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Craig's RESTORATIVE DENTAL MATERIALS

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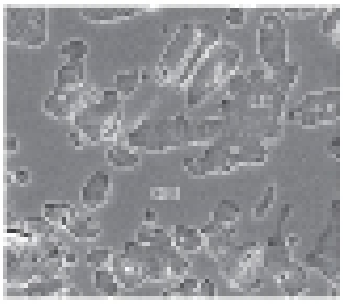
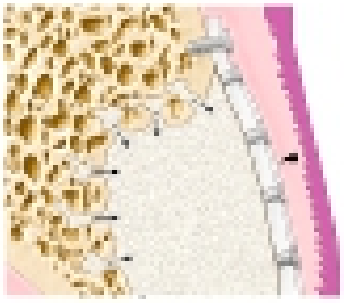
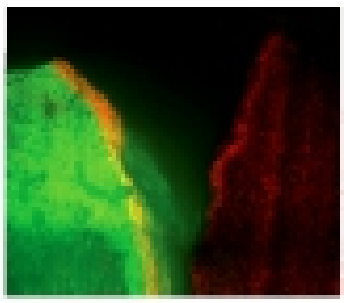
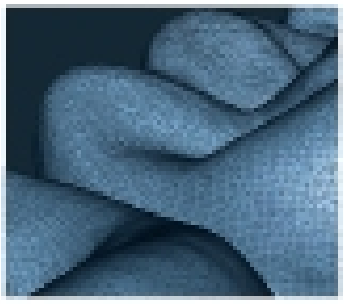

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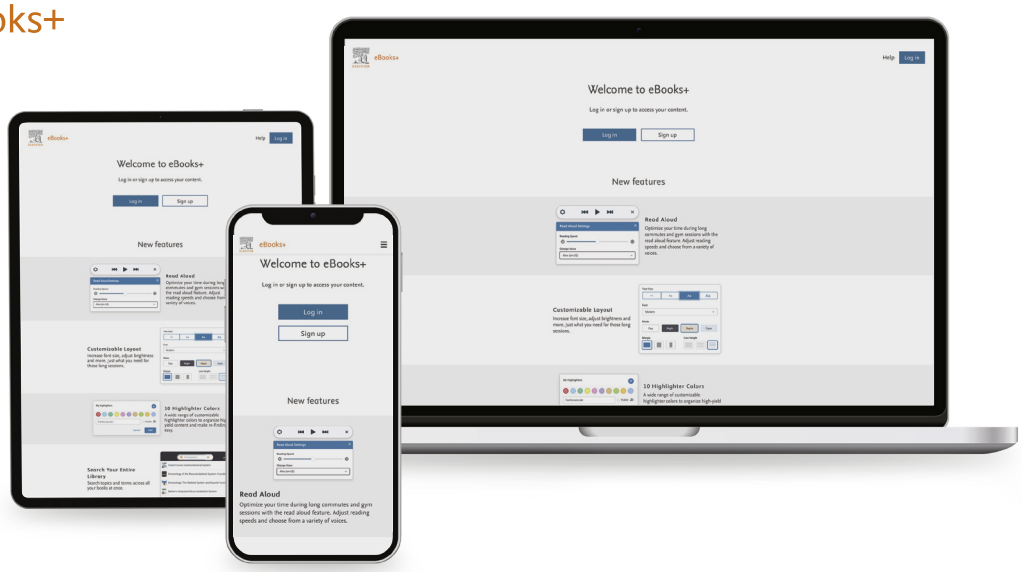

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Craig's RESTORATIVE DENTAL MATERIALS

FIFTEENTH EDITION

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To the many mentors, mentees, and colleagues
with whom we have collaborated

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Preface

The 15th edition of this classic textbook has been extensively updated to include many recent developments in dental biomaterials science and new materials for clinical use. The sequencing of the materials has also been streamlined. The book continues to be designed for predoctoral dental students and also provides an excellent update of dental biomaterials science and clinical applications of restorative materials for students in graduate programs and residencies.

Dr. Carmem S. Pfeifer takes on the lead editor role from Dr. Ronald L. Sakaguchi, who has served in that capacity for the 13th and 14th editions and now serves as coeditor. Dr. Pfeifer is professor and division head of Biomaterial and Biomedical Sciences, Department of Oral Rehabilitation and Biosciences at the School of Dentistry, Oregon Health & Science University (OHSU), with a joint appointment in the Department of Biomedical Engineering, School of Medicine, in Portland, Oregon. She earned her DDS and PhD in Dental Materials Sciences from the University of São Paulo, Brazil.

Dr. Sakaguchi serves as Dean of the School of Dentistry at OHSU. He earned a BS in cybernetics from the University of California Los Angeles (UCLA), a DDS from Northwestern University, an MS in prosthodontics from the University of Minnesota, a PhD in biomaterials and biomechanics from Thames Polytechnic (London, England; now the University of Greenwich), and an MBA in entrepreneurship from Babson College.

Dr. Jack L. Ferracane returns as coeditor of the 15th edition. Dr. Ferracane serves as professor and chair of the Department of Oral Rehabilitation and Biosciences at the School of Dentistry (OHSU) in Portland, Oregon. He earned a BS in biology from the University of Illinois and an MS and a PhD in biological materials from Northwestern University.

We thank our many chapter authors for their effort and expertise in revising the text from the previous edition: Dr. Hongseok An, Dr. Juliana Branco da Costa, and Dr. Justin Merritt from Oregon Health & Science University; Dr. Roberto R. Braga from the University of São Paulo; Dr. Jason Alan Griggs from the University of Mississippi; Dr. John C. Mitchell from Midwestern University; Dr. Danielle P. Wingrove from the University of Utah; and Dr. Yu Zhang from the University of Pennsylvania.

