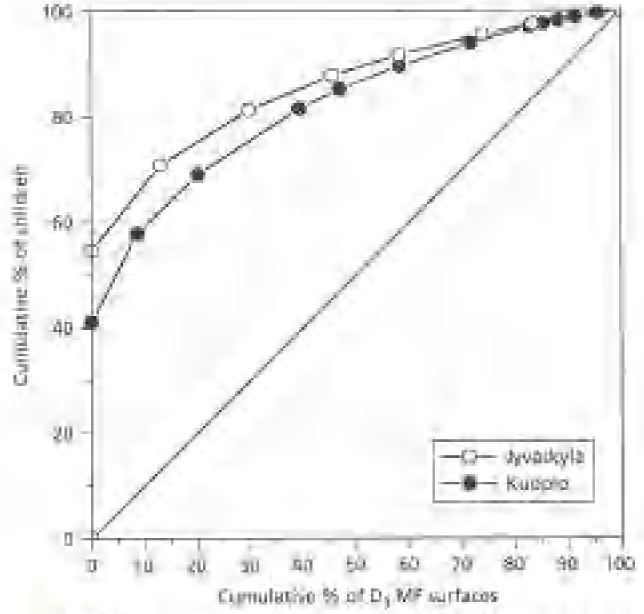


Figure 23.2 Cumulative percentage distribution of 12-year-olds in Kuopio and Jyväskylä in 1998 plotted against the cumulative distribution of their D_3MF counts (Lorenz curve). If all children had had the same number of D_3MF surfaces, the curves would have coincided with the diagonal.

Suppose the high-caries individuals who have ended up in the right-hand tail of the distributions in Fig. 23.1 (corresponding to the upper right-hand corner of the distributions in Fig. 23.2) had been detected *in advance*; that is, before their high risk had materialized and turned them into high-caries individuals. Suppose also that these individuals had been provided with a potent individually tailored caries control regimen. If such were the case, these high-caries individuals might instead have been found among the majority with little or no decay. This is illustrated graphically in Fig. 23.3. If the high-risk susceptible individuals can be accurately identified and offered effective individual caries control, a truncation of the risk distribution should occur. When this approach is applied at the population level, it is called the high-risk strategy for prevention [49]. At the dental practice level, many professional organizations and academic institutions recommend the adoption of a risk assessment strategy for the caries management, so that the clinicians may individualize their decisions regarding the use of diagnostic procedures, caries control regimens, and recall appointments [65].

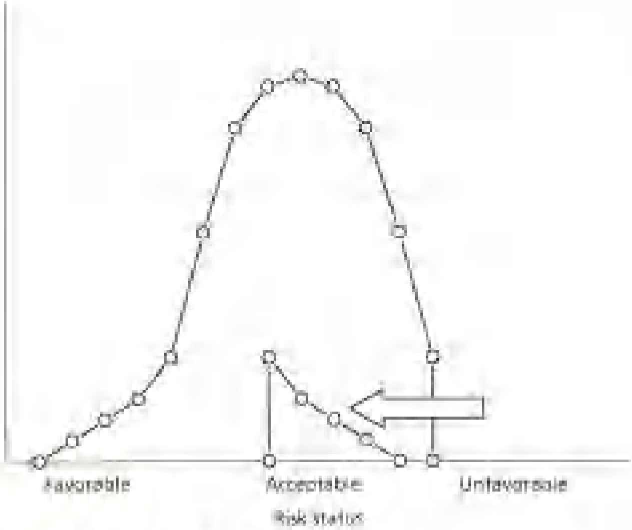


Figure 23.3 A graphical look at the high-risk strategy.

There are three basic prerequisites for a successful application of the high-risk strategy to control dental caries in the population. First, the occurrence of caries must be low enough to justify the effort and expense of identifying individuals who are believed to be at risk of developing an unacceptably high number of caries lesions. Second, accurate, acceptable, and feasible methods are needed for identifying the subjects with a high risk. Third, effective and feasible regimens must be available for controlling caries among the high-risk individuals. In this chapter an attempt is made to address the second prerequisite: can we identify with a sufficient accuracy those individuals who need individualized caries control to avoid developing an unacceptably high number of caries lesions?

The risk of developing caries lesions cannot be observed directly for an individual patient

For the purposes of this chapter, the risk of developing caries lesions is defined as the probability that an individual will develop one or more caries lesions reaching a given stage of disease progression during a specified period. We will use the term 'predictor' as a collective designates covering both true risk factors (i.e., factors for which a causal association with caries development has been established) and risk markers or risk indicators (i.e., factors that are statistically associated with caries development, but for which the relationship does not need to be a causal one).

Unfortunately, there is no way to observe directly the risk for an individual patient. This important point is perhaps best illustrated by an analogy: even though we know that smoking is a major cause of lung cancer, it is impossible for us to say if the smoker who is sitting in front of us will ever develop lung cancer. The closest we can get is to use epidemiological information on lung cancer development among different groups of smokers to estimate the probability that a certain type of smoker will develop lung cancer within a specified period. Similarly, we can use information on caries development among groups of people for whom the levels of the relevant risk factors are similar to those of the patient at issue to get an estimate of the risk that a person with such a set of risk factors will develop caries. This information can be acquired from longitudinal epidemiological studies, in which risk assessments are afterwards evaluated against the true course of events. Such studies always concern the past time, since the actual development of caries lesions can only be summarized at the end of a follow-up. A clinician's risk assessment, in turn, concerns the development of dental decay in the future. Since conditions such as the occurrence of caries lesions in the population may change over time, the risk estimates obtained should be taken only as suggestive probability statements that may be helpful for distinguishing between patients who should be provided with intensified caries control and those who are not likely to benefit from such effort.

The course of a typical study for evaluating the accuracy of a prediction

In studies that aim to identify risk factors that compromise the population's health, the effect is typically expressed by using measures of association such as differences in mean values, correlation coefficients, risk differences, risk ratios, or odds ratios. Significant associations have been found between the development of new caries lesions and a number of factors, such as past caries experience, microbial counts, and salivary parameters. However, even a fairly strong association does not necessarily imply that a factor can be used for predicting future onset of caries lesions. The same holds for other diseases as well. For instance, the observed strong association between tobacco smoking and lung cancer justifies efforts to prevent lung cancer by means of reducing the exposure to tobacco smoke. Yet, information on smoking status cannot be used to accurately predict the onset of lung cancer. Quite a few smokers escape lung cancer and die from other causes, and lung cancer can occur even in nonsmokers.

Instead, we use the same measures that are used for assessing the accuracy of diagnostic tests, such as sensitivity and specificity, to evaluate the predictive accuracy of a potential predictor. Figure 23.4 shows the outline of a cohort study for evaluating the accuracy of a prediction of the development of caries lesions. At the start of the study, all members of the study group have their baseline caries status and their level of the potential predictor(s) assessed. Caries recordings at the end of the follow-up period make it possible to assess the caries increment during the period for all members of the study group. We believed some of the participants to be at high risk, and the results of the study show that this belief was correct in some cases (those labeled *a*) and erroneous in other cases (those labeled *b*). Similarly, we believed some of the participants to be at low risk, which turned out to be false for some (those labeled *c*) and correct for others (those labeled *d*). Thus, group *a* in Fig. 23.4 consists of correctly classified individuals, true positives, for whom the risk was predicted to be high and whose actual caries increment was high. Correspondingly, group *d* represents correctly classified true negatives. For individuals falling into groups *b* and *c* a misclassification has occurred. For the false positives in group *b* a high risk was predicted, but the true caries increment was low. The false negatives in group *c* were predicted to have a low risk, but their actual caries increment was high.

For facilitating the estimation of the accuracy of the above classification (the four groups in Fig. 23.4), the number of subjects in each of the groups *a*, *b*, *c*, and *d* are organized in the form of a 2 × 2 table. Table 23.1 shows such a table and a list of different measures that may be considered for the estimation of the accuracy. Reports of prediction studies may include any of these measures. A brief definition of each of them is therefore now given.

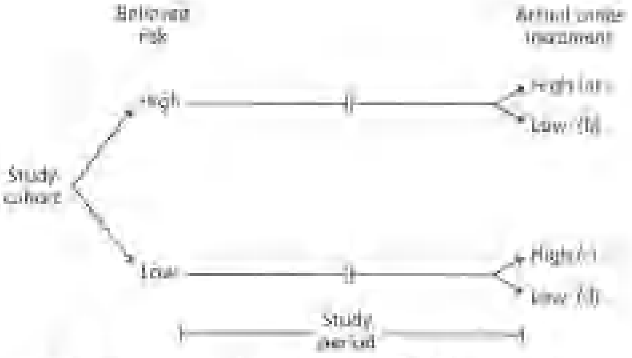


Figure 23.4 Outline of a typical follow-up study for evaluating the predictive power of a dichotomous predictor of caries risk.

Table 23.1. A 2 × 2 table for evaluating the accuracy of a dichotomous prediction and formulae for selected measures of accuracy

Believed risk	Actual caries increment		Total
	High	Low	
High	a	b	$a + b$
Low	c	d	$c + d$
	$a + c$	$b + d$	n

a: true positives (TP); b: false positives (FP); c: false negatives (FN); d: true negatives (TN).

Se = TPR = $a/(a + c)$, where Se is sensitivity and TPR is true-positive rate

Sp = TNR = $d/(b + d)$, where Sp is specificity and TNR is true-negative rate

FPR = $b/(b + d)$ = 1 − Sp, where FPR is the false-positive rate

FNR = $c/(a + c)$ = 1 − Se, where FNR is the false-negative rate

PV+ = $a/(a + b)$, where PV+ is the positive predictive value

PV− = $d/(c + d)$, where PV− is the negative predictive value

CHR = Proportion of Correctly Classified = $(a + d)/n$, where CHR is the crude hit rate

J = 1 − (FPR + FNR) = 1 − ((1 − Sp) + (1 − Se)) = Se + Sp − 1, where J is the Youden index

DOR = $(a \times d)/(c \times b)$, where DOR is the diagnostic odds ratio

LR+ = Se/(1 − Sp), where LR+ is the positive likelihood ratio

LR− = (1 − Se)/Sp, where LR− is the negative likelihood ratio.

Sensitivity, specificity, false-positive rate, and false-negative rate

Sensitivity is the proportion of those with a high caries increment that had also been predicted to be at high risk among all the ones with a high caries increment. Specificity is the proportion of those with a low caries increment that had also been predicted to be at low risk among all those with a low caries increment. Thereby, the *sensitivity* estimates the probability that a person who has experienced a high caries increment was also deemed at high risk. Similarly, the *specificity* estimates the probability that a person who has experienced a low caries increment was, in fact, also deemed at low risk. The sensitivity is often dubbed the true-positive rate (TPR), and specificity the true-negative rate (TNR), though both are proportions rather than true rates. In Table 23.1, these measures have been presented as proportions with values ranging from 0 to 1, but they are often expressed as percentages in the literature. It should be noted that the maximum sensitivity of 1 or 100% could easily be achieved by using an entirely useless predictor; for example, one that predicts everybody to be at high risk. This will, however, result in a specificity of zero. Conversely, the specificity may be 1 or 100% if the predictor indicates that everybody belongs to the low-risk group, but in such a case the sensitivity will be zero. Consequently, one should never look at the sensitivity or specificity alone; both are needed to determine the utility of a predictor. The false-positive and false-negative rates carry exactly the same information as sensitivity and specificity, but they express proportions of misclassified subjects. The false-positive rate (FPR) is the proportion of those with a low caries increment that had actually been deemed at high risk among all the ones with a low caries increment, and the false-negative rate (FNR) is the proportion of subjects predicted to be at low risk among those who actually had a high caries increment. When using the percentage expressions, the values of 1 in the formulae of Table 23.1 need to be replaced by 100.

Positive and negative predictive values

The positive predictive value is the proportion of those with a predicted high risk that also turned out to experience a high caries increment among all those for whom high risk was predicted, and the negative predictive value is the proportion of subjects whose actual caries increment was low among those predicted to be at low risk. The predictive values are not a property of the predictor alone. They are determined by the sensitivity and specificity of the predictor, but also by the occurrence of the disease in the population that is going to be screened for the predictor. Formulae based on Bayes' theorem [6] can be used for estimating predictive values for settings with different levels of expected caries increment.

Crude hit rate, the Youden index, and diagnostic odds ratio

The crude hit rate, Youden index, and diagnostic odds ratio (Table 23.1) summarize the accuracy of the prediction as a single numeric value. The crude hit rate, also called the proportion of correctly classified subjects, is easy to understand, and it has been used frequently in the dental literature. In low-caries populations, however, overoptimistically high values of the crude hit rate can be obtained even in instances where the test has not been able to detect a single true-positive individual. For those who prefer to explore the potential of a predictor by looking at a single numeric value only, the Youden index J is more advisable because it gives a realistic summary of its performance irrespective of the level of caries increment. If the prediction is invariably correct (i.e., the false-positive rate is zero) and at the same time the false-negative rate is zero, the index takes its maximum value $J = 1$. If a candidate for a predictor is totally worthless, which is the case when the true-positive rate and the false-positive rate are equal, the index takes the value $J = 0$. The diagnostic odds ratio DOR can take values between zero and infinity. High DOR values indicate good predictive accuracy. If DOR = 1, the predictor is worthless. Values <1 are equivalent to negative Youden index values. Even though the Youden index and diagnostic odds ratio are not likely to give a distorted picture of the usefulness of a predictor, they have the disadvantage of not carrying any information about the direction of the misclassifications. *For a patient, however, the consequences of being a false positive are very different from those of being a false negative*

Positive likelihood ratio and negative likelihood ratio

The remaining two measures, LR+ and LR−, can take any nonnegative value. LR+ indicates *how many times* more likely a person who is believed to have a high risk is to have a high caries increment than a low increment. LR− expresses the same ratio for a person who is believed to have a low risk. If the predictor is at all useful (TPR > FPR), the resulting value of LR+ is bigger and the value of LR− smaller than one. These likelihood ratios have the valuable property that by using them one can calculate the post-test probability of having a high increment with taking into consideration the pre-test probability (see later).

A real-life example of using a single, dichotomous predictor

In the following, we illustrate the concepts outlined above using data from a study by Alaluusua and Malmivirta [2]. In their study, the risk for developing caries lesions was considered high if visible plaque was detected on the labial surfaces of all four incisors in 19-month-old toddlers, and low otherwise (Table 23.2). The toddlers were examined for caries lesions at the age of 36 months.

As can be seen from Table 23.2, 83% of the toddlers who had caries at the end of the study had been identified correctly (sensitivity), and among those for whom the risk had been considered low the assessment was correct for 92% (specificity). The false positives and negatives were 8% and 17% respectively.

The observed positive predictive value reveals that 63% of the children for whom the risk had been considered high actually developed caries lesion(s) during the follow-up. Correspondingly, 97% of the children who had been deemed at low risk were free from cavitated caries lesions at the age of 36 months (negative predictive value). It should be noted that these predictive-value estimates have here been calculated only for demonstration purposes, since predictive values can only be generalized to other populations if the caries experience in those populations is equal to that observed among the study group.

The crude hit rate (91%) clearly gives an optimistic picture of the performance of the prediction, which is due to the fact that plaque and caries lesion(s) were detected in a minor proportion of the children (18% and 13% respectively). The Youden index value of 0.75 may give rise to less optimism as this index has a maximum value of 1. The value of the diagnostic odds ratio (60.83) indicates that the risk of caries lesions developing was about 60 times greater in a toddler with plaque on all labial surfaces of the four incisors at age 19 months than in a toddler where plaque is less common. The LR+ of 10.38 indicates that a child with visible plaque on all labial surfaces of the four incisors at age 19 months was 10.38 times more likely to have, than not to have, caries at the end of the follow-up. Similarly, the LR− of 0.18 indicates that a 19-month-old child who did not have plaque on all four incisors was 0.18 times more likely to have, than not to have, caries at the age of 36 months.