The organization of the 15th edition was updated so that each chapter focuses on a specific class of materials. The chapter on testing of dental materials and biomechanics is now provided as online content only. One new chapter dedicated to dental adhesives was created (Chapter 7), encompassing the new adhesive technologies. The chapter on dental composites (Chapter 8) has been extensively revised to include newer technology in photopolymerization. Chapter 13, on technology, has also seen a major update, with a focus not only on CAD-CAM but also on additive manufacturing technologies applied to dentistry.

An enhanced ebook version, included with every new print purchase, is available for this textbook. Included is the majority of the procedural, or materials handling, content that was in the previous editions. In addition, newly produced interactive videos for the most common procedures in dentistry are available at http://ebooks.health.elsevier.com/. The Evolve Resources website, available for instructors at http://evolve.elsevier.com/Pfeifer/restorative/, includes an image collection and PowerPoint lecture slides to supplement the print version of the book.

Carmem Pfeifer
Jack Ferracane
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We are deeply grateful to Lauren Boyle and Kelly Skelton, Senior Content Strategists at Elsevier, for guidance in the initial planning and approval of the project; to Suddha Satwa Sen, Senior Developmental Editor at Elsevier, for the many suggestions and support throughout the design process and writing of the manuscript.

Thanks also to many others at Elsevier for their behind-the-scenes work and contributions to the book.

Lastly, we thank our colleagues in our respective institutions for the many informal chats and suggestions offered and our families who put up with us being at our computers late in the evenings and on many weekends. It truly does take a community to create a work like this textbook, and we thank you all.

Carmem Pfeifer
Jack Ferracane
Ronald Sakaguchi

Contents

1

Role and Significance of Restorative Dental Materials

RONALD SAKAGUCHI

CHAPTER OUTLINE

Developments in materials science, tissue engineering, regenerative dentistry, imaging and subtractive computer-aided design/computer-aided manufacturing (CAD/CAM), and additive (3D printing) manufacturing have dramatically changed the way we look at the replacement of components of the human anatomy. The replacement of tooth structure lost to disease, wear, and injury continues to be a large part of general dental practice. Restorative dental materials are the foundation for the replacement of tooth structure.

Form and function are important considerations in the replacement of lost tooth structure. Although tooth form and appearance are aspects most easily recognized, the function of the teeth and supporting tissues contributes greatly to the quality of life. The links between oral and general health are well known. Proper function of the elements of the oral cavity, including the teeth and soft tissues, is needed for eating, speaking, swallowing, proper breathing, and smiling.

Restorative dental materials make the reconstruction of the dental hard tissues possible. In many areas, the development of dental materials has progressed more rapidly than for other anatomical prostheses. Because of their long-term success, patients often expect dental prostheses to outperform the natural materials and structures they replace. The application of materials science is unique in dentistry because of the complexity of the oral cavity, which includes bacteria, high forces, ever-changing pH, and a warm, fluid environment. The oral cavity is considered to be the harshest environment for a material in the body. In addition, when dental materials are placed directly into tooth cavities as restorative materials, there are very specific requirements for manipulation of the material. Knowledge of materials science and biomechanics is very important when choosing materials for specific dental applications and when designing the best solution for restoration of tooth structure and replacement of teeth.

A review of the history of dentistry may be found on the book's website at http://evolve.elsevier.com/sakaguchi/restorative.

Scope of Materials Covered in Restorative Dentistry

Restorative dental materials include representatives from the broad classes of materials: metals, polymers, ceramics, and composites. Dental materials include such items as resin composites, ceramics, cement, glass ionomers, metals, gypsum materials, impression materials, denture base resins, casting investments, dental amalgams, and other materials used in restorative procedures. The requirements for material characteristics and performance range from high flexibility required by impression materials to high stiffness required in crowns and fixed dental prostheses. Materials for dental implants require integration with bone. Some materials are cast to achieve excellent adaptation to existing tooth structures, whereas others are machined under digital control to produce very reproducible dimensions and structured geometries. When describing these materials, physical and chemical characteristics are often used as criteria for comparison. To understand how a material works, we study its chemical structure, its physical and mechanical characteristics, and its manipulation to result in the best performance.

Most restorative materials are characterized by physical, chemical, and mechanical parameters that are derived from test data. Improvements in these characteristics might be shown in laboratory studies, but the real test is the material's performance in function in the mouth and the ability of the material to be manipulated properly by the dental team. In many cases, errors and variations in handling and manipulation can negate the improvements in physical, chemical, and mechanical properties. Therefore it is very important for the dental team to understand how to manipulate dental materials appropriately.

A Systems Approach to Restorative Materials

The practice of clinical dentistry requires a complete understanding of the various clinical techniques and a solid foundation of knowledge of the biological, chemical, and physical principles of human anatomy and function. It is important to understand the "how" and "why" associated with the function of natural and synthetic dental materials. The best patient outcomes will be achieved when a systems approach is used to assess the chemical, physical, and mechanical aspects of dental materials and oral function, together with the physiological, structural, and other biological properties of the tissues that support the restorative and

rehabilitative constructs. This integrative approach, when combined with the best available scientific evidence, clinician experience, patient preferences, and patient modifiers, results in the best patient-centered care.

Application of Various Sciences

In the chapters that follow, fundamental characteristics of materials are presented, along with numerous practical examples of how the basic principles relate to clinical applications. Test procedures and fabrication techniques are discussed briefly but not emphasized. Many of the details of manipulation are found on the book's website at http://evolve.elsevier.com/sakaguchi/restorative.