Table 23.2 A summary of the results of a study where visible plaque on the labial surfaces of maxillary incisors at the age of 19 months was used for predicting the onset of at least one caries lesion by the age of 36 months

Visible plaque at 19 months	Signs of caries at 36 months		Total
	Present	Absent	
Present	10[a]	6[b]	16
Absent	2[c]	73[d]	75
	12	79	91

Data from [2].
Se = 10/12 = 0.83 = 83%; Sp = 73/79 = 0.92 = 92%;
FPR = 6/79 = 0.08 = 8%; FNR = 2/12 = 0.17 = 17%;
PV+ = 10/16 = 0.63 = 63%; PV− = 73/75 = 0.97 = 97%;
CHR = 83/91 = 0.91 = 91%; J = 1 − (0.08 + 0.17) = 0.75;
DOR = (10 × 73)/(2 × 6) = 60.83; LR+ = 0.83/0.08 = 10.38;
LR− = 0.17/0.92 = 0.18.

[a] TP.

[b] FP.

[c] FN.

[d] TN.

Interpretation and use of the measures of prediction accuracy

The problem that prompted this review of measures for prediction accuracy was a simple, clinical question: Can we predict who will develop caries lesions (within a specified future time period) and who will not? The first thing to note is that, even in the absence of any information about our patients, we still have an idea of how many of our patients (i.e., what proportion of them) will develop caries. This idea may come from our personal clinical experience, or an estimate may have been reported in the literature. As an example, Holmén *et al.* [24] recently reported that 42.5% of the 16-year-olds in the county of Halland, Sweden, developed *new* caries lesions over the 3-year period from the age of 16 to the age of 19 years. Therefore, for a Swedish dentist working in Halland who has read the paper by Holmén *et al.*, the best guess on the risk of new caries lesions over a 3-year period in a 16-year-old patient would be 42.5%. In the context of prediction, this estimate, which is called the *pre-test probability*, represents our best guess on the risk of the development of caries lesions in the absence of any other information.

On a similar note, the data presented in Table 23.2 could be taken to indicate that the pre-test probability of caries development among 19-month-old toddlers is 13%, since 12 of 91 toddlers developed caries between the ages of 19 and 36 months. We note from Table 23.2 that sensitivity is

83% and specificity is 92% for the presence of plaque as a predictor of caries development among these toddlers. The question is to what extent knowledge about plaque presence can be used to improve our prediction of who will develop caries and who will not. What we hope to achieve is information that when plaque is present the probability of caries development is much greater than 13% (and preferably close to 100%), and that when plaque is absent the probability of caries development is much less than 13% (and preferably close to 0%). We can actually calculate these two post-test probabilities using the information given in Table 23.2.

First, we need to convert the pre-test probability to pre-test odds using the formula $odds = p/(1-p)$, where p stands for the probability. Thus, the pre-test odds are $0.13/(1-0.13) = 0.15$. Now, the post-test odds can be calculated as a product of the pre-test odds and the likelihood ratios (LR+ and LR−). For a child with plaque, the post-test odds are $0.15 \times 10.38 = 1.56$, and for a child without plaque they are $0.15 \times 0.18 = 0.03$. The two post-test odds can be converted to probabilities using the formula $p = odds/(odds + 1)$. Thus, the post-test probability that a 19-month-old child with plaque will develop caries lesions before the age of 36 months is $1.56/(1.56+1) = 0.61 = 61\%$, and for a child with no plaque the post-test probability is $0.03/(0.03+1) = 0.03 = 3\%$.

An alternative way is to use the sensitivity and specificity estimates to calculate the numbers in each of the four cells in the 2×2 table, assuming a pre-test probability of caries development of 13%. A pre-test probability of 13% means that 130 of 1000 toddlers will develop caries, while 870 will not. The 83% sensitivity means that 83% of the 130 toddlers with new caries (i.e., 108) will also have plaque present, while the remainder (i.e., 22) will not. The 92% specificity means that 92% of the 870 toddlers with no new caries (i.e., 800) will not have plaque present, while the remaining 70 will. We can now calculate the two desired post-test probabilities as follows.

The post-test probability (risk) that a 19-month-old toddler with plaque present will develop new caries is $108/(108+70) = 0.61$ (61%). Similarly, the post-test probability that a 19-month-old toddler with no plaque present will develop new caries is $22/(22+800) = 0.03$ (3%).

Since the post-test probability for a child with plaque is much higher (61%) and the post-test probability for child with no plaque is clearly lower (3%) than the pre-test probability estimate of 13%, it may be concluded that among these toddlers the presence of visible plaque on the maxillary incisors was a fairly strong predictor of the subsequent caries experience.

Other types of predictors and their combinations

In the preceding example, only a single dichotomous predictor was used. However, many candidate predictors of caries increments are not dichotomous by nature, but may be ordinal (lactobacilli and mutans streptococci counts), or discrete numeric, such as prior caries experience (e.g., the D_1MFS count). Moreover, contemporary caries risk assessment systems may consider up to 25 predictors at the same time [65].

The aforementioned design can be used for a single predictor at a time. In practice, we often want to evaluate several predictors simultaneously, and we therefore need to condense the information on many predictors into a single variable, which can then be used as the basis for the prediction of high versus low risk. The condensation techniques range from combinations of two variables – for instance, mutans streptococci count and lactobacilli count – to sophisticated regression-based multivariable methods.

So far, we have considered risk as a dichotomy, in the sense that we have distinguished between high risk and low risk. However, risk predictors are usually not natural dichotomies. For instance, salivary flow rate is a continuous variable, and microbiological dip-slide tests can take several values. To be able to generate the four groups of interest for the evaluation of the prediction (i.e., true and false positives and true and false negatives), such multilevel predictors need to be artificially dichotomized. A threshold value is selected above which the risk is considered high and below which the risk is believed to be low. The same is true for the outcome; that is, the true caries increment, which is a count of the number of new DMF teeth or surfaces. The dichotomization can be done using different threshold values. Each threshold level for believed high risk and for observed high true caries increment leads to a different distribution of the subjects studied among the four groups of interest (true and false positives, and true and false negatives). When interpreting the results of a prediction study it is important to take into consideration the threshold levels that have been used.

Our second example deals with several predictors. The subjects were initially 13-year-old children ($n = 384$) who participated in a clinical trial comparing an intensified and a basic caries control regimen among high-risk subjects [21]. A low-risk comparison group (LRR) was also included. At baseline, the salivary flow rate, mutans streptococci score, lactobacilli score, and buffer capacity score were determined. Caries lesions were graded as D_i (inactive lesion with no break in the continuity of enamel), D_a (active lesion with no break in the continuity of enamel), D_2 (enamel lesion with loss of tooth substance), and D_3 (lesion with loss of tooth substance extending into the dentin). The examiners also estimated how many new fillings each child would need after 1 year if the level of prevention were to remain as before the entry to the trial. The risk of developing caries lesions was considered high if at least one of the following conditions was met.

- estimated number of new fillings needed after 1 year ≥2;
- salivary flow rate ≤0.7 mL/min and buffer capacity score equal to 1;

- two or more dentinal caries lesions;
- one or more dentinal caries lesions on the approximal surfaces of incisors;
- one dentinal caries lesion and lactobacilli score ≥3 and mutans streptococci score ≥2;
- Lactobacilli score equal to 3 and mutans streptococci score equal to 3.

Figure 23.5 shows the distribution of the number of new D$_3$MFS during the 3-year follow-up among the predicted high- (HRB) and low-risk children (LRB) [23]. On average, the high-risk individuals developed substantially more new D$_3$MFS (mean increment: 5.1; standard deviation (SD): 5.0) than did their low-risk counterparts (mean increment: 2.0; SD: 2.4). The predicted high-risk group included individuals who had no new lesions, however, and among the believed low-risk group there were subjects who developed D$_3$MFS up to 12. So, at the individual level, the risk assessment was far from perfect.

Single predictors with multiple possible threshold levels

These data can be used to look at the performance of a few of those predictors of future caries experience that may take many values. We use the following predictors as educational examples: baseline DMFS count and salivary lactobacilli, mutans streptococci and buffer capacity score. The use of past caries experience as an indicator of future caries increment has been justly criticized by the argument that we should aim at detecting the high-risk susceptible individuals before there are any signs of past caries experience. The fact is, however, that *past caries experience still remains the most potent single predictor of future caries increment*, and one could also argue that if some past caries experience were already visible then it would be a mistake not to use this information in assessing the risk of new cavities. Let us therefore first consider the baseline DMFS count as a predictor. Figure 23.6 shows the percentage distribution of the children according to their baseline D$_3$MFS counts, which ranged between 0 and 25. The shape of the distribution shows that, apart from perhaps the distinction between zero and at least one D$_3$MFS, there is no natural threshold that could be used to discriminate between subjects with a high and a low caries experience. To obtain an overall idea of the predictive potential of the baseline D$_3$MFS, 10 different dichotomies were therefore formed so that the selected threshold levels were distributed throughout the range of baseline D$_3$MFS. The results appear in Table 23.3, where each row represents a 2 × 2 table like the one in Table 23.1. The first row of Table 23.3 shows the results when the risk for new lesions was considered high if the baseline D$_3$MFS score was ≥1 and low if the score was zero. Correspondingly, the last row represents a prediction where the risk was considered high if the baseline D$_3$MFS value exceeded 13, and low if the value was 0–13. Throughout Table 23.3 the true 3-year D$_3$MFS increment was considered high when it exceeded four new lesions (which occurred in 27% of the children) and low if it was zero to four surfaces (which occurred in 73% of the children). The last column (BHR) gives the percentage of subjects who were predicted to be at high risk ('test positives') at the different dichotomizations of the baseline D$_3$MFS counts. This is the percentage of subjects who should be treated as high-risk susceptible individuals if the given threshold level were to actually be applied for identifying patients in need of intensified individual caries control.

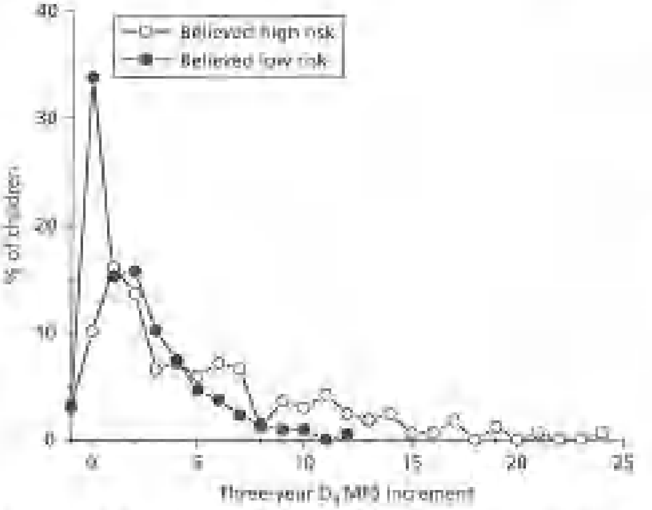


Figure 23.5 The percentage distribution by the number of new D$_3$MFS surfaces in a 3-year period among subjects for whom the risk of developing caries lesions was considered high and for whom it was considered low in a cohort of 384 initially 13-year-old children living in Vantaa, Finland. For the criteria of high and low risk, see text.

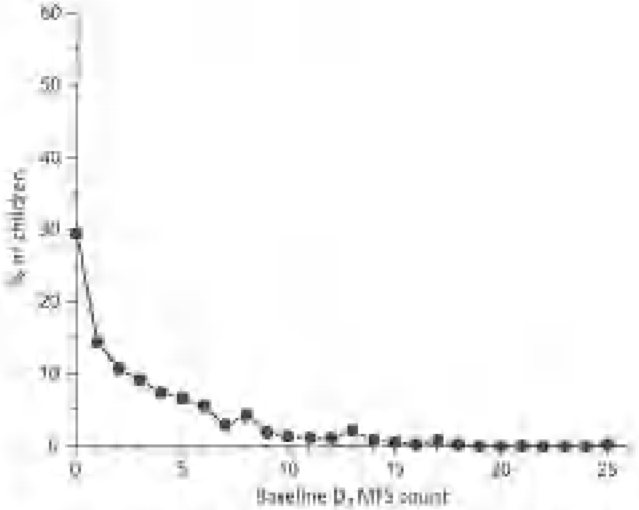


Figure 23.6 The percentage distribution of subjects according to D$_3$MFS counts at baseline in a cohort of 384 initially 13-year-old children living in Vantaa, Finland.

Table 23.3 Prediction of 3-year D_3MFS increment ≥5 ($n = 104$) by baseline D_3MFS score in a cohort of 384 initially 13-year-old children living in Vantaa, Finland.

Baseline D_3MFS count	TP	FP	FN	TN	Se (%)	Sp (%)	J	BHR (%)
≥1	96	175	8	105	92	38	0.3	71
≥2	86	130	18	150	83	54	0.4	56
≥3	77	98	27	182	74	65	0.4	46
≥4	66	74	38	206	63	74	0.4	36
≥5	57	55	47	225	55	80	0.4	29
≥6	46	41	58	239	44	85	0.3	23
≥7	39	27	65	253	38	90	0.3	17
≥8	33	22	71	258	32	92	0.3	14
≥9	25	14	79	266	24	95	0.2	10
≥14	10	1	94	279	10	100	0.1	3

TP true positives; FP false positives; FN, false negatives; TN, true negatives; Se, sensitivity; Sp, specificity; J is the Youden index; BHR is percentage children predicted to be at high risk

The key question is: Which level of baseline D_3MFS count provides the best prediction of a high caries increment in the future? The question is not easy to answer, since the distribution of the subjects, among the true positives, false positives, false negatives and true negatives, varies considerably across the different threshold levels. The same is therefore also true for the percentage of children predicted to be at high risk (Table 23.3, last column). From a practical point of view, however, there is little sense in identifying high-risk groups if they comprise more than 40% of the target population. If the proportion of high-risk individuals in a population exceeds this level then the occurrence of caries is not sufficiently low to justify the effort and expense of identifying the high-risk individuals. In such a situation the caries control efforts should rather be targeted to the whole population. This means that, in the current cohort, threshold counts of baseline D_3MFS smaller than ≥4 are useless, irrespective of the accuracy of the classification. Moreover, the use of a predictor makes no sense if the sensitivity value falls below 50%, which implies that the false-negative rate exceeds the true-positive rate. This leaves only two rows of Table 23.3 to look at (baseline D_3MFS ≥4 and ≥5), and it may be concluded that, by aiming to pick up a manageable percentage of high-risk individuals (29–36%), the use of baseline D_3MFS count as a predictor of at least five new D_3MFS over a 3-year period gives us a sensitivity in the range of 55–63% and specificity of 74–80%. This level of predictive accuracy is consistent with the literature on baseline DMFS/T counts as a predictor of caries increment [20, 43].

Using the pre-test/post-test probability calculations just outlined, we can assess the usefulness of these two threshold counts of baseline D_3MFS as predictors of high future caries development. Remember that the pre-test probability was 27% and that the sensitivity and specificity estimates at baseline D_3MFS ≥4 were 63% and 74% respectively (Table 23.3). We expect the post-test probability (i.e., the probability that a child with a high baseline D_3MFS will have a high future caries development) to substantially exceed the pre-test probability of 27%, and preferably it would be close to 100%. Similarly, we would hope to observe that a child with a low baseline D_3MFS would be very unlikely to have a high future caries development. In fact, we may calculate a post-test probability of 47% that a child with a baseline D_3MFS ≥4 will develop at least five new D_3MFS over a 3-year period, and a post-test probability of 16% that a child with a baseline D_3MFS ≤3 will develop at least five new D_3MFS. The post-test probabilities calculated for the baseline D_3MFS ≥5 translate into post-test probabilities of 51% and 17% respectively. These results indicate that the predictive potential of the two baseline D_3MFS levels (≥4 and ≥5) as indicators of high future caries increment is rather modest.

The receiver operating characteristic curve

For many people, diagrams are easier to interpret than tables with lots of numbers. Receiver operating characteristic (ROC) curves are an alternative way of summarizing the predictive potential of a predictor that can take many values. In ROC curves, the values of sensitivity (true-positive rate) at different levels of the predictor are plotted against the values of 1 – specificity (the false-positive rate) at the respective levels. The ROC curve for D_3MFS in Fig. 23.7 shows the results of Table 23.3 in such a form. The diagonal from the lower left-hand corner to the upper right-hand corner represents the curve for a useless predictor (true-positive rate and false-positive rate are equal at all levels). The bigger the area under the curve is, the more powerful is the predictor. For a predictor that results in a perfect classification at all levels, the area covers the whole box. For a detailed introduction to the meaning of the area under an ROC curve, see Hanley and McNeil [16]. In the case of baseline D_3MFS (Fig. 23.7), the curve is clearly above the diagonal, which indicates that D_3MFS does have some predictive potential, although it is modest, as our post-test probability calculations showed. Adding active enamel lesions (D_{1a} and D_2) to the baseline D_3MFS score improves the prediction, which shows from the ROC curve for baseline $D_{1a}MFS$ (Fig. 23.7). The fact that the area above even this curve is fairly large reveals that the predictive accuracy of past caries experience is far from perfect. By looking at ROC curves one can quickly and easily obtain an overall picture of the performance of predictors. There is one major disadvantage, however: information about the percentages of individuals for whom high risk is suggested (BHR in Table 23.3) is not available from the curves.

The performance of the five-level salivary lactobacilli score is summarized in Table 23.4, which is organized similarly to Table 23.3. From the point of view of a manageable

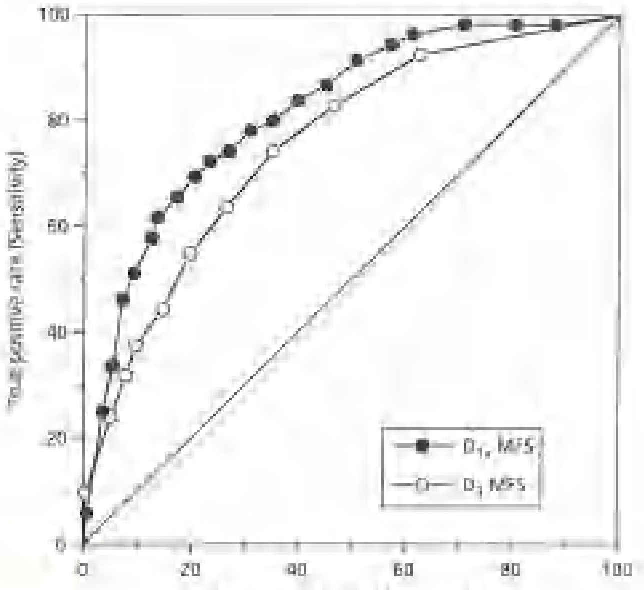


Figure 23.7 ROC curves illustrating the relationship of the true- and false-positive rates at different threshold levels of baseline D_{1a}MFS count. For D_3MFS, the figures are the same as in Table 23.3 where this count was used as a predictor of 3-year D_3MFS increment ≥5.

Table 23.4 Prediction of 3-year D_3MFS increment ≥5 ($n = 104$) by baseline lactobacilli score (LB) in a cohort of 384 initially 13-year-old children living in Vantaa, Finland.

Baseline LB score	TP	FP	FN	TN	Se (%)	Sp (%)	J	BHR (%)
≥1	96	235	8	45	92	16	0.1	86
≥2	75	153	29	127	72	45	0.2	59
≥3	63	107	41	173	61	62	0.2	44
4	27	47	77	233	26	83	0.1	19

For abbreviations, see Table 23.3.

percentage of individuals predicted to be at high risk, only the last row (score of 4) is worth looking at. At this level, the sensitivity is so low that it would make no sense to use the lactobacilli score for identifying high caries risk susceptible individuals among the target population. The potential of the remaining two predictors (i.e., salivary mutans streptococci and buffer capacity score) is even more modest. Therefore, the results regarding them are only given as ROC curves in Fig. 23.8, which also includes the curve for baseline D_{1a}MFS score for comparison. It can be concluded that none of the three salivary parameters were useful predictors of future caries experience, which is in line with the literature [12, 43, 69, 79].

Finally, an effort was made to find out whether combining the information of all the four predictors (Fig. 23.8) (i.e., baseline D_{1a}MFS score and salivary lactobacilli, mutans streptococci, and buffer capacity score) would lead to a more accurate prediction of the 3-year D_3MFS increment than was achieved by regarding each of the predictors separately. For this purpose, a logistic regression model was constructed with all four predictors as independent variables. As the outcome, the logistic regression analysis produces for each individual a risk score ranging between zero and one. By using these risk scores, the study cohort was divided into nine percentiles (Table 23.5). In risk percentile 10 (the first row of Table 23.5), the 90% of the study cohort with the highest risk scores were included in the predicted high-risk group, and the 10% with the lowest scores in the predicted low-risk group. In the last row, the situation is

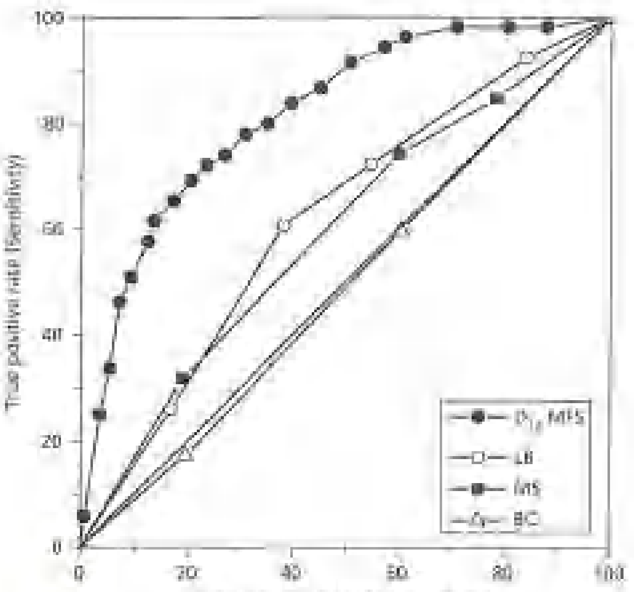


Figure 23.8 ROC curves for baseline D_{1a}MFS, salivary lactobacilli (LB), mutans streptococci (MS), and buffer capacity score (BC) in a cohort of 384 initially 13-year-old children living in Vantaa, Finland.

Table 23.5 Prediction of 3-year D_3MFS increment ≥5 ($n = 104$) by a logistic risk function in a cohort of 384 initially 13-year-old children living in Vantaa, Finland.

Risk percentile	TP	FP	FN	TN	Se (%)	Sp (%)	J	BHR (%)
10	102	244	2	36	98	13	0.1	90
20	100	210	4	70	96	25	0.2	81
30	97	172	7	108	93	39	0.3	70
40	95	136	9	144	91	51	0.4	60
50	87	106	17	174	84	62	0.5	50
60	80	74	24	206	77	74	0.5	40
70	67	50	37	230	64	82	0.5	30
80	52	25	52	255	50	91	0.4	20
90	28	11	76	269	27	96	0.2	10

Predictors included in the risk function: baseline D_{1a}MFS count, lactobacilli score (0–4), mutans streptococci score (0–3), and buffer capacity score (0–3). For abbreviations, see Table 23.3.

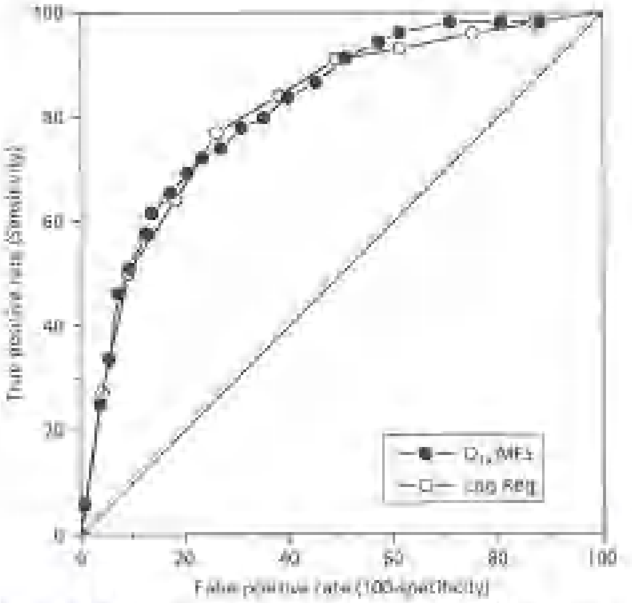


Figure 23.9 ROC curve for the logistic risk function (Table 23.5) including all four predictors (LogReg). The ROC curve for baseline D_{14}MFS (Figs 23.7 and 23.8) has been repeated for comparison.

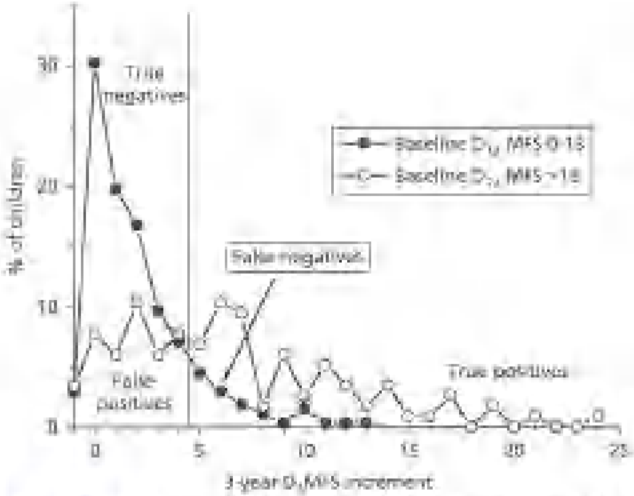


Figure 23.10 Percentage distribution of subjects according to 3 year D_3MFS increment among those with baseline D_{14}MFS counts of 0–13 and ≥14 respectively in a cohort of 384 initially 13-year-old children living in Vantaa, Finland.

reversed. According to the latter threshold, the 10% of subjects with the highest scores were believed to have a high risk and the 90% with the lowest scores a low risk. As in the case of baseline D_3MFS (Table 23.3), the threshold levels were selected throughout the range of the risk scores to obtain an overall picture of the performance of the risk function. The predictive power of the risk function including all the four predictors was very similar to that of baseline D_{14}MFS score alone (Fig. 23.9). It is apparent that practically all the predictive power of the logistic regression function comes from the baseline D_{14}MFS score. The remaining three predictors did not add to the accuracy of the prediction, even when regarded together. The importance of past caries experience among the predictors included in a risk model is in line with previous findings [43, 65, 79]. Still, as justly stated by Hänsel Petersson *et al.* [19], past caries experience is the consequence of the disease process, not its cause. If caries is properly controlled, past caries experience loses its predictive potential.

The coin has two sides

So far, the evaluations of caries prediction have been based entirely on measures that are derived from the distribution of the study subjects among the true and false positives, and true and false negatives. This is consistent with the clinical decision problem: Should this patient be treated as a high-risk individual or not? Keeping in mind the threshold for observed high caries increment used throughout the last example (≥5 lesions within 3 years), one could argue that it is not a big issue to miss a few individuals whose true caries increment is just a little higher than the threshold level. Let us therefore take a closer look at the extent of misclassifications, especially among the false negatives. In Fig. 23.10, the percentage distribution of the study subjects according to the observed number of new D_3MFS has been given separately for the subgroups whose baseline D_{14}MFS score was 0–13 or ≥14 (the most promising dichotomization for this risk predictor). The latter group represents the individuals who would have been treated as high-risk individuals, if this particular threshold had been used for assessing high versus low risk for new cavities. As can be seen from Fig. 23.10, the false negatives (i.e., those who would erroneously have been treated as having low risk) included individuals who developed up to 13 new D_3MFS within 3 years. This means that severe errors can take place if a certain maximum level of past caries experience is used as a criterion for picking up individuals with a low risk of developing new lesions. Figure 23.11 shows the distribution of the 3-year caries increments among individuals whose baseline D_3MFS score was zero (29% of the cohort). Their mean 3-year D_3MFS increment was 1.3 (SD: 2.1) with a maximum value of 12. When D_{14}MFS = 0 was used as a screening criterion, the mean D_3MFS increment was 0.6 (SD: 1.3) and the highest increment was five (Fig. 23.11). In the latter case, the error rate might have been tolerable. The small percentage of 'test positives' (only 9% of the cohort had no D_{14}MFS caries experience at baseline), however, calls into question the practical value of this screening criterion.

What level of accuracy would be sufficient in everyday practice?

A perfect predictor has a sensitivity of 100% and a specificity of 100%. Consequently, both the positive and negative predictive values will equal 100%. A perfect accuracy means that the predicted high-risk group would consist of true high-risk individuals only and that only true low-risk

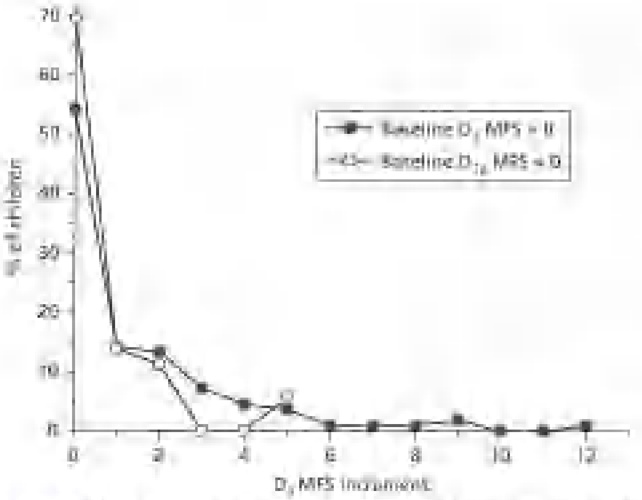


Figure 23.11 Percentage distribution of subjects with no baseline DMFS according to D_3MFS increment in a cohort of 394 initially 13-year-old children living in Vantaa, Finland.

individuals would be included in the predicted low-risk group. Unfortunately, no such predictor is available for the risk of developing caries lesions. Errors must be accepted. There are no generally accepted rules, however, as to what the acceptable error rate might be. The pre- and post-test probability calculations shown above provide the most informed basis for decisions as to whether or not to rely on a potential predictor, but such calculations may be uncertain owing to the need for a valid estimate of the pre-test probability.

It has been suggested that the sum of sensitivity and specificity should be at least 160% before a predictor can be considered a candidate for targeting individualized caries control [29]. This is in agreement with an alternative suggestion [77], according to which a sensitivity and specificity of 80% would be acceptable for practical use in the community. Neither of these suggestions takes into account the fact that *the consequences of errors related to poor sensitivity are different from those related to poor specificity*. In other realms of medicine, such as prenatal diagnostics, utility gains and losses related to true and false positives and negatives are being used for evaluating the performance of tests and for setting their threshold values (for an example, see [16]). While awaiting similar developments in cariology we may use the above suggestions [29, 77] as a tentative benchmark in evaluating the performance of proposed markers for a high risk of developing caries lesions. Using this benchmark would immediately dismiss any of the candidate predictors discussed in the preceding examples.

What level of accuracy can be achieved?

Signs of past caries experience

The past caries experience summarizes the cumulative effect of all risk factors, known and unknown, to which an individual has been exposed, and has usually been the most accurate single predictor of future caries increment [1, 4, 14, 25, 31, 37, 45, 50, 72, 77]. The study by Alaluusua *et al.* [4] is a typical example of a setting where the past caries experience has been used for prediction. In that study, the cut-off point for baseline D_3MFS was selected so that 29% of the subjects were included in the predicted high-risk group. The observed sensitivity was 61% and specificity 82%. These numbers are clearly below the above benchmark values.