Knowledge and application of fundamental principles of materials and mechanics are essential for the design and optimal prognosis of restorations. For example, the prognosis of long-span fixed dental prostheses, or bridges, is dependent on the stiffness and fracture resistance of the materials. When considering aesthetics, the hardness of the material is an important property because it influences the ability to polish the material. Some materials release fluoride when exposed to saliva, which might be beneficial in high-caries-risk patients. When selecting a ceramic for CAD-CAM fabrication of an all-ceramic crown, the machining and wear characteristics of the ceramic are important. For implants, surface texture, coating, and geometry are critical considerations for bone and soft tissue adaptation. These are just a few examples of the many interactions between the clinical performance of dental materials and fundamental scientific principles.

Future Developments in Biomaterials

The 2021 Global Burden of Disease Study reported that among the 371 diseases and injuries assessed, oral disorders were the most prevalent Level 3 diseases: dental caries in permanent teeth (#1), periodontal diseases (#8), dental caries in deciduous teeth (#14), and edentulism (#20) (GBD 2021 Diseases and Injuries Collaborators 2021). These oral diseases and conditions affect about 3.69 billion people worldwide.

In the United States, about 50% of adults aged 20 to 64 have lost at least one permanent tooth to an accident, periodontal disease, a failed root canal, or tooth decay. In adults aged 65 and older, 13% have lost all of their natural teeth. That number is twice as large for adults aged 75 and over (18%) than for adults aged 65 to 74 (9%) (CDC/NCHS, National Health and Nutrition Examination Survey). For children aged 5 to 19 years, 13% have untreated dental caries. For adults aged 20 to 44, that number is 26%.

The demand for restorative care continues to be high, although there are many inequities in the dental care available to and utilized by marginalized populations. For some populations, there has been a shift from removable prostheses to implant-supported, fixed prostheses. For single-tooth loss, implants enable restoration of single crowns rather than multiunit, longer-span restorations. Research into implant coatings, surface textures, graded properties, alternative materials, and new geometries will continue to grow. These advances will improve the viability of implants, with enhancements to bone and soft tissue health.

Dental and orofacial aesthetics will continue to be a focus for some consumers, which will promote the development and sales of tooth-whitening systems, Botox, and aesthetic restorations. A more natural-looking appearance with character is preferred by many over a uniform, dazzling white dentition, which was the trend of the last decade. There will be more demand for materials that mimic natural dentition and provide the same depth of color and optical characteristics as natural teeth.

With the aging of the population, exposed root surfaces, dry mouth, and worn dentitions will be more common. These are challenging conditions to restore, and materials will need to function in an environment with reduced salivary flow and atypical salivary pH and chemistry. This population will be managing multiple chronic illnesses with many medications and will have limitations in maintaining adequate oral home care. Restorative materials will be challenged in this difficult environment.

Advances in tissue regeneration are accelerating. Our understanding of the oral microbiome is expanding. Biofabrication and 3D bioprinting methods are creating new and more natural structures and materials. This is a very exciting time for materials research, and clinicians will have much to look forward to in the near future as this body of research develops new materials for expanded clinical applications.

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2

The Oral Environment

JUSTIN MERRITT

CHAPTER OUTLINE

The tooth contains three specialized calcified tissues: enamel, dentin, and cementum (Fig. 2.1). Enamel is unique in that it is the most highly calcified tissue in the body and contains the least organic content of any of these tissues. Enamel provides the hard outer covering of the crown that allows efficient mastication. Dentin and cementum, like bone, are vital, hydrated, biological composite structures formed mainly of a collagen type I matrix reinforced with the calcium phosphate mineral called *apatite*. Dentin forms the bulk of the tooth and is joined to the enamel at the dentin–enamel junction (DEJ). The dentin of the tooth root is covered by cementum, which provides a connection of the tooth to the alveolar bone via the periodontal ligament. Although the structure of these tissues is often described in dental texts, their properties are often discussed only superficially. However, these properties are important with regard to the interrelationships of the factors that contribute to the performance necessary for the optimum function of these tissues.

In restorative dentistry, we are interested in providing preventive treatments that will maintain tissue integrity and replace damaged tissues with materials that ideally mimic the natural appearance and performance of those tissues when necessary. Thus knowledge of the structure and properties of these tissues is desirable both as a yardstick to measure the properties and performance of restorative materials and as a guide to the development of materials that will mimic their structure and function. In addition, many applications, such as dental bonding, require us to attach synthetic materials to the calcified tissues, and these procedures rely on detailed knowledge of the composition, structure, and properties of the adhesive tissue substrates.

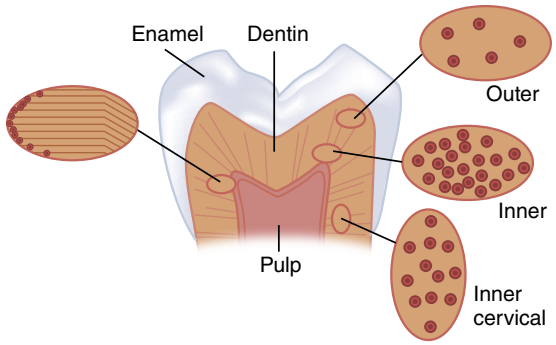
Enamel

Fig. 2.1 shows a schematic diagram of a posterior tooth sectioned to reveal the enamel and dentin components. Enamel forms the hard outer shell of the crown and, as the most highly calcified tissue, is well suited to resisting wear due to mastication.

Enamel is formed by ameloblasts starting at the DEJ and proceeding outward to the tooth surface. The ameloblasts exchange signals with odontoblasts located on the other side of the DEJ at the start of the enamel and dentin formation, and the odontoblasts move inward from the DEJ as the ameloblasts move outward to form the enamel of the crown. Most of the enamel organic matrix, which is composed of amelogenins and enamelins, is resorbed during tooth maturation to leave a calcified tissue that is largely composed of minerals and a sparse organic matrix. The structural arrangement of enamel forms keyhole-shaped structures known as *enamel prisms* or *rods* that are about 5 µm across, as seen in Fig. 2.2.