Initial caries counts seem to correlate with subsequent caries increment more strongly than do FS or D_3S counts [31, 57]. Sensitivity increased from 49% to 51% and specificity from 76% to 78% when initial caries lesions (whose activity was not known) were added to FS and D_3S scores in a study that sought to predict the 5-year DMFS increments among 11–13-year-old children [57]. Inclusion of initial caries lesions resulted in a sensitivity of 62% and specificity of 82% in a study where caries experience in the fissures of the permanent molars at the age of 7 years was used as a predictor for the of D_3FS increment (0 versus >0) between the ages of 7 and 11 years [71]. When only cavities and fillings were used for prediction, the sensitivity was 31% and specificity 95%.

Despite major changes in the occurrence of caries during the past few decades, the correlation between caries in the primary and permanent dentition has remained fairly strong and stable [23]. When past caries experience in the primary dentition has been used as the predictor of the onset of caries lesions in the permanent dentition, the reported predictive accuracies have been in the same range as those in settings where past caries experience in the permanent dentition has been used as the predictor [34, 38, 59, 66, 70]. Slightly more accurate predictions have been obtained by using statistical models including information on the state of both primary teeth and first permanent molars [22, 62].

There is a well-documented cross-sectional association between the individual's coronal and root caries experience [13, 15, 36, 73]. Moreover, a positive correlation between baseline root surface caries score and the individual's later root-surface caries experience has been observed in a number of longitudinal studies (for a review see [48]). However, it seems unclear whether past caries experience alone is a potent predictor of root caries increment.

Finally, when considering the use of past caries experience in risk assessment, one must take into account the fact that an already established high DMF score will remain high independently of possible subsequent changes in caries risk. *A person with a high DMF score may have little risk for further lesions if their oral conditions no longer favor demineralization. The opposite situation is also possible.*

Microbiological tests

Use of microbiological tests is based on the principle that subjects carrying in saliva high numbers of bacteria that are capable of surviving and multiplying in acidic conditions should be identified and treated before signs of clinical caries lesions develop. The assessment of microorganisms in saliva is based on the findings that there is an association between types and numbers of bacteria in dental plaque and those in saliva [52]. Caution should be observed when interpreting the results of salivary microbiological tests, however, since the oral microflora is complex and the role of different bacteria in the caries process may not be fully understood [8].

Salivary lactobacilli

A high level of lactobacilli in saliva is considered to be an indicator of abundant consumption of easily fermentable carbohydrates, and thus also an indicator of an increased risk for developing cavities. The use of the lactobacilli score as a screening test, however, seems to be of limited value. Although repeated lactobacilli tests appeared to have a very good predictive ability in the early study by Snyder [60], in most later studies the lactobacilli counts have not proven as potent for the assessment of the risk for developing dental decay [1, 11, 41, 46, 50, 51, 73, 74, 77]. A typical example of their predictive ability has been reported in the study by Alaluusua *et al.* [4], in which sensitivity was 55% and specificity 68% when 38% of the children studied were regarded as having a high risk of developing decay on the basis of the level of lactobacilli in saliva. This is comparable to the predictive power of lactobacilli score in our previous example (Table 23.4, Fig. 23.8).

Salivary *mutans* streptococci

Numerous cross-sectional studies have shown an association between the past caries experience and the level of mutans streptococci in saliva or plaque in both children and adults (for reviews, see [7, 10, 67]). The caries predictive power of the level of salivary mutans streptococci, however, has consistently been modest [4, 46, 50, 51, 53, 54, 61, 64, 72, 74, 77, 80]. The ROC curve in Fig. 23.8 gives a fairly good idea of the predictive potential of the salivary mutans streptococci test. At present, the salivary mutans streptococci count cannot be considered useful for the assessment of the risk of developing dental decay. There is evidence [3, 13, 42, 56, 68, 79] that the level of salivary mutans streptococci is a slightly more accurate predictor of future caries increment among small children than it is in other age groups (for reviews, see [39, 67]). Still, its predictive power is not sufficient for everyday risk assessment.

Salivary yeasts

The value of salivary yeasts in caries prediction has rarely been studied. Pienihäkkinen *et al.* [41] evaluated the caries predictive value of salivary counts of lactobacilli and yeasts (*Candida* species) in 6–11-year-old children over a period of 3 years. The predictive ability was in the same range as that of lactobacilli, which means that the level of salivary yeasts is a fairly weak predictor of future caries increment. The same was true when the level of yeasts in saliva was used to identify older adults with a high risk of root caries [54].

Other salivary factors

In the context of risk assessment, the two most commonly considered salivary factors are the flow rate and buffer capacity. Severe reduction in the flow rate of saliva is known to predispose to caries lesions [44, 47]. Thus, a patient whose salivation is compromised is in need of individualized caries control. Apart from true hyposalivation, however, the predictive potential of salivary flow rate is modest. Although a negative correlation between buffering capacity of saliva and the occurrence of caries lesions has been found in some studies, the predictive power of buffer capacity is so low that it cannot be used for identifying high-risk individuals (Fig. 23.8). Other properties of saliva, such as pH, ammonia and protein concentrations, calcium and phosphorus concentrations, and enzyme activity, seem to be of even less value for caries prediction [40].

Dietary habits and oral hygiene

The value of self-reported dietary habits for predicting the onset of caries lesions is unclear. Both a positive correlation and a lack of correlation between the intake of sucrose-containing foods and the occurrence of caries lesions have been reported. The vague correlations in industrialized countries may be due to the almost universal exposure to fluoride from different sources and the minor variation in the generally high sucrose intake in the groups studied. In addition, obtaining accurate information about dietary habits is difficult. Self-reported sucrose intake seems to have little value as a means of identifying high- and low-risk individuals.

A relationship between the presence of plaque and dental caries is also clearly established. It has been shown that professional plaque removal can result in a significant reduction in the development of caries lesions [35]. However, the relationship between caries and the amount of plaque on teeth or the frequency of self-reported oral hygiene measures is vague [9]. Preschool children may be an exception, as shown in the study by Alaluusua and Malmivirta [2], in which the presence of plaque on the labial surfaces of upper incisors at the age of 19 months fulfilled the benchmark criteria for an acceptable predictor of caries lesions at the age of 36 months (Table 23.2), just as the post-test probability calculations led us to conclude. In another study among infants and toddlers [78], however, the predictive power of oral hygiene was more modest.

High sucrose consumption and bad oral hygiene are often found in the same individual, and the effect of one of these two factors may vary with the degree of exposure to the other. In a study of 9–13-year-olds, the occurrence of caries lesions increased significantly with increasing sugar consumption only when oral hygiene was simultaneously poor [30]. In another study, 5-year old children with clean teeth had a low caries experience, irrespective of their dietary habits [55]. Likewise, in adults and the elderly, only oral hygiene was associated with root caries experience, and was considered the only relevant predictor of risk of further lesion development [13].

Social factors

Dietary and health habits are affected by income, education, and social environment. It has been shown convincingly that in high-income countries, people of low socioeconomic status tend to have more caries lesions than do people with a high socioeconomic status [26]. In spite of the clear correlation between social status and caries, the reported sensitivities and specificities have been low when social factors have been used in the assessment of risk for developing caries lesions [20]. It is helpful, however, to consider the social background of the patient as a natural part of the dental history when assessing their caries risk.

Joint predictive power of multiple predictors

The fact that the predictive ability of any single factor has not been satisfactory has led to attempts to improve the accuracy of risk assessment by using screening criteria based on multiple factors. Combining the information of past caries experience and one microbial test makes a simple example of this approach. For instance, Alaluusua *et al.* [4] formed a risk group using a high DFS count and a high mutans streptococci score. This resulted in a predicted high-risk group including 32% of the target population. The sensitivity was 71% and the specificity 81%. The observed accuracy was higher than that for DFS or mutans streptococci score alone, but even these figures cannot be considered satisfactory for targeting preventive measures.

When considering more than three predictors simultaneously, multivariable prediction models are generally used. The methods applicable in the assessment of caries risk include different regression techniques, discriminant analysis [32], and classification tree prediction models [63].

Perhaps the most extensive attempt to produce statistical models for the assessment of caries risk was made in the context of the Caries Risk Assessment Study of the University of North Carolina [14]. With 25% of the target population in the predicted high-risk group, they aimed at a sensitivity of at least 75% and a specificity of 85%. The original data included 30 clinical, microbiological, sociodemographic, and behavioral factors. In the logistic regression model for the 5–6-year-olds, nearly 20 predictors were used. The sensitivity was 59%, the specificity 83–84% and the corresponding Youden Index value 0.42–0.43. The predictive power of the models stemmed mostly from information based on clinical examinations, while the microbiological predictors contributed little to the power of the models.

The caries predictive potential of multifactorial prediction models has been reviewed by Powell [45]. Among the 30 models for which sensitivity and specificity values were given, the average sum of sensitivity and specificity was 148%, which implies a simultaneous sensitivity and specificity of 74% if the false-negative rate and false-positive rate are equal. In general, the accuracy of multivariable approaches seems to be lower than one would expect on the basis of the performance of individual predictors. The main part of the predictive power seems to originate from information related to past caries experience, with the status of the most recently exposed tooth surface (in children) being especially informative. The most powerful model, whose sensitivity was 87% and specificity 83% [17], dealt with the prediction of 2.5-year caries increment among initially 1-year-old children. This confirms the findings that caries can be predicted more accurately in infancy than in older age groups. The fact that the importance of single predictors in the models varied considerably among the target populations reveals that even the most sophisticated multifactorial models do not remove the inescapable uncertainty in the assessment of the risk of developing caries lesions.

Clinical caries risk assessment: is it possible?

The clinical dentists have been provided with quite a few guidelines/tools for multivariable caries risk assessment. Four of the most frequently named ones were critically appraised by Tellez *et al.* [63] for their ability to predict the future onset of caries lesions. They included the tool proposed by the American Academy of Pediatric Dentistry, the Caries Management by Risk Assessment System (CAMBRA), the American Dental Association caries risk assessment forms, and Cariogram, a computerized program that was developed at the Lund University School of Dentistry, Sweden. In order to use any of these tools, one must record the level of a number of factors. This number is smallest for Cariogram (nine items) and largest for CAMBRA (25 items for adults and 20 for children). The four tools consider different categories of risk factors. All of them, however, cover at least some aspects of past caries experience, saliva, diet, fluoride exposure, and general health conditions. Published evidence for the caries predictive ability was only found for Cariogram and CAMBRA, and prospective cohort studies were available only for Cariogram. According to these studies, Cariogram was clinically useful for assessing the risk of developing caries lesions among the elderly and, to a lesser extent, among children. Still, the evidence on its usefulness for achieving better health outcomes and cost savings across different settings was considered limited. Overall, the evidence supporting the validity of the reviewed caries risk assessment tools/guidelines was regarded weak [65].

How valuable are the proposed measures?

If one attempts to identify a manageable proportion of the individuals with the highest risk of developing cavities, the most powerful measures of risk assessment today result in sensitivities in the range of 70–80% and specificities of 80–90%. Even at this level of performance the rate of misclassifications, false negatives and false positives, is intolerably high. It can be concluded that the accuracy of even the best predictors that are currently available is modest [65]. In fact, *none of the reported measures of assessing caries risk are sufficiently accurate to be relied upon when selecting patients for intensified caries control*. Consequently, any screening program that relies on currently available methods fails to identify a considerable proportion of persons with a true high risk, and/or suggests a high risk for an unacceptably high number of persons with actual low risk.

The difficulty of predicting the onset of caries lesions is no surprise. The multifactorial etiology of dental caries makes it likely that even the most sophisticated models using known risk factors and risk markers cannot predict future caries development very accurately. Moreover, even a perfect test is only capable of predicting a person's future caries experience if the conditions on which the prediction is based remain stable. In most industrialized countries, where virtually all the prediction studies have been conducted, the populations are exposed to a variety of professional caries control and treatment regimens as well as self-care, which, if applied selectively, most probably reduce the observed power of such studies. Living conditions and oral health behaviors may change over time, thus modifying a person's caries risk over time. For these reasons it is not likely that we will be able to accurately assess the risk for developing decay in the foreseeable future. If accurate predictions were possible they would necessarily imply that it is hard to affect an individual's established risk. This would be disappointing for all parties involved in the control of dental caries.

As no mechanical algorithms are applicable in deciding whether a person needs intensified caries control or not, the dental professional must make this decision for each individual patient. The clinical examination and the taking of a proper dental history are the most important sources of information underpinning this decision, along with the subjective judgment of the experienced clinician [5, 27, 63]. However, clinicians must come to terms with the fact that their predictions are far from perfect, and that the uncertainty related to their decisions is not markedly reduced by information on a multitude of factors [65], such as microbiological or salivary parameters.

Concluding remarks

The purpose of this chapter has been to discuss whether sufficiently accurate measures for identifying the high-risk susceptible individuals are available to justify the application of the high-risk strategy (Fig. 23.3) to control dental caries. The other requirements mentioned in the beginning of the chapter were a sufficiently low occurrence of dental caries to justify the effort and expense of identifying high-risk individuals, and the availability of effective measures to control caries among them. At present, it may well be that none of these requirements is fully met. Despite the declining trends, dental caries is still a common disease. The experiences from the dental clinics reveal that the service system may be unable to offer proper caries control to the most caries-prone individuals. There is even scientific evidence to the fact that it is difficult to reduce the risk among high-risk individuals to acceptable [31, 38, 58]. Therefore, caries control should primarily be based on the whole population strategy [49] or on the targeted or directed population strategy [75]. The classic paper by Rose [49] lists more reasons why a cautious approach to the high risk strategy should be adopted. Instead of being too concerned with predicting the future of their patients, clinical dentists should focus on giving due consideration to the control of caries lesions that their patients have at present. Appropriate treatment of active initial lesions, the prerequisite for which is proper self-care, also helps to prevent the onset of future cavities.

Background literature

Bader JD, ed. *Risk assessment in dentistry*. Chapel Hill, NC: University of North Carolina Dental Ecology, 1990.

Johnson NW, ed. *Risk markers for oral diseases. Vol. 1. Dental caries: markers of high and low risk groups and individuals*. Cambridge: Cambridge University Press, 1991.

Stamm JW, Stewart PW, Bohannan HM, Disney JA, Graves RC, Abernathy JR. Risk assessment for oral diseases. *Adv Dent Res* 1991; 5: 4–17.

References

1. Alaluusua S. Salivary counts of mutans streptococci and lactobacilli and past caries experience in caries prediction. *Caries Res* 1993; 27 (Suppl 1): 68–71.
2. Alaluusua S, Malmivirta R. Early plaque accumulation – a sign for caries risk in young children. *Community Dent Oral Epidemiol* 1994; 22: 273–6.
3. Alaluusua S, Renkonen O-V. *Streptococcus mutans* establishment and dental caries experience in children from 2 to 4 years old. *Scand J Dent Res* 1983; 91: 453–7.
4. Alaluusua S, Kleemola-Kujala E, Grönroos L, Evälahti M. Salivary caries-related tests as predictors of future caries increment in teenagers. A three-year longitudinal study. *Oral Microbiol Immunol* 1990; 5: 77–81.
5. Alanen P, Hurskainen K, Isokangas P, Pietilä I, Levänen J, Saarni UM, Tiekso J. Clinician's ability to identify caries risk subjects. *Community Dent Oral Epidemiol* 1994; 22: 86–9.
6. Altman DG, Bland JM. Diagnostic tests 2: Predictive values. *BMJ* 1994; 309: 102.

7. Beighton D. The value of salivary bacterial counts in the prediction of caries activity. In: Johnson NW, ed. *Risk markers for oral diseases, Vol. 1. Dental caries: markers of high and low risk groups and individuals.* Cambridge: Cambridge University Press, 1991: 312–26.
8. Beighton D. The complex oral microflora of high-risk individuals and groups and its role in the caries process. *Community Dent Oral Epidemiol* 2005; 33: 248–55.
9. Bellini HT, Arneberg P, von der Fehr FR. Oral hygiene and caries. A review. *Acta Odontol Scand* 1981; 39: 257–65.
10. Bratthall D. The global epidemiology of mutans streptococci. In: Johnson NW, ed. *Risk markers for oral diseases, Vol. 1. Dental caries: markers of high and low risk groups and individuals.* Cambridge: Cambridge University Press, 1991: 287–312.
11. Crossner C-G. Salivary lactobacillus counts in the prediction of caries activity. *Community Dent Oral Epidemiol* 1981; 9: 182–90.
12. Demers M, Brodeur J-M, Simard PL, Mouton C, Veilleux G, Fréchette S. Caries predictors suitable for mass-screenings in children: a literature review. *Community Dent Health* 1990; 7: 11–21.
13. DePaola PF, Soparkar PM, Tavares M, Kent RL. Clinical profiles of individuals with and without root surface caries. *Gerodontology* 1989; 8: 9–15.
14. Disney JA, Graves RC, Stamm JW, Bohannan HM, Abernathy JR, Zack DD. The University of North Carolina Caries Risk Assessment study: further developments in caries risk prediction. *Community Dent Oral Epidemiol* 1992; 20: 64–75.
15. Ellefsen BS, Morse DE, Waldemar G, Holm-Pedersen P. Indicators for root caries in Danish persons with recently diagnosed Alzheimer's disease. *Gerodontology* 2012; 29: 194–202.
16. Felder S, Robra BP. A preference-based measure for test performance with an application to prenatal diagnostics. *Stat Med* 2006; 25: 3696–706.
17. Grindefjord M, Dahllöf G, Nilsson B, Modéer T. Prediction of dental caries development in 1-year-old children. *Caries Res* 1995; 29: 343–8.
18. Hanley JA, McNeil BJ. The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology* 1982; 143: 29–36.
19. Hänsel Petersson G, Twetman S, Bratthall D. Evaluation of a computer program for caries risk assessment in schoolchildren. *Caries Res* 2002; 36: 327–40.
20. Hausen H. Caries prediction – state of the art. *Community Dent Oral Epidemiol* 1997; 25: 87–96.
21. Hausen H, Kärkkäinen S, Seppä L. Application of the high-risk strategy to control dental caries. *Community Dent Oral Epidemiol* 2000; 28: 26–34.
22. Helfenstein U, Steiner M, Marthaler TM. Caries prediction on the basis of past caries including precavity lesions. *Caries Res* 1991; 25: 372–6.
23. Helm S, Helm T. Correlation between caries experience in primary and permanent dentition in birth-cohorts 1950–70. *Scand J Dent Res* 1990; 98: 225–7.
24. Holmén A, Strömberg U, Magnusson K, Twetman S. Tobacco use and caries risk among adolescents – a longitudinal study in Sweden. *BMC Oral Health* 2013; 13: 31.
25. Honkala E, Nyyssönen V, Kolmakow S, Lammi S. Factors predicting caries risk in children. *Scand J Dent Res* 1984; 92: 134–40.
26. Hunt RJ. Behavioral and sociodemographic risk factors for caries. In: Bader JD, ed. *Risk assessment in dentistry.* Chapel Hill, NC: University of North Carolina Dental Ecology, 1990: 29–34.
27. Isokangas P, Alanen P, Tiekso J. The clinician's ability to identify caries risk subjects without saliva tests – a pilot study. *Community Dent Oral Epidemiol* 1993; 21: 8–10.
28. Källestål C. The effect of five years' implementation of caries-preventive methods in Swedish high-risk adolescents. *Caries Res* 2005; 39: 20–6.
29. Kingman A. Statistical issues in risk models for caries. In: Bader JD, ed. *Risk assessment in dentistry.* Chapel Hill, NC: University of North Carolina Dental Ecology, 1990: 193–200.
30. Kleemola-Kujala E, Räsänen L. Relationship of oral hygiene and sugar consumption to risk of caries in children. *Community Dent Oral Epidemiol* 1982; 10: 224–33.
31. Klock B, Krasse B. A comparison between different methods for prediction of caries activity. *Scand J Dent Res* 1979; 87: 129–39.
32. Koch GG, Beck JD. Statistical concepts: a matrix for identification of model types. In: Bader JD, ed. *Risk assessment in dentistry.* Chapel Hill, NC: University of North Carolina Dental Ecology, 1990: 174–92.
33. Köhler B, Andréen I, Jonsson B. The earlier the colonization by mutans streptococci, the higher the caries prevalence at 4 years of age. *Oral Microbiol Immunol* 1988; 3: 14–17.
34. Li Y, Wang W. Predicting caries in permanent teeth from caries in primary teeth: an eight-year cohort study. *J Dent Res* 2002; 81: 561–6.
35. Lindhe J, Axelsson P, Tollskog G. Effect of proper oral hygiene on gingivitis and dental caries in Swedish schoolchildren. *Community Dent Oral Epidemiol* 1975; 3: 150–5.
36. Locker D, Slade GD, Leake JL. Prevalence of and factors associated with root decay in older adults in Canada. *J Dent Res* 1989; 68: 768–72.
37. Mattiasson-Robertson A, Twetman S. Prediction of caries incidence in schoolchildren living in a high and a low fluoride area. *Community Dent Oral Epidemiol* 1993; 21: 365–9.
38. Motohashi M, Yamada H, Genkai F, Kato H, Imai T, Sato S, Sugaya A, Maeno M. Employing dmft score as a risk predictor for caries development in the permanent teeth in Japanese primary school girls. *J Oral Sci* 2006; 48: 233–7.
39. Parisotto TM, Steiner-Oliveira C, Silva CM, Rodrigues LK, Nobre-dos-Santos M. Early childhood caries and mutans streptococci: a systematic review. *Oral Health Prev Dent* 2010; 8: 59–70.
40. Pearce EIF. Salivary inorganic and physical factors in the aetiology of dental caries, and their role in prediction. In: Johnson NW, ed. *Risk markers for oral diseases. Vol. 1. Dental caries: markers of high and low risk groups and individuals.* Cambridge: Cambridge University Press, 1991: 358–81.
41. Pienihäkkinen K, Scheinin A, Bánóczy J. Screening of caries in children through salivary lactobacilli and yeasts. *Scand J Dent Res* 1987; 95: 397–404.
42. Pienihäkkinen K, Jokela J, Alanen P. Assessment of caries risk in preschool children. *Caries Res* 2004; 38: 156–62.
43. Powell LV. Caries prediction: a review of the literature. *Community Dent Oral Epidemiol* 1998; 26: 361–71.
44. Powell LV, Mancl LA, Senft GD. Exploration of prediction models for caries risk assessment of the geriatric population. *Community Dent Oral Epidemiol* 1991; 19: 291–5.
45. Raitio M, Pienihäkkinen K, Scheinin A. Assessment of single risk indicators in relation to caries increment in adolescents. *Acta Odontol Scand* 1996; 54: 113–17.
46. Ravald N, Birkhed D. Factors associated with active and inactive root caries in patients with periodontal disease. *Caries Res* 1991; 25: 377–84.
47. Ravald N, Hamp S-E. Prediction of root surface caries in patients treated for advanced periodontal disease. *J Clin Periodontol* 1981; 8: 400–14.
48. Ritter AV, Shugars DA, Bader JD. Root caries risk indicators: a systematic review of risk models. *Community Dent Oral Epidemiol* 2010; 38: 383–97.
49. Rose G. Sick individuals and sick populations. *Int J Epidemiol* 1985; 14: 32–8.
50. Russell JI, MacFarlane TW, Aitchison TC, Stephen KW, Burchell CK. Prediction of caries increment in Scottish adolescents. *Community Dent Oral Epidemiol* 1991; 19: 74–7.
51. Sánchez-Pérez L, Golubov J, Irigoyen-Camacho ME, Moctezuma PA, Acosta-Gío E. Clinical, salivary, and bacterial markers for caries risk assessment in schoolchildren: a 4-year follow-up. *Int J Paediatr Dent* 2009; 19: 186–92.
52. Schaeken MJM, Creugers TJ, van der Hoeven JS. Relationship between dental plaque indices and bacteria in dental plaque and those in saliva. *J Dent Res* 1987; 66: 1398–403.
53. Scheinin A, Pienihäkkinen K, Tiekso J, Holmberg S. Multifactorial modeling for root caries prediction. *Community Dent Oral Epidemiol* 1992; 20: 35–7.
54. Scheinin A, Pienihäkkinen K, Tiekso J, Holmberg S, Fukuda M, Suzuki A. Multifactorial modeling for root caries prediction: 3-year follow-up results. *Community Dent Oral Epidemiol* 1994; 22: 126–9.

55. Schröder U, Granath L. Dietary habits and oral hygiene as predictors of caries in 3-year-old children. *Community Dent Oral Epidemiol* 1983; **11**: 308–11.
56. Seki M, Karakama F, Terajima T, Ichikawa Y, Ozaki T, Yoshida S, Yamashita Y. Evaluation of mutans streptococci in plaque and saliva: correlation with caries development in preschool children. *J Dent* 2003; **31**: 283–90.
57. Seppä L, Hausen H. Frequency of initial caries lesions as predictor of future caries increment in children. *Scand J Dent Res* 1988; **96**: 9–13.
58. Seppä L, Hausen H, Pöllänen L, Kärkkäinen S, Helasharju K. Effect of intensified caries prevention on approximal caries in adolescents with high caries risk. *Caries Res* 1991; **25**: 392–5.
59. Skeie MS, Raadal M, Strand GV, Espelid I. The relationship between caries in the primary dentition at 5 years of age and permanent dentition at 10 years of age – a longitudinal study. *Int J Paediatr Dent* 2006; **16**: 152–60.
60. Snyder ML. Correlation and comparison of laboratory findings with the clinical evidence of caries activity in a group of sixty-six children. *J Am Dent Assoc* 1942; **29**: 2001–11.
61. Söderholm G, Birkhed D. Caries predicting factors in adult patients participating in a dental health program. *Community Dent Oral Epidemiol* 1988; **16**: 374–7.
62. Steiner M, Helfenstein U, Marthaler TM. Dental predictors of high caries increment in children. *J Dent Res* 1992; **71**: 1926–33.
63. Stewart PW, Stamm JW. Classification tree prediction models for dental caries from clinical, microbiological, and interview data. *J Dent Res* 1991; **70**: 1239–51.
64. Sullivan Å, Schröder U. Systematic analysis of gingival state and salivary variables as predictors of caries from 5 to 7 years of age. *Scand J Dent Res* 1989; **97**: 25–32.
65. Tellez M, Gomez J, Pretty I, Ellwood R, Ismail A. Evidence on existing caries risk assessment systems: are they predictive of future caries? *Community Dent Oral Epidemiol* 2013; **41**: 67–78.
66. Ter Pelkwijk A, van Palenstein Helderman WH, van Dijk JWE. Caries experience in the deciduous dentition as predictor for caries in the permanent dentition. *Caries Res* 1990; **24**: 65–71.
67. Thenisch NL, Bachmann LM, Imfeld T, Leisebach Minder T, Steurer J. Are mutans streptococci detected in preschool children a reliable predictive factor for dental caries risk? A systematic review. *Caries Res* 2006; **40**: 366–74.
68. Thibodeau EA, O'Sullivan DM. Salivary mutans streptococci and caries development in the primary and mixed dentitions of children. *Community Dent Oral Epidemiol* 1999; **27**: 406–12.
69. Twetman S, Fontana M. Patient caries risk assessment. *Monogr Oral Sci* 2009; **21**: 91–101.
70. Vanobbergen J, Martens L, Lesaffre E, Bogaerts K, Declerck D. The value of a baseline caries risk assessment model in the primary dentition for the prediction of caries incidence in the permanent dentition. *Caries Res* 2001; **35**: 442–50.
71. van Palenstein Helderman WH, ter Pelkwijk L, van Dijk JWE. Caries in fissures of permanent first molars as a predictor for caries increment. *Community Dent Oral Epidemiol* 1989; **17**: 282–4.
72. van Palenstein Helderman WH, Mikx FH, van't Hof MA, Truin G, Kalsbeek H. The value of salivary bacterial counts as a supplement to past caries experience as caries predictor in children. *Eur J Oral Sci* 2001; **109**: 312–5.
73. Vehkalahti MM. Relationship between root caries and coronal decay. *J Dent Res* 1987; **66**: 1608–10.
74. Vehkalahti M, Nikula-Sarakorpi E, Paunio I. Evaluation of salivary tests and dental status in the prediction of caries increment in caries-susceptible teenagers. *Caries Res* 1996; **30**: 22–8.
75. Watt RG. Strategies and approaches in oral disease prevention and health promotion. *Bull World Health Organ* 2005; **83**: 711–18.
76. Wendt LK, Hallonsten AL, Koch G, Birkhed D. Oral hygiene in relation to caries development and immigrant status in infants and toddlers. *Scand J Dent Res* 1994; **102**: 269–73.
77. Wilson RF, Ashley FP. Identification of caries risk in schoolchildren: salivary buffering capacity and bacterial counts, sugar intake and caries experience as predictors of 2-year and 3-year caries increment. *Br Dent J* 1989; **167**: 99–102.
78. Yoon RK, Smaldone AM, Edelstein BL. Early childhood caries screening tools: a comparison of four approaches. *J Am Dent Assoc* 2012; **143**: 756–63.
79. Zero D, Fontana M, Lennon AM. Clinical applications and outcomes of using indicators of risk in caries management. *J Dent Educ* 2001; **65**: 1126–32.
80. Zhang Q, Bian Z, Fan M, van Palenstein Helderman WH. Salivary mutans streptococci counts as indicators in caries risk assessment in 6–7-year-old Chinese children. *J Dent* 2007; **35**: 177–80.

24

Caries control in low-caries populations

H. Hausen, M. Jøssing, and O. Fejerskov

Introduction

Low-caries populations are typical in high-income countries, where the expenditure on dental treatment is high. Despite the low overall occurrence of dental decay, a considerable part of this expenditure is due to dental caries and its sequelae [1]. Major inequalities in oral health also occur among low-caries populations [19]. The first part of this chapter focuses on controlling dental caries among low-caries child populations in high-income countries, but the concepts presented may be applicable in lower income countries as well. We will demonstrate the outcome of controlled clinical trials conducted among various populations in Finland and the outcome of a Danish municipality program where the concept of caries control was applied. The study designs are very different, but taken together the results show that population-based oral health promotion combined with early noninvasive treatment of active caries lesions among all people who have such lesions is superior to targeting caries control measures to 'high-risk' individuals.

A low caries frequency entails the polarization of the caries problem

As was pointed out in Chapter 23, the distribution of subjects according to the number of decayed, missing, filled surfaces (DMFS) is highly skewed in low-caries child populations. The lower the level of caries frequency is, the stronger is the skewness. This is due to the fact that a DMFS score cannot be smaller than zero. In low-caries populations, the individuals with the highest caries scores, such as the ones in Fig. 23.1, manifest themselves distinctively from the no- or low-caries majority. This phenomenon, which is generally described as the polarization of caries, often raises a lot of concern. However, a right-hand tail including the

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

individuals with the highest number of caries lesions among the population can be found in all caries frequency distributions. As a matter of fact, the high-caries individuals of low-caries populations are a lot better off than their counterparts in populations where the level of caries frequency is high.

The worst-off quarter of 12-year-olds account for 70–80% of all DMFS in populations, for which the average DMFS score is around one, as shown in Fig. 23.2. At first sight, it would be a tempting idea to apply the high-risk strategy to control dental caries among such populations. The term 'high-risk strategy' or 'high-risk approach' stems from Rose [15] and stands for attempts to identify the high-risk susceptible individuals and to provide them with individual protection against the disease. A pure application of this approach includes no attempts to affect the risk among the population at large. According to Rose [15], a major advantage of this strategy is that an intervention is appropriate for an individual who has been found to have a high risk. This is likely to enhance the motivation of both the high-risk individual and the health professional taking care of them. Targeting the intervention to the high-risk individuals is also likely to be cost-effective. At the same time, it also entails a favorable benefit/risk ratio. *However, difficulties and costs of screening are an important disadvantage of the strategy.* The approach is also palliative and temporal in the sense that it does not prevent further individuals constantly being subjected to high risk. In addition, the strategy has limited potential for both the high-risk individual and the population at large. Moreover, it is behaviorally inappropriate. For the high-risk individual, it may be socially unacceptable to adopt a lifestyle that is different from that of their peers [15].