The overall composition of enamel is about 96% mineral by weight, with 1% lipid and protein and the remainder being water. The organic portion and water probably play important roles in tooth function and pathology, and it is often more useful to describe the composition on a volume basis. On that basis, we see that organic components make up about 3% and water 12% of the structure. The mineral is formed and grows into very long crystals of hexagonal shape about 40 nm across; these crystals have yet to be synthetically duplicated. There is some evidence that the crystals may span the entire enamel thickness, but this is difficult to prove because most preparation procedures lead to fracture of the individual crystallites. It appears that they are at least thousands of nanometers long. If this is true, then enamel crystals provide an extraordinary "aspect" ratio (length-to-width ratio) for a nanoscale material, and they are very different from the much smaller dentin crystals. The crystals are packed into enamel prisms or rods that are about 5 µm across, as shown in Fig. 2.2. These prisms are revealed easily by acid etching, extending in a closely packed array from the DEJ to the enamel surface and lying roughly perpendicular to the DEJ, except in cuspal areas where the rods twist and cross, known as *decussation*, which may increase fracture resistance. About 100 crystals of the mineral are needed to span the diameter of a prism, and the long axes of the crystals tend to align themselves along the prism axes, as seen in Fig. 2.2.

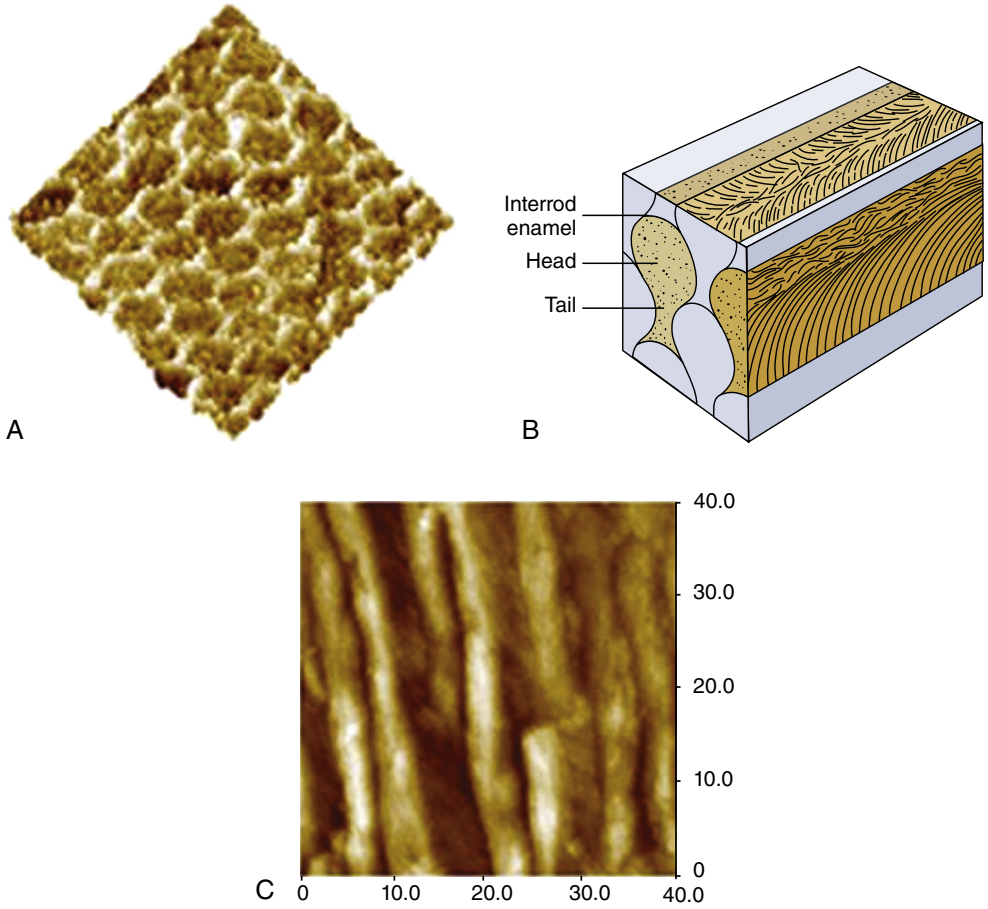
The crystals near the periphery of each prism deviate somewhat from the long axis toward the interface between prisms. The deviation in the tail of the prism is even greater. The individual crystals