One of the main conclusions of Chapter 23 was that, for the present, no accurate measures are available for identifying in advance the subjects who have a high risk for developing dental decay. This reduces markedly the attractiveness of the high-risk approach as the principal strategy for controlling dental caries. As mentioned in Chapter 23, another precondition for adopting a high-risk strategy is that effective and feasible measures must be available for protecting the high-risk individuals from developing dental decay. Whether this prerequisite can be fulfilled will be discussed in the next section of this chapter.

Are effective and feasible measures available for protecting the high-risk individuals from dental decay?

In the late 1980s, an effort was made to address the high-risk susceptible teenagers in the city of Kuopio, Finland [16]. From among all the 13-year-olds living there, 37% were selected to a high-risk group on the basis of the level of salivary mutans streptococci and/or DS (decayed surfaces) score. The children for whom a consent was received ($n = 265$) were randomly divided into two groups. For the experimental group, instructions concerning intensified prevention were given and the dentists were specifically informed about the high risk of the children. Children in the control group continued receiving the same kind of preventive care that they had received before the study. For comparison, a group comprising a randomly selected half of the 13-year-olds whose risk for developing decay had been considered low was included in the study ($n = 248$). No instructions were given concerning the treatment of these children.

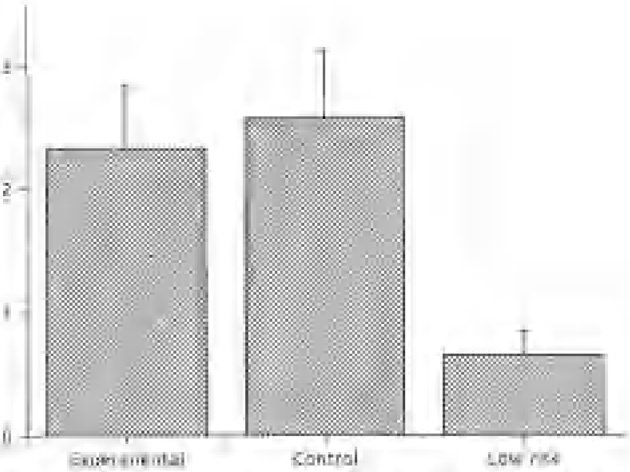


Figure 24.1 Mean approximal DMFS increment in 2 years among initially 13-year-old participants of a caries trial performed in Kuopio, Finland, in the late 1980s. Data from [16].

After 2 years, the mean approximal caries increment in the two high-risk groups was about three times that of the low-risk group (Fig. 24.1). There was no significant difference between the two risk groups in spite of the fact that markedly more preventive procedures had been provided for children in the experimental group than for those in the conventional treatment group. It could be concluded that the experimental regimen had failed to give the children additional protection but the possible beneficial effect of the conventional treatment remained unknown. Even the conventional treatment probably included more intensive prevention for the high-risk than for the low-risk children. Consequently, it can be safely concluded that the risk assessment procedure had resulted in high-risk groups whose mean DMFS increment scores were clearly higher than that of the remaining low-risk children. The average scores, however, do not tell how accurate the risk assessment was at the individual level.

In the mid 1990s, the potential of the high-risk strategy to control dental caries was studied in a randomized clinical trial in the City of Vantaa, Finland [6]. The risk for developing dental decay was assessed among 12-year-olds ($n = 1465$)

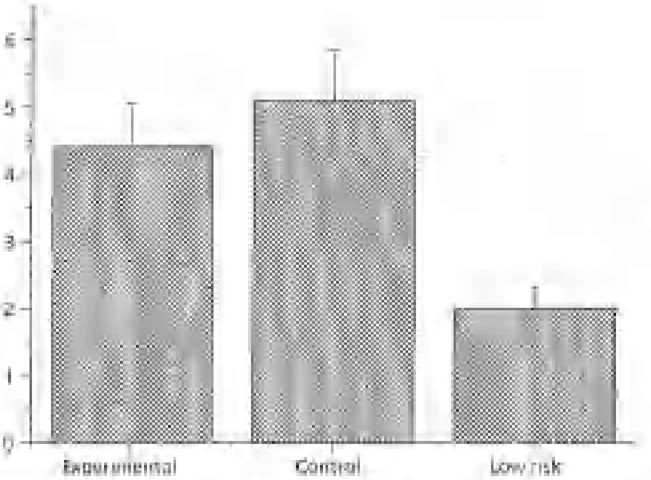


Figure 24.2 Mean DMFS increment in 3 years among initially 12-year-old participants of a caries trial performed in Vantaa, Finland, in the middle 1990s. Data from [6].

using data from clinical examinations and salivary tests. The children who were regarded as having a high risk were randomized into two groups. Those in the experimental group were offered intensive measures for controlling caries, while the control group received the same basic prevention that was given to the low risk children. The intensive caries control comprised fluoride varnish applications every sixth month, sealants for all newly erupted second molars as well as premolars with deep fissures, and extensive counseling on oral hygiene and diet. Brushing with fluoride dentifrice, sucking fluoride lozenges, and chewing xylitol gum were recommended as self-care. The subjects having an elevated salivary mutans streptococci score were provided with prophylaxis with chlorhexidine-fluoride gel. The basic caries control regimen included applications of fluoride varnish once a year. Sealants were placed only on newly erupted second molars with deep fissures. The importance of good oral hygiene and appropriate diet were mentioned, but detailed counseling was not given. The recommended self-care only included brushing with fluoride dentifrice.

At the end of the 3-year follow-up, DMFS increment was assessed among the two high-risk groups and among a random sample of the children whose risk was initially considered low. Only a small statistically nonsignificant difference was found between the two high-risk groups. For the low risk group, the increment score was less than half of that for the high-risk groups (Fig. 24.2). The negligible difference between the two high risk groups implies that intensifying caries control had produced practically no additional benefit. By offering all children only basic prevention, virtually the same preventive effect could have been obtained with substantially less effort and lower costs.

Comparison between the two groups who received basic caries control reveals that the procedure for assessing the risk of developing decay had been moderately successful in terms of mean DMFS increment among the groups. However, 32% of the children with a low risk developed at least one new lesion during the follow-up with the maximum number of new DMF surfaces being 12. Thus, the identification of high-risk individuals was far from being accurate. The results strongly suggest that it is not advisable to rely exclusively on the high-risk strategy for controlling dental caries among populations of low-caries teenagers. The effect on the high-risk individuals is weak and, by definition, there is absolutely no effect on the low-risk majority of the target population.

Quite a few other caries-control trials have been conducted among school-age children believed to have an elevated risk for developing decay [5, 10, 11, 20]. These studies considered different approaches to caries control but *none of them reported a clinically or statistically significant beneficial effect*. Rather than trying to help the high-risk individuals individually, it may be preferable to use some sort of targeted or directed population approach [18] which involves focusing action on population groups having an elevated risk. *These approaches do not include efforts to screen individuals for a high risk*. Instead, epidemiological and/or sociodemographic data are used for defining the target group. Candidates for such interventions include deprived residential areas, immigrants from low-income countries, dependent elderly and disabled people, drug addicts, and so on. In addition to measures of population-based oral health promotion, intensified efforts of individual health counseling and caries control may be targeted to all members of the target group.

Noninvasive treatment of early caries lesions among teenagers exposed to community-wide oral health promotion

Owing to the limited success of the high-risk approach in clinical trials among low-caries teenage populations, a novel approach was tried among teenagers in the City of Pori, Finland [7]. The aim of this study was to investigate whether DMFS increment can be decreased among schoolchildren with active initial caries by oral hygiene and dietary counseling and by using noninvasive preventive measures if the children are living in a community where the rationale of caries control is raised on the public agenda through a population-based health promotion program.

All fifth and sixth graders (11- and 12-year-olds) in the City of Pori, Finland, who started the 2001–2002 school year, except for mentally disabled and handicapped children attending special schools, were called to a baseline screening appointment. Those 93% who complied ($n = 1575$) were screened for the presence of active initial caries lesions. The children with at least one active lesion were invited to participate in the study and the ones for whom an informed

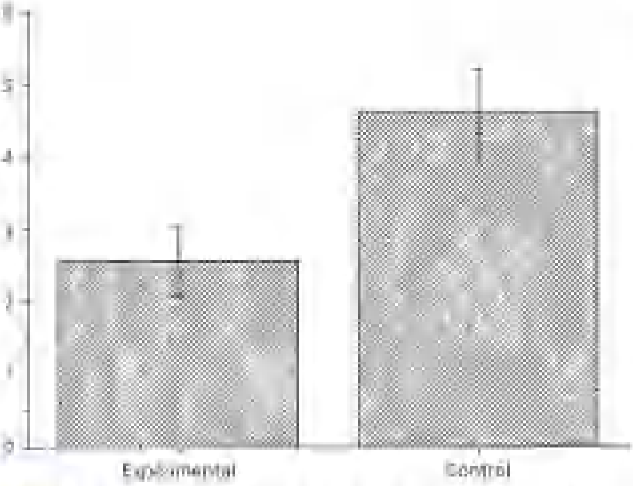


Figure 24.3 Mean DMFS increment in 3.4 years among initially 11–12-year-old participants of a caries trial performed in Pori, Finland, in the early 2000s. Data from [7].

consent was received ($n = 577$) were randomized into two groups. Children in the experimental group were offered an individually designed patient-centered caries control program aimed at identifying and eliminating factors that had led to the presence of active caries. The program included counseling sessions with the emphasis on enhancing the use of the children's own resources in everyday life. Toothbrushes, fluoride toothpaste, and fluoride and xylitol lozenges were distributed to the children. They also received applications of fluoride and/or chlorhexidine varnish. The children in the control group received basic caries control offered as standard in the public dental clinics in Pori. For both groups, the average follow-up period was 3.4 years. A community-level program of oral health promotion was run in Pori throughout this period.

The children in the experimental group received markedly more varnish applications and oral hygiene and diet counseling than did children in the control group. Filling teeth and using local anesthesia were less common in the experimental group. The mean DMFS increment for the experimental group was significantly lower than that for the control group (Fig. 24.3) with the prevented fraction being 44.3% ($p < 0.001$). The incremental cost-effectiveness ratio was €34 per averted DMF surface [9].

The study design did not make it possible to assess the effect of the community-level oral health promotion program, but the fact that the whole population was exposed to the same advice that the children in the experimental group received individually may have enhanced the effect of the experimental regimen. These results revealed that caries increment can be significantly reduced among caries-active children living in an area where the overall level of caries experience is low and where the children and the persons involved in their everyday life are exposed to community-level oral health promotion.

In contrast to the results of most of the studies, the high-risk approach was reported to be effective for controlling dental caries among preschool children by Pienihäkkinen and Jokela [13]. The success, however, may largely have been due to the fact that a part of the children who were considered to have a high risk of developing caries lesions already had active initial caries lesions at the beginning of the follow-up. The experimental group comprised 299 initially 2-year-old residents of [illegible] Korpilahti, Central Finland, who were treated at their local municipal health center. They were compared with 226 children of the same age who were residing and treated in Saarijärvi, another municipality in Central Finland. Both groups were followed-up for 3 years. All children received regular oral health care annually. The children in the experimental group were screened for the presence of mutans streptococci (MS) in plaque and active initial caries lesions. The MS-positive children ($n = 59$) received health education and a fluoride varnish application twice a year. For those who had active initial lesions ($n = 31$), the caries control also included chlorhexidine-varnish applications given four times a year.

At the age of 5 years, the percentage of children with cavitated caries or fillings was significantly lower in the experimental group (11.3%) than in the control group (23.7%). The treatment effect was strongest for the children who had had active initial caries lesion(s) at the beginning of the follow-up (odds ratio: 10.3; 95% confidence interval: 2.5, 43.1). A separate follow-up study [14] revealed that, at the age of 12 years, the decayed, missing, filled teeth (DMFT) score was significantly associated with the presence of MS in plaque and/or active initial caries lesions at the age of 2 years. The children who had belonged to the experimental group had a significantly lower average DMFT score than their counterparts in the former control group ($p < 0.001$). The estimated average running costs for the dental care between the ages of 5 and 12 years were significantly lower for the former experimental group (mean €506; standard deviation €240) than for the control group (€656; €304). The findings reveal that early caries control efforts can be both clinically and economically effective even in the long run.

A model for controlling caries in low-caries child populations

Figure 24.4 shows an outline of a model for controlling dental caries among a child population where the overall level of caries frequency is low. This model, which is based on experiences from the above studies performed among children in Finland, probably fits with contemporary child populations of other high-income countries as well. The sizes of the boxes

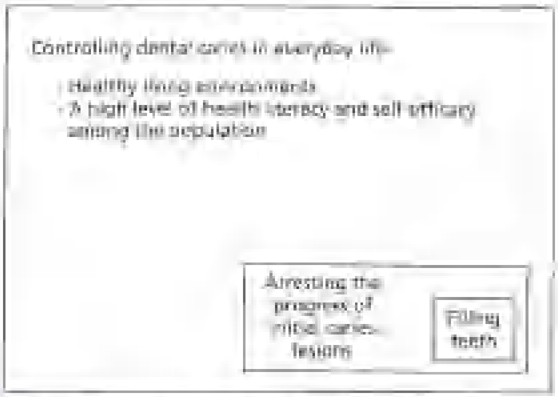


Figure 24.4 A model for controlling dental caries in cooperation between people, health professionals, and the society.

illustrate the volume of the activities. Controlling caries in everyday life is meant to cover the entire population. If the actual target group comprises children, it is important that the program also reaches all people and parties who are involved in their lives. Both of the smaller boxes are in front of an underlying box, which reveals that the activities depicted in them are meant to complement the actions included in the underlying box(es). So, people in need of arresting the progress of initial caries lesions must also be exposed to population-wide efforts for enhancing caries control, and no filling should be placed without having exposed the patient to the principles of both population-based caries control and the individual self-care for stopping the progress of existing caries lesions and for preventing the onset of new ones. The sizes of the smaller boxes should be taken as a long-term goal rather than a realistic description of the current situation. As a matter of fact, roughly half of the 12-year-olds in a typical contemporary high-income low-caries country do have at least one filled permanent tooth surface or a decayed surface that needs to be filled (Fig. 23.1).

In the following section we shall demonstrate how these principles have worked in a Danish municipality.

A demonstration case in 0–18-year-old Danes

The public dental health care for children and adolescents in Denmark

In 1972, Denmark passed a law on municipal dental health care (law no. 217/1972) according to which all children and adolescents up to the age of 18 years are offered free dental health care provided either by the public school dental health system or by private practitioners. At regular intervals the dentists have to provide the National Board of Health (NBH) with the oral health status of all children. The NBH can thus generate national dental health statistics of a unique nature (see Fig. 4.2). Since the 1970s the occurrence of dental caries has shown a steady decline, and despite variation between the different municipalities (see Fig. 3.16) it can be concluded that Denmark has experienced one of the world's largest documented reductions in dental caries (about a 90% reduction over the last half century). One of the advantages of the unique health statistics is that individual municipalities can compare their DMFS scores with the age-specific national mean values. The municipalities whose scores are higher than the national average values are likely to reconsider their strategies and priorities.

The explanation for the substantial improvement of oral health will not be discussed in this chapter, but it is important to emphasize that Denmark never introduced artificial water fluoridation and the natural waters in most areas contain between 0.1 and 0.4 ppm fluoride. Fluoride tablet regimes were introduced in the late 1970s, but as clinical studies demonstrated they had no effect on dental caries, but only introduced dental fluorosis [12, 17], they never gained ground. Fortnightly mouthrinsing programs (0.2% fluoride) were widely used in the school dental services for more than a decade, but when the occurrence of caries declined they were gradually stopped because it became apparent that their efficiency (the cost/benefit ratio) was too low [8]. The overriding concept has been not to build up complicated caries control programs, but to keep them simple by focusing on oral hygiene and on the use of fluoridated toothpaste as their basic components. However, there is total freedom for the different municipalities to choose their own strategies for caries control and treatment.