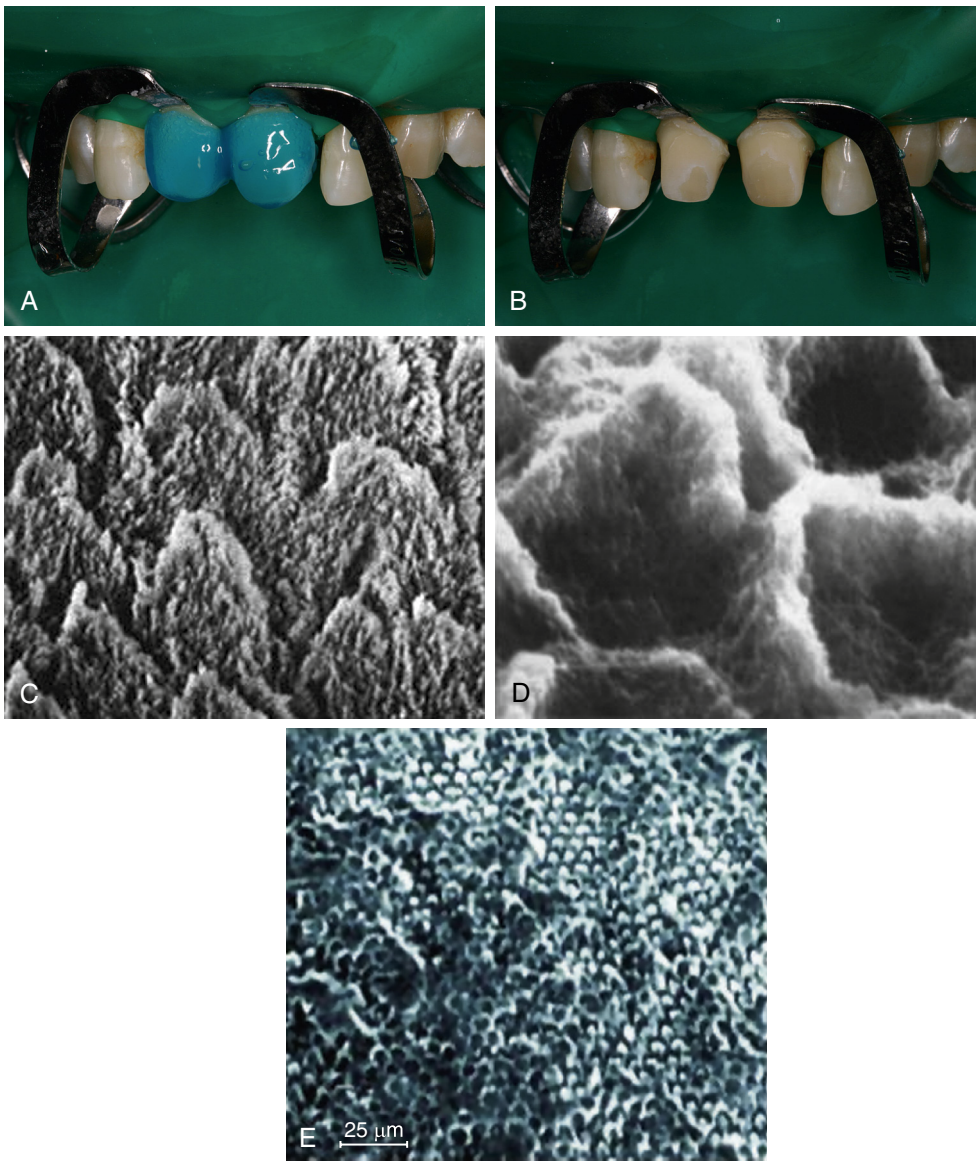
• **Fig. 2.1** Schematic diagram of a tooth cut longitudinally to expose the enamel, dentin, and the pulp chamber. On the *right* side are illustrations of dentin tubules as viewed from the top, which show the variation in the tubule number with location. On the *left* is an illustration of the change in direction of the primary dentin tubules as secondary dentin is formed. (From Marshall SJ, Balooch M, Breunig T, et al. Human dentin and the dentin-resin adhesive interface. *Acta Mater*. 1998;46:2529–2539).

within a prism are also coated with a thin layer of lipid and/or protein that plays important roles in mineralization, although much remains to be learned about the details. Recent work suggests that this protein coat may lead to increased toughness of the enamel. The interfaces between prisms, or interrod enamel, contain the main organic components of the structure and act as passageways for water and ionic movement. These areas, also known as *prism sheaths*, are of vital importance in etching processes associated with bonding and other demineralization processes, such as caries.

Etching of enamel with acids such as phosphoric acid, commonly used in enamel bonding, eliminates smear layers associated with cavity preparation, dissolves persisting layers of prismless enamel in deciduous teeth, and differentially dissolves enamel crystals in each prism. The pattern of etched enamel is categorized as type 1 (preferential prism core etching; Fig. 2.2A), type 2 (preferential prism periphery etching; Fig. 2.3C), and type 3 (mixed or uniform). Sometimes these patterns appear side by side on the same tooth surface (Fig. 2.3E). No differences in micromechanical bond strength of the different etching patterns have been established. In a standard cavity preparation for a composite, the orientation of the enamel surfaces being etched could be perpendicular to enamel prisms (perimeter of the cavity outline), oblique, cross section of the prisms (beveled occlusal or proximal margins), and axial walls of the prisms (cavity preparation walls). During the early stages of etching, when only a small amount of enamel crystal dissolution occurs, it may be difficult or impossible to detect the extent of the process. However, as the etching pattern begins to develop, the surface etched with phosphoric acid develops a frosty appearance (Fig. 2.3B), which has been used as the



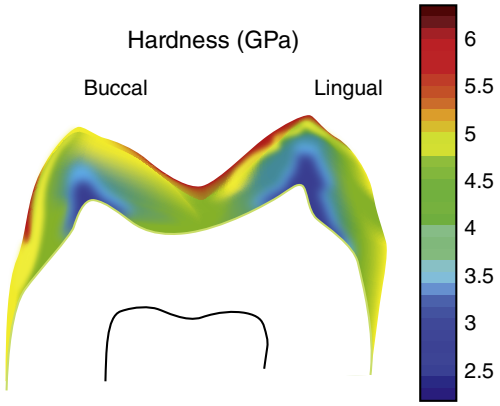
• **Fig. 2.2** Enamel microstructure. (A) Atomic force microscopy images showing prism cross sections. (B) Schematic diagram of keyhole-shaped enamel prisms or rods about 5 μm in diameter. (C) Atomic force microscopy images showing the axes of the prisms. Crystallite orientation deviates in the interrod and tail area and the organic content increases in the interrod area. (Modified from Habelitz S, Marshall SJ, Marshall GW, et al. Mechanical properties of human dental enamel on the nanometer scale. *Arch Oral Biol*. 2001;46:173–183.)



• **Fig. 2.3** Etching enamel. (A) Gel etchant dispensed on the enamel portion of the preparation. (B) Frosty appearance after etching, rinsing, and drying. (C) Magnified view of etch pattern with preferential prism periphery etch (type 1). (D) Bonding agent revealed after dissolving enamel. (E) Mixed etch patterns showing type 1 (light prisms with dark periphery) and type 2 (dark cores with light periphery) etching on the same surface. (C and D, After Marshall GW, Olson LM, Lee CV. SEM Investigation of the variability of enamel surfaces after simulated clinical acid etching for pit and fissure sealants. *J Dent Res*. 1975;54:1222–1231; E, After Marshall GW, Olson LM, Lee CV. SEM investigation of the variability of enamel surfaces after simulated clinical acid etching for pit and fissure sealants. *J Dent Res*. 1975;54:1222–1231; E, from Marshall GW, Marshall SJ, Bayne SC. Restorative dental materials: scanning electron microscopy and x-ray microanalysis. *Scanning Microsc*. 1988;2:2007–2028.)

traditional clinical indicator for sufficient etching. This roughened surface provides the substrate for infiltration of bonding agents that can be polymerized after penetration of the etched enamel structure so that they form micromechanical bonds to the enamel when polymerized. With weaker acids in most self-etching bonding agents, this frosty appearance typically cannot be detected.

There are two other important structural variations of enamel. Near the DEJ, the enamel prism structure is not as well developed in the very first enamel formed, so that the enamel very close to the DEJ may appear aprismatic or without the prism-like structure. Similarly, at the completion of the enamel surface, the ameloblasts degenerate and leave a featureless layer called *prismless enamel* on the outer surface of the crown. This layer is more often observed in deciduous teeth and is often worn off in permanent teeth. However, if present, this causes some difficulty in creating an effective etching pattern and may require roughening of the surface or additional etching treatments. The outer surface of the enamel is of great clinical significance because it is the surface subjected to daily wear and undergoes repeated cycles of demineralization and remineralization. As a result of these cycles, the composition of the enamel crystals may change, for example, as a result of exposure to fluoride. Thus the properties of the enamel might be expected



• **Fig. 2.4** Nanoindentation mapping of the mechanical properties of human molar tooth enamel. (From Cuy JL, Mann AB, Livi KJ, et al. Nanoindentation mapping of the mechanical properties of human molar tooth enamel. *Arch Oral Biol*. 2002;47(4):281–291.)

to vary from the external to the internal surface. Such variations, including a thin surface veneer of fluoride-rich apatite crystals, create differences in the enamel properties within the enamel. Enamel is usually harder at the occlusal and cuspal areas and less hard nearer the DEJ. Fig. 2.4 shows an example of the difference in hardness.

The Mineral

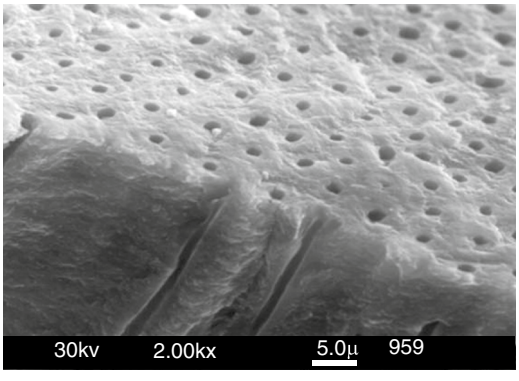
The mineral of all calcified tissues is a highly defective relative of the mineral hydroxyapatite (HA). The biological apatites of calcified tissues are different from the ideal HA structure in that the defects and chemical substitutions generally make them weaker and more soluble in acids. HA has the simple formula $Ca_{10}(PO_4)_6(OH)_2$, with an ideal molar ratio of calcium to phosphorus (Ca/P) of 1.67 and a hexagonal crystal structure. The apatite of enamel and dentin has a much more variable composition that depends on its formative history and other chemical exposures during maturity. Thus the mineral in enamel and dentin is a calcium-deficient, carbonate-rich, and highly substituted form related to HA. Metal ions such as magnesium (Mg) and sodium (Na) may substitute for calcium, whereas carbonate substitutes for the phosphate and hydroxyl groups. These substitutions distort the structure and make it more soluble. Perhaps the most beneficial substitution is the fluorine (F) ion, which substitutes for the hydroxyl group (OH) in the formula and makes the structure stronger and less soluble. Complete substitution of F for (OH) in HA yields fluorapatite mineral, $Ca_{10}(PO_4)_6(F)_2$, which is much less soluble than HA or the defective apatite of calcified tissues. It is worth noting that HA has attracted considerable attention as an implantable calcified tissue replacement. It has the advantage of being a purified and stronger form of the natural mineral and releases no harmful agents during biological degradation. Its major shortcoming is that it is extremely brittle and sensitive to porosity or defects, and therefore it fractures easily in load-bearing applications.

The approximate carbonate contents of the enamel and dentin apatites are significantly different, about 3% and 5% carbonate, respectively. In addition, the dentin apatite crystals are much smaller than the enamel crystals. This means that the dentin crystals present a higher surface area for attacking acids, and contain many more defects per unit volume, and thus exhibit considerably higher solubility than enamel crystals. Finally, as discussed further in the following section, the dentin mineral occupies only about 50% of the dentin structure, so there is not as much apatite in the dentin as there is in the enamel. All of these factors multiply the susceptibility of dentin to acid attack and provide insight into the rapid spread of caries when it penetrates the DEJ.