For many years it was not appreciated how important the filling component of the DMFT/S was when assessing the level of caries experience. In the early 1980s, a study on the radiographic diagnosis and clinical tissue changes in relation to the treatment of approximal carious lesions showed that there was a heavy restorative overtreatment in the school dental services [2]. Consequently, the departments of cariology and restorative dentistry of the two Danish dental schools joined forces in organizing intensive courses for dentists in the school dental services in an attempt to change their treatment criteria. The outcome of this was dramatic for the overall caries decline during the 1980s. During the 1990s and into the start of the 21st century, the caries levels continued to decline gradually. There have been periods of minor fluctuations, but in contrast to occasional claims from the international research community there is no evidence of a return to a caries increase. The Danish population can therefore be considered as a low caries population. For the time being, it is important to consider how dental caries may be further reduced in such populations and how the improved oral health can be maintained lifelong.

This section will therefore describe the attempts made to introduce the caries control concept in a small municipality, Odder, south of Aarhus in Jutland over a period of 6 years. In principle, the concept is based on the line of thinking advanced in the second edition of this textbook and the general reflections presented in the previous section of this chapter.

The Odder municipality dental health-care program

The municipality comprises around 21 500 inhabitants predominantly belonging to the middle class strata of the society. In the age group from 0 to 18 years of age there are a total of 5013 children and adolescents. In addition to this age group, the public service is also offered to disabled elderly persons (110 in total, predominantly living in care homes) as well as physically and/or mentally disabled persons (42). The service comprises diagnosis, caries control, and operative treatment. Moreover, up to 25% of children may receive orthodontic treatment. The Odder experience has been presented recently [4].

To provide these services, the person years of a total of 3.3 dentists, 3.3 dental hygienists, and 10.1 dental assistants are available. These cadres work together in teams so that two teams of 0.85 dentists, 1.2 hygienists, and 2.25 dental assistants are each responsible for about 2500 children. The dental teams are placed in two separate dental clinics. The entire school dental program is coordinated by a dentist in charge of the services assisted by two of the dental assistants.

Figure 24.5 presents the average DMFS for 18-year-olds in Odder from 1999 to 2012 together with the corresponding national average scores. It is seen that in the early 2000s the caries experience was above the national average. A new dentist in charge took over in 2005 and analyzed the dental records of some of the children having the most caries lesions. It became obvious that the predominant treatment had been filling without any recorded indications of instruction in oral hygiene, dietary counseling, or recommendations on the use of fluoride-containing toothpaste.

Consider two case reports:

1. A girl born in 1989. Until the end of 2005 she had been to the clinic 90 times, which included 40 examinations and operative treatment during 38 visits. Two primary molars had been filled nine times before being extracted.
2. A boy born in 1989. Until the end of 2005 he had visited the clinic 52 times. He had had 14 examinations and operative treatment during 30 visits. Two primary molars had been filled eight times before being extracted.

The analyses revealed that apparently little had been done to interfere with the ongoing disease processes except excavating caries lesions and repairing previous restorations. Moreover, the focus on restorative procedures often resulted in dental anxiety amongst the children. The municipal dental service decided to apply the current theoretical knowledge about dental caries as presented in the second edition of this textbook and formulated the following goals:

1. In every age cohort the percentage of caries-free children should increase every year and the defs/DMFS scores should continue to decline and be below the national values.
2. At the age of 18 years, where children are leaving the public service, they should predominantly have sound teeth or very few fillings. This age group should by then have been trained in and have developed good oral hygiene habits. They should know about healthy dietary and drinking habits. They should have no dental anxiety.
3. When leaving public service, each individual should be carefully informed about their oral health status and the chosen private dentist is provided with records about past disease experience and caries control and operative treatment.
4. Parents should preferably participate in the visits to the clinics until the child has reached the age of 12 years.
5. The communication with children and parents should focus on the concepts of appreciative inquiry. This means that the communication focuses on possibilities rather than limitations and points out even the smallest positive changes.

The role of each member of the dental team was specifically defined with these goals in mind so as to achieve the most cost-effective use of the resources.

The dentists became team leaders and consultants. They were supposed to perform traditional restorative care only when needed.

The dental hygienists became key persons, as they were given the responsibility for most of the dental examinations, and they were taught to 'assess risk', that is, to observe even the slightest signs of active caries lesions and factors affecting their development, such as unhealthy oral health habits. Moreover, they were allowed to perform adjustments of poorly accessible approximal areas between deciduous molars to allow for optimal oral hygiene performed by the child and the parents (for principles, see Chapter 13).

The dental assistants were given an important role in caries control, having their own patients with responsibility for oral hygiene instruction, application of topical fluoride, sealing of surfaces if needed, and caring for children with anxiety for dental intervention. Children along with their parents are invited for the first meeting with the municipal dental service around the age of 1½–2 years. A hygienist or dental assistant conducts an interview and instructs the parents with focus on the importance of oral hygiene (toothbrushing and dental floss), appropriate diet, and feeding habits.

All children are invited for examination at repeated intervals of 20 months. At each examination special emphasis is put on: (1) assessment of oral hygiene (disclosing solution used); (2) signs of early caries lesions in enamel; (3) past experience on dental caries and its treatment, (4) dental caries experience amongst siblings and (5) eruption of teeth.

Based on this assessment, an individual caries control plan is developed. This consists primarily of support for better oral hygiene (plaque control and recording plaque index), instruction in appropriate toothbrushing (twice a day) and use of dental floss (recommended use twice a week), topical fluoride treatment, and, if needed, fissure sealing and diet counseling. The intervals between these visits are highly individual, depending on response of the child. *If the child is not considered to be at risk for developing caries lesions the next recall is after 20 months.*

Concomitant with setting these specific oral health goals, the municipality established in 2006 a working group in order to advance a general health policy. This group consisted of politicians, leaders of the elderly care and rehabilitation programs, physicians, dentists, labor market representatives, and people from voluntary organizations. A health policy and an action plan were adopted by the city council in 2007 and a 'health coordinator' was appointed. For the first 4 years the focus of the policy was on diet and physical exercise. A zero-sugar policy has been adopted for kindergartens and schools as part of the food policy by the municipality.

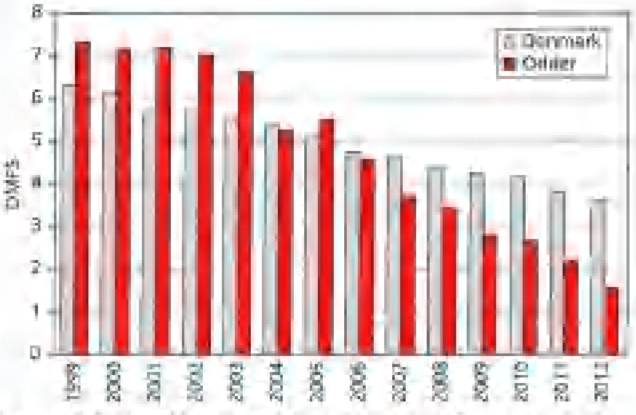


Figure 24.5 Mean DMFS for all 18-year-olds in the Odder municipality from 1999 to 2012 compared with the national average for 18-year olds in Denmark. Data from the Danish Health and Medicines Authority.

The results of this basically simple general and specific dental health program are dramatic, as seen in Figs 24.5, 24.6, 24.7, and 24.8. From 2002 to 2012 the DMFS score amongst 15-year-olds dropped from ~3 to <1 (Fig. 24.6). In fact, this was the goal for 2015, which the dental service had already achieved by 2011. The percentage of caries-free children by the age of 15 was 67% in 2011 and 69% in 2012.

In the target group, the 18 year-olds, Fig. 24.7 shows a decline in DMFS from 6.6 prior to 2003 to about 1.5 by 2012. A 60–70% caries reduction had taken place in 6 years in a population already considered to be a low-caries population. Figure 24.8 demonstrates that 52% of the 18 year olds left the public service with sound teeth in 2012, and only 5% had more than eight filled surfaces (the red category). It should be noted that this cohort has only been exposed to the new caries control concept for the last 6 years.

In addition to these quantitative results, questionnaires have shown that parents and children consider the municipal dental health-care system as very supportive and positive, which adds to the impression among the various members of the dental teams of a mutual mission with success.

Is this model also applicable in low-caries populations in less-privileged populations around the world?

In the aforementioned model we have focused on the effects of a caries control concept and a general municipal health policy amongst a low-caries population in a high income country. But can it also be applied in lower income countries, including poor populations of Africa, South America, and China? We would argue that it is possible because:

- the concept involves the municipality as a whole, and oral health care is totally integrated with a general health-care policy;

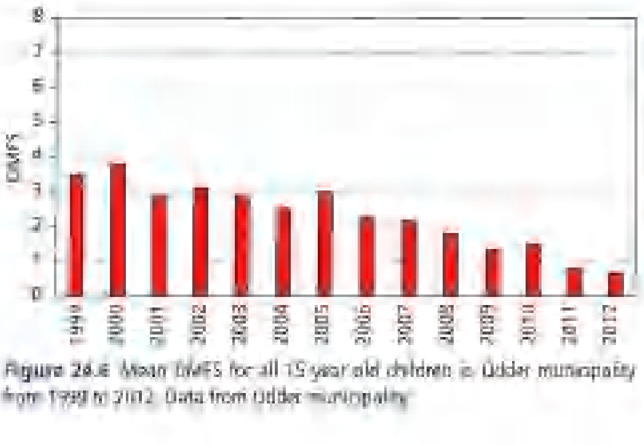


Figure 24.6 Mean DMFS for all 15 year old children in Odder municipality from 1999 to 2012. Data from Odder municipality.

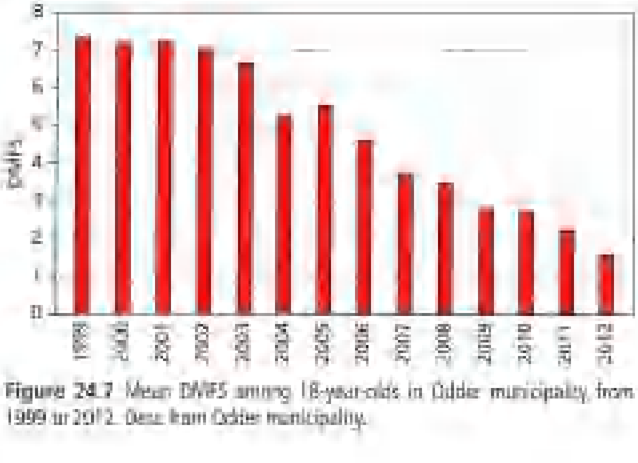


Figure 24.7 Mean DMFS among 18-year-olds in Odder municipality from 1999 to 2012. Data from Odder municipality.

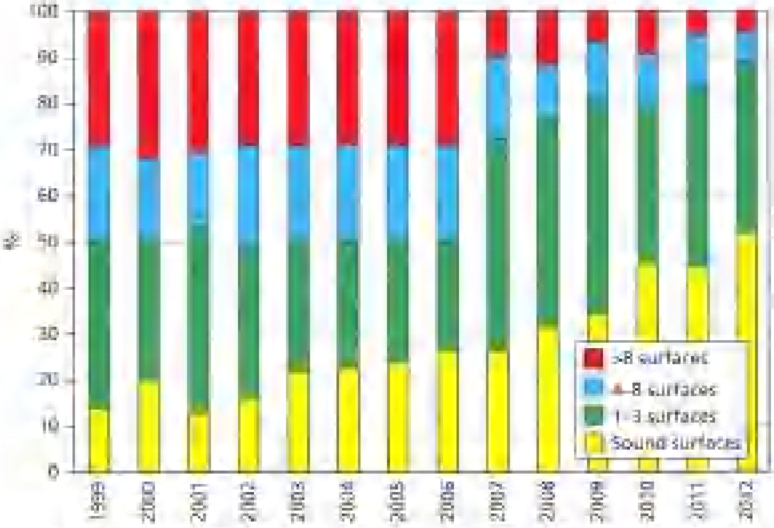


Figure 24.8 The frequency distribution of 18-year-olds in Odder municipality according to their caries experience from 1999 to 2012. Data from Odder municipality.

- the oral health-care concept is that of a *nonoperative caries control*;
- the concept involves a population from birth to adulthood, with the main focus on keeping the children pain free and avoiding drilling and filling as far as possible.

For applying the concept, the dental team includes *dental hygienists and dental assistants supervised by a dentist*. However, it is our experience from Kenya that a similar program can be successfully established by recruiting primary health-care workers (PHCWs) from the local community and training them for a few months. After proper training these workers are able to perform pain relief using hand instruments and to provide their patients with instruction on how to perform proper oral hygiene measures (see Chapter 15). This may lead to the conversion of ongoing caries lesions from active to inactive. If necessary, such program can also be expanded to involve simple atraumatic restorative treatment procedures (see Chapter 19).

An essential part of the concept is that parents – in most countries the mothers – should be involved up to the age of 12 to ensure that children learn good oral hygiene habits and good health habits in general. All people ought to be brought up with the appreciation that they themselves are responsible for maintaining the oral cavity free from conditions causing pain. This requires regular access to PHCWs – but attending a dentist is necessary only on the rare occasions when the PHCWs cannot diagnose and ameliorate pathologic conditions in the oral cavity. The costs are low as PHCWs should have a moderate salary. Dentists are way too expensive, and as a rule they predominantly tend to perform restorative dentistry without appropriate concomitant caries control.

A major challenge for the application of the concept is that in many populations people cannot afford toothbrushes and fluoridated toothpaste, not to mention dental floss. In parts of Africa, *mswakis* (wooden sticks) are very useful substitutes for a toothbrush [3] – see also Chapter 15. The concept avoids any type of 'passive' preventive measures, such as dental sealants, as these are not in accord with the ultimate goal of enabling the individuals themselves to take the responsibility for maintaining a functioning dentition lifelong.

Concluding remarks

The cornerstones of the everyday management of dental caries are healthy lifestyles that for most people should be sufficient to prevent the onset of decay. Teeth must be brushed twice a day using fluoridated toothpaste. Dietary patterns must not favor oral microorganisms whose metabolic products are capable of demineralizing dental enamel. This means that food and drinks containing sugar should be eaten sparingly and not between meals. In particular, it is important to refrain from continuously nibbling sugary snacks or other food items that include easily fermentable carbohydrates. Plain water should be used for quenching thirst.

Living environments conducive to health are vital for promoting healthy lifestyles. For children and adolescents, candy- and soda-free day-care centers, schools, and organized leisure activities make good examples of such settings. Creating healthy environments is usually beyond the powers of an individual oral health professional. Instead, joint efforts of multiple parties are usually necessary. The role of oral health professionals is essential in working out the cooperation among the relevant parties. Good health literacy and a strong sense of self-efficacy are essential elements of personal life skills. *Families do have the primary responsibility of taking care that a child adopts a healthy lifestyle at an early age.* Daycare centers, schools, and other parties involved in the upbringing of the child should support the families in their parenting. Population-wide efforts for promoting oral health skills, such as different campaigns, may not immediately lead to measurable changes in the oral health-related lifestyles. Still, they may be behaviorally justified. For individuals in need of arresting the progress of caries lesions, for instance, it may be more acceptable to adopt the necessary self-care if the means that are suggested to them are prominently advocated for the whole population as well.