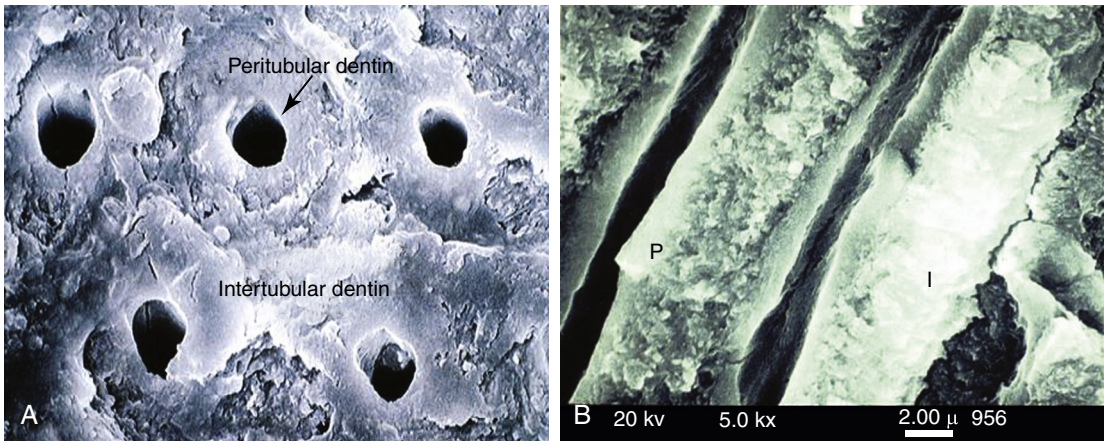
Dentin

Dentin is a complex, hydrated biological composite structure that forms the bulk of the tooth. Furthermore, dentin is modified by physiological, aging, and disease processes that result in different forms of dentin. These altered forms of dentin may be the precise forms that are most important in restorative dentistry. Some of the recognized variations include primary, secondary, reparative or tertiary, sclerotic, transparent, carious, demineralized, remineralized, and hypermineralized. These terms reflect alterations in the fundamental components of the structure as defined by changes in their arrangement, interrelationships, or chemistry. A number of these may have important implications for our ability to develop long-lasting adhesion or bonds to dentin.

Primary dentin is formed during tooth development. Its volume and conformation, reflecting tooth form, vary with the size and shape of the tooth. Dentin is composed of about 50 volume percent (vol%) carbonate-rich, calcium-deficient apatite; 30 vol% organic matter, which is largely type I collagen; and about 20 vol% fluid, which is similar to plasma. Other noncollagenous proteins are thought to be involved in dentin mineralization and other functions, such as controlling crystallite size and orientation. The role of noncollagenous proteins in biomineralization, or simpler molecules that can mimic some of their functions, may lead to dentin remineralization methods, and is the subject of ongoing research efforts. The major components are distributed into distinctive morphological features to form a vital and complex hydrated composite in which the morphology varies with location and undergoes alterations with age or disease. The tubules, one distinct and important feature of dentin, represent the tracks taken by the odontoblastic cells from the DEJ or cementum at the root to the pulp chamber and appear as tunnels piercing the dentin structure (Fig. 2.5). The tubules converge on



• **Fig. 2.5** Scanning electron microscopy image of normal dentin showing its unique structure as seen from two directions. At the *top* is a view of the tubules, each of which is surrounded by peritubular dentin. Tubules lie between the dentin–enamel junction and converge on the pulp chamber. The perpendicular surface at the bottom shows a fracture surface revealing some of the tubules as they form tunnel-like pathways toward the pulp. The tubule lumen normally contains fluid and processes of the odontoblastic cells. (From Marshall GW. Dentin: microstructure and characterization. *Quintessence Int*. 1993;24:606–617.)



• **Fig. 2.6** Fracture surface of the dentin. (A) Viewed from the occlusal direction. (B) Viewed longitudinally. Peritubular (*P*; also called *intratubular*) dentin forms a cuff or lining around each tubule. The tubules are separated by intertubular dentin *(I)*. (Courtesy G.W. Marshall.)

the pulp chamber, and therefore tubule density and orientation vary from location to location (see Fig. 2.1). Tubule number density is lowest at the DEJ and highest at the predentin surface at the junction to the pulp chamber, where the odontoblastic cell bodies lie in a closely packed array. Lower tubule densities are found in the root. The contents of the tubules include odontoblast processes as well as fluid. The extent of the odontoblast process is still uncertain, but evidence is mounting that it extends all the way to the DEJ. For most of its course, the tubule lumen is lined by a highly mineralized cuff of peritubular dentin approximately 0.5 to 1 µm thick (Fig. 2.6). Because the peritubular dentin forms after the tubule lumen has formed, some argue that it may be more properly termed *intratubular dentin*, and it contains mostly apatite crystals with little organic matrix. A number of studies have concluded that the peritubular dentin does not contain collagen, and therefore might be considered a separate calcified tissue. The tubules are separated by intertubular dentin composed of a matrix of type I collagen reinforced by apatite (see Figs. 2.5 and 2.6). This arrangement means that the amount of intertubular dentin varies with location. The apatite crystals are much smaller (approximately 5 × 30 × 100 nm) than the apatite found in enamel and contain about 5% carbonate. The small crystallite size, heterogeneous structure, and higher carbonate content lead to the greater dissolution susceptibility, as described earlier.

Estimates of the size of tubules, the thickness of the peritubular region, and the amount of intertubular dentin have been reported in a number of studies. Calculations for occlusal dentin as a function of position from these data show that the percentage tubule area and diameter vary from about 22% and 2.5 µm near the pulp to 1% and 0.8 µm at the DEJ, respectively. Intertubular matrix area varies from 12% at the predentin to 96% near the DEJ, whereas peritubular dentin ranges from over 60% down to 3% at the DEJ. Tubule densities are compared in Table 2.1 based on work by various investigators. It is clear that the structural components will vary considerably over their course and necessarily result in location-dependent variations in morphology, distribution of the structural elements, and other important properties, such as permeability, moisture content, and available surface area for bonding. They may also affect bond strength, hardness, and other properties.

Because the odontoblasts come to rest just inside the dentin and line the walls of the pulp chamber after tooth formation, the dentin–pulp complex can be considered a vital tissue. This is different from mature enamel, which is acellular. Over time, secondary dentin forms, and the pulp chamber gradually becomes smaller. The border between primary and secondary dentin is usually marked by a change in orientation of the dentin tubules. Furthermore, the odontoblasts react to form tertiary dentin in response to insults, such as caries or tooth preparation, and this form of dentin is often less well organized than the primary or secondary dentin.