Despite population-based efforts to promote oral health, there will always be individuals who develop caries lesions whose management requires professional attention. If a lesion is not reaching deep into the dentin and if the surface of the lesion can be kept free from bacterial deposits or tightly sealed, the lesion is a good candidate for noninvasive treatment that can make filling unnecessary. The essential elements of the noninvasive treatment include removing the biofilm from the surface of the lesion and keeping the surface clean. Topical fluoride *may* be applied to active caries lesions for enhancing the remineralization of the lesions. For tooth surfaces with fissures and/or pits, a sealant may be placed to prevent the bacteria that cannot be removed from the fissure system obtaining nutrients. The clinical procedures performed by an oral health professional may be necessary and effective in the short term. *In the long run, however, an active contribution by the patient is crucial for making the outcome of the treatment sustainable.* Consequently, efforts of noninvasive caries treatment are likely to fail if the treatment is not carried out in close cooperation with the patient. A successful contribution of the patient should also be able to prevent the onset of further lesions needing professional attention. If fillings are necessary for an individual patient, special care must be taken to establish the necessary cooperation with the patient in order to control caries and to avoid need for further fillings from occurring.

References

1. Batchelor PA, Sheiham A. The distribution of burden of dental caries in schoolchildren: a critique of the high-risk caries prevention strategy for populations. *BMC Oral Health* 2006; **6**: 3.
2. Bille J, Thylstrup A. Radiographic diagnosis and clinical tissue changes in relation to treatment of approximal carious lesions. *Caries Res* 1982; **16**: 1–6.
3. Danielsen B, Baelum V, Manji F, Fejerskov O. Chewing sticks, toothpaste, and plaque removal. *Acta Odontol Scand* 1989; **47**: 121–5.
4. Fejerskov O, Escobar G, Jøssing M, Baelum V. A functional natural dentition for all – and for life? The oral healthcare system needs revision. *J Oral Rehabil* 2013; **40**: 707–22.
5. Forgie AH, Paterson M, Pine CM, Pitts NB, Nugent ZJ. A randomised controlled trial of the caries-preventive efficacy of a chlorhexidine-containing varnish in high-caries-risk adolescents. *Caries Res* 2000; **34**: 432–9.
6. Hausen H, Kärkkäinen S, Seppä L. Application of the high-risk strategy to control dental caries. *Community Dent Oral Epidemiol* 2000; **28**: 26–34.
7. Hausen H, Seppä L, Poutanen R, Niinimaa A, Lahti S, Kärkkäinen S, Pietilä I. Noninvasive control of dental caries in children with active initial lesions. A randomized clinical trial. *Caries Res* 2007; **41**: 384–91.
8. Heidmann J, Poulsen S, Arnbjerg D, Kirkegaard E, Laurberg L. Caries development after termination of a fluoride rinsing program. *Community Dent Oral Epidemiol* 1992; **20**: 118–21.
9. Hietasalo P, Seppä L, Lahti S, Niinimaa A, Kallio J, Aronen P, Sintonen H, Hausen H. Cost-effectiveness of an experimental caries-control regimen in a 3.4-yr randomized clinical trial among 11–12-yr-old Finnish schoolchildren. *Eur J Oral Sci* 2009; **117**: 728–33.
10. Johnston DW, Lewis DW. Three-year randomized trial of professionally applied topical fluoride gel comparing annual and biannual applications with/without prior prophylaxis. *Caries Res* 1995; **29**: 331–6.
11. Källestål C. The effect of five years' implementation of caries-preventive methods in Swedish high-risk adolescents. *Caries Res* 2005; **39**: 20–6.
12. Kalsbeek H, Verrips E, Dirks OB. Use of fluoride tablets and effect on prevalence of dental caries and dental fluorosis. *Community Dent Oral Epidemiol* 1992; **20**: 241–5.
13. Pienihäkkinen K, Jokela J. Clinical outcomes of risk-based caries prevention in preschool-aged children. *Community Dent Oral Epidemiol* 2002; **30**: 143–50.
14. Pienihäkkinen K, Jokela J, Alanen P. Risk-based early prevention in comparison with routine prevention of dental caries: a 7-year follow-up of a controlled clinical trial; clinical and economic aspects. *BMC Oral Health* 2005; **5**: 2.
15. Rose G. Sick individuals and sick populations. *Int J Epidemiol* 1985; **14**: 32–8.
16. Seppä L, Hausen H, Pöllänen L, Kärkkäinen S, Helasharju K. Effect of intensified caries prevention on approximal caries in adolescents with high caries risk. *Caries Res* 1991; **25**: 392–5.
17. Thylstrup A, Fejerskov O, Bruun C, Kann J. Enamel changes and dental caries in 7-year-old children given fluoride tablets from shortly after birth. *Caries Res* 1979; **13**: 265–76.
18. Watt RG. Strategies and approaches in oral disease prevention and health promotion. *Bull World Health Organ* 2005; **83**: 711–18.
19. Watt R, Sheiham A. Inequalities in oral health: a review of the evidence and recommendations for action. *Br Dent J* 1999; **187**: 6–12.
20. Zimmer S, Bizhang M, Seemann R, Witzke S, Roulet JF. The effect of a preventive program, including the application of low-concentration fluoride varnish, on caries control in high-risk children. *Clin Oral Investig* 2001; **5**: 40–4.

25

Epilogue. Controlling the global burden of dental caries: the evidence calls for a reorganization of the oral health-care system

O. Fejerskov, V. Baelum, B. Nyvad, and E.A.M. Kidd

In the prologue, we stated: 'Dental caries is ubiquitous – it is omnipresent in all populations and is as old as mankind. The caries incidence rate varies extensively between and within populations. With increasing age, signs and symptoms of dental caries accumulate, and in most adult populations the caries prevalence approaches 100%.'

In Chapter 4 we expanded on the occurrence of dental caries and trends in different populations. It was shown that the caries incremental lines in cohorts of Danish children continue to grow with increasing age, although from one cohort to a new cohort the starting level decreased and the slope of lines becomes less. In other words, the overall prevalence is decreasing. In Chinese populations it has also been shown that dental caries continues to accumulate with age, and the incidence rate in the elderly is as great as that earlier in life. This is fully in accord with the results from the Dunedin cohort (New Zealand), where caries has been tracked in each individual from 5 years to over 30 years [4]. Dunedin is fluoridated and all children have been seen regularly, and at no charge, in school by dental nurses. However, the trend lines do not bend, suggesting that the way in which this community had approached caries 'prevention' has had limited effect – maybe because they did not think in terms of caries control rather than 'prevention,' believing that fluoride alone would be the solution? (see Chapter 14).

We have tried in this edition to gradually explain why our understanding of the various biological determinants of dental caries (Chapters 5–9) may help us in selecting a simple approach to a clinically relevant diagnosis of caries (Chapters 10–12). In Chapters 13–18 we have then discussed how caries control may work, and in Chapters 19–21 we presented evidence that the traditional concepts prevailing in restorative dentistry are part of the concept of caries control. Finally, Chapters 22–24 focus on how to achieve a better oral health in different populations.

Dental caries is still responsible for most of the oral disease burden in populations worldwide. Despite the dramatic changes in dental caries patterns during the last 30 years, most dental curricula remain largely unaffected – and we still produce even more dentists focusing on high-tech treatment solutions, apparently without appreciating what the need of populations may be in the years ahead. The philosophy and ethos of the dental profession is very focused on a downstream, patient-centered, curative and rehabilitative approach to oral disease [2]. We do not think that the oral problems of future generations can be solved by striving to produce more dentists who all should be

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.

trained in oral medicine, cariology and periodontology, implantology, endodontics, and prosthodontics, not to mention to be familiar with developments in stem-cell biology, informatics, metabolomics, genomics, proteomics, and so on.

We suggest that it is necessary to reconsider the organization of oral health care in order to improve oral health cost-effectively *to achieve a functioning natural dentition from cradle to grave* for all members of the population [6]. As we see it, the necessary reorganization involves the development of new types of dental health professionals capable of carrying out cost-effective and evidence-based oral disease control programs for all. In addition, we must provide the optimal diagnosis and specialized oral rehabilitation for specific subgroups in all populations – not least the growing number of elderly.

In most populations, people now live much longer healthy lives. For a further few decades, we will experience a growing number of elderly who retain an increasing number of teeth resulting in dentitions in need of complex treatment. These cohorts represent the result of the 'restorative era.' Looking beyond this peak of complex needs for high-tech rehabilitation among the oldest sections of our populations, we see new cohorts of middle-aged with a lower disease burden. When they grow old they are likely to have a much lower need for advanced dental treatment as a result of the 'disease-control' era. Already now we can follow these young and middle-aged cohorts and see that each of these continue to have less caries and less periodontal disease and retain more teeth with fewer and smaller restorations than the immediately preceding cohorts. In most high-income countries, substantial fractions of young and middle-aged cohorts are unlikely ever to develop a treatment need that matches the competencies of the 'fully' trained, classical dentist.

Many before us have reflected on the need for responsible dental educators and academic leaders to take action on the delivery of oral health care. While most have discussed a need for adjustments of the dental curriculum in response to rapidly changing oral disease patterns [1, 5, 7, 8], or a perceived need for expansion of the dental specialist training, few have dared to suggest that the structure and organization of the oral health-care system is a major obstacle to achieving a functional natural dentition for life for all. Tomar and Cohen [9] emphasized the urgent need to integrate oral health care into general health care, and we think that their 'diagnosis' of the problem in the USA covers much broader scenarios. They stated that:

> *in the coming decades, the US population will continue to shift toward an older age distribution and an increasing number of Americans will reach their 'golden years' with relatively intact dentitions, chronic disease, and multiple medications. (…) Because of the tremendous overlap of risk factors that threaten oral health and those that increase the risk for other chronic diseases, an integrated system may be able to reap broader benefits from health promotion and disease prevention.*

It is now painfully evident to those with a zest for the health of the public that the current practice-based approach to dental treatment and rehabilitation in individuals represents a cul-de-sac from social, ethical, and cost-effectiveness points of view. The ideal oral health-care system cannot be achieved through minor adjustments of the dental curriculum, or of the number of dental specialties, the payment systems or the solo-practice-based delivery system. In our view, it necessitates a more profound break with long-standing traditional thinking in dental education and in oral health-care delivery.

Currently, the traditional 'fully trained dentist' is complemented by a varying number of dental specialties, which may include orthodontics, oral surgery, periodontics, oral pathology, pedodontics, prosthodontics, endodontics, dental radiology, occlusion and temporomandibular joint disorders, and dental public health. We suggest that the time has come to realize that this dental workforce should be replaced by two new types of dental professionals: the oral health-care provider (OHCP), who will comprise the vast majority of the group of dental professionals, and the oral clinical specialist (OCS) – for detailed arguments, see [6].

The OHCP should be at the center of health services to meet the needs of most individuals, families, and communities and address the health-care needs in all age groups with a principal focus on evidence-based diagnosis and oral disease control. The OHCP is a cost-effective health professional who has a profound understanding of oral disease control and oral health as part of general health and well-being, and who is willing to cope with social needs in a critical, creative, and pertinent way.

The OHCP should be competent and skilled not only in the diagnosis and control of oral diseases, but importantly also in public health, basic health economy, management, and communication. A major role of the OHCP is to *lead* and supervise teams of oral health personnel. These may include auxiliaries/dental assistants/hygienists/therapists according to the particular fabric for each country. The OHCP will lead at community level, planning health care and setting priorities involving all age groups, including all the currently un- or underserved groups in the community. *Their activities should be integrated into the general health-care services. The OHCPs and their staff will be able to cater for the oral health care needs of the large majority of the population.* The OHCPs and their staff should therefore be the gatekeepers with respect to advanced oral health-care needs. The OHCPs will also, when needed, be able to perform simple restorative treatments. For a few OHCPs there should be a postgraduate training in orthodontics.

However, a subtraction of the population will remain, who, in addition to basic disease control measures, are also in need of more advanced oral care, including complex rehabilitation. These patients are increasingly likely to be characterized by overlap of risk factors that threaten oral health and those that increase the risk for other chronic diseases, in addition to the growing fraction of older people with chronic diseases and multiple medications. We need a new cadre, the OCS, to cater for some of their needs. To ensure that complex oral care for individuals with chronic diseases and multiple medications becomes integrated with general health care, we suggest that the OCS *is a medically trained person* who has a comprehensive postgraduate training either in oral rehabilitation or in oral surgery and medicine.

Many of the arguments developed here may, at a first glance, seem to apply primarily to the industrialized countries with a well-developed health-care system. However, our experiences from Africa, South-East Asia, China, and South America have convinced us that one of the worst things that could happen in many of these countries would be the uncritical attempt to replicate the oral health-care systems prevailing in Europe and North America. In this context, we would like to cite from a previous publication [3]:

> *Broadly speaking, the oral disease profile of populations in low-income countries in Africa, China, Southeast Asia and South America are typically characterized by a relatively low occurrence of caries, poor oral hygiene conditions, widespread and severe gingivitis, and considerable periodontal breakdown, which, however, does not result in major tooth loss endangering a functional dentition, except for a sub-fraction of the population. The existing oral health care services are often rudimentary, and the challenge for such countries is to avoid the implementation of dental services based on the high-technology clinical approach well known from the Western high-income countries. Unless regulatory steps are taken it is easy to foresee that private initiatives in case of socio-economic growth will result in such services. In the early phase such private enterprises will serve only the relatively small, but affluent, subgroup of the population that can pay. Gradually, the next phase is entered where the existing services are too limited and the economic means of the general population too small to be compatible with dental treatment and the disease affected teeth are therefore extracted. Provided economic growth continues, the third phase is characterized by the dental services gradually approaching the contents and extent well known from the high-income countries in the hey day of restorative dentistry.*

Increasing availability and access to "classic restorative dentists" as they are known from Europe and North America would, in our opinion, have deleterious consequences. As classic dentistry will not give priority to disease control based on biologically sound principles, we surmise that our proposal for OHCPs and OCSs applies equally to countries presently developing their services.

It is our view that only by thoroughly reconsidering the oral health-care workforce can we continue to stride toward the ideal oral health-care system, which has the attributes of being integrated, health promotional and disease control oriented, monitoring, evidence based, cost-effective, sustainable, equitable, universal, comprehensive, ethical, quality assuring, culturally competent and empowering.

References

1. Albino JEN, Inglehart MR, Tedesco LA. Dental education and changing oral health care needs: disparities and demands. *J Dent Educ*, 2012; **76**: 75–88.
2. Baelum V. Dentistry and population approaches for preventing dental diseases. *J Dent* 2011; **39** (Suppl 2): S9–S18.
3. Baelum V, van Palenstein Helderman W, Hugoson A, Yee R, Fejerskov O. A global perspective on changes in the burden of caries and periodontitis: implications for dentistry. *J Oral Rehabil* 2007; **34**: 872–906.
4. Broadbent JM, Thomson WM, Poulton R. Trajectory patterns of dental caries experience in the permanent dentition to the fourth decade of life. *J Dent Res* 2008; **87**: 69–72.
5. DePaola D, Slavkin C. Reforming dental health professions education: a white paper. *J Dent Educ* 2004; **68**: 1139–50.
6. Fejerskov O, Escobar G, Jøssing M, Baelum V. A functional natural dentition for all – and for life? The oral healthcare system needs revision. *J Oral Rehabil* 2013; **40**: 707–22.
7. Kassebaum DK, Hendricson WD, Taft T, Haden NK. The dental curriculum at North American dental institutions in 2002–03: a survey of current structure, recent innovations, and planned changes. *J Dent Educ* 2004; **68**: 914–31.
8. Plasschaert AJM, Holbrook WP, Delap E, Martinez C, Walmsley AD. Profile and competences for the European dentist. *Eur J Dent Educ* 2005; **9**: 98–107.
9. Tomar SL, Cohen LK. Attributes of an ideal oral health care system. *J Public Health Dent* 2010; **70** (Suppl 1): S6–S14.

Index

Page numbers in *italic* refer to figures; **bold** refer to tables and page numbers with suffix 'b' refer to boxes

Dental Caries: The Disease and Its Clinical Management, Third Edition. Edited by Ole Fejerskov, Bente Nyvad, and Edwina Kidd.