TABLE 2.1 Comparison of Mean Numerical Density of Tubules in Occlusal Dentin

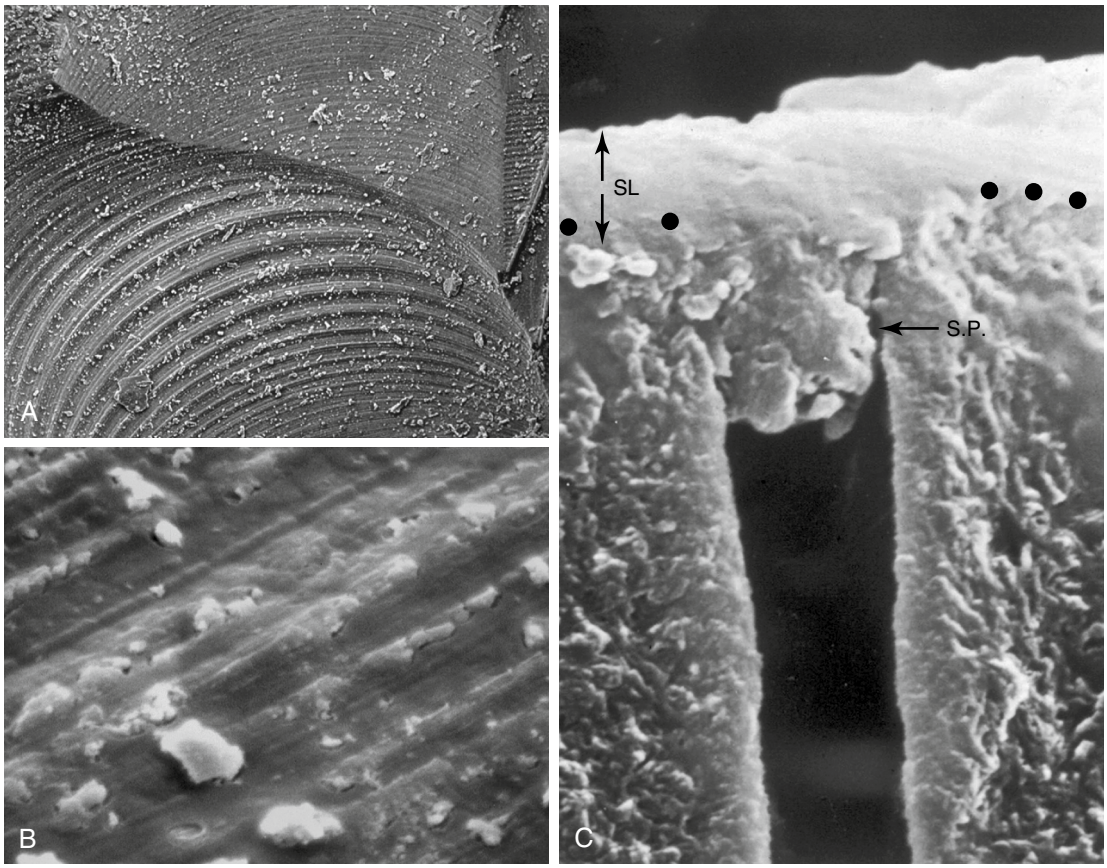
Outer Dentin	Middle Dentin	Inner Dentin
15,000/mm²	35,000/mm²	65,000/mm²
20,000/mm²	35,000/mm²	43,000/mm²
24,500/mm²	40,400/mm²	51,100/mm²
18,000/mm²	39,000/mm²	52,000/mm²

From data reported in Marshall GW. Dentin: microstructure and characterization. *Quintessence Int.* 1993;24:606–617.

Early enamel carious lesions may be reversed by remineralization treatments. However, effective remineralization treatments are not yet available for dentin, and therefore the current standard of care dictates surgical intervention to remove highly damaged tissue with subsequent restoration as needed. Thus it is important to understand altered forms of dentin and the effects of such clinical interventions.

When dentin is cut or abraded by dental instruments, a smear layer develops and covers the surface, obscuring the underlying structure (Fig. 2.7). The bur cutting marks are shown in Fig. 2.7A and at higher magnification in Fig. 2.7B. Fig. 2.7C shows the smear layer thickness from the side and the development of smear plugs as the cut dentin debris is pushed into the dentin tubule lumen. The advantages and disadvantages of the smear layer have been extensively discussed for several decades. It reduces permeability and therefore aids in maintaining a drier field, and it reduces infiltration of noxious agents into the tubules and perhaps the pulp. However, it is now generally accepted that it is a hindrance to dentin bonding procedures and therefore is normally removed or modified by some form of acid conditioning.

Acid etching or conditioning allows for the removal of the smear layer and alteration of the superficial dentin, opening



• **Fig. 2.7** Smear layer formation. (A) Bur marks on dentin preparation. (B) Higher magnification showing smear layer surface and cutting debris. (C) Section showing smear layer *(SL)* and smear plugs *(SP).* (A and B, from Marshall GW, Marshall SJ, Bayne SC. Restorative dental materials: scanning electron microscopy and x-ray microanalysis. *Scanning Microsc*. 1988;2:2007–2028; C, from Pashley DH, Tao L, Boyd L, et al. Scanning electron microscopy of the substructure of smear layers in human dentine. *Arch Oral Biol*. 1988;33(4):265–270.)

channels for infiltration by bonding agents. Fig. 2.8 shows what happens in such an etching treatment. The tubule lumens widen as the peritubular dentin is preferentially removed because it is mostly mineral with sparse protein. The widened lumens form a funnel shape that is not very retentive.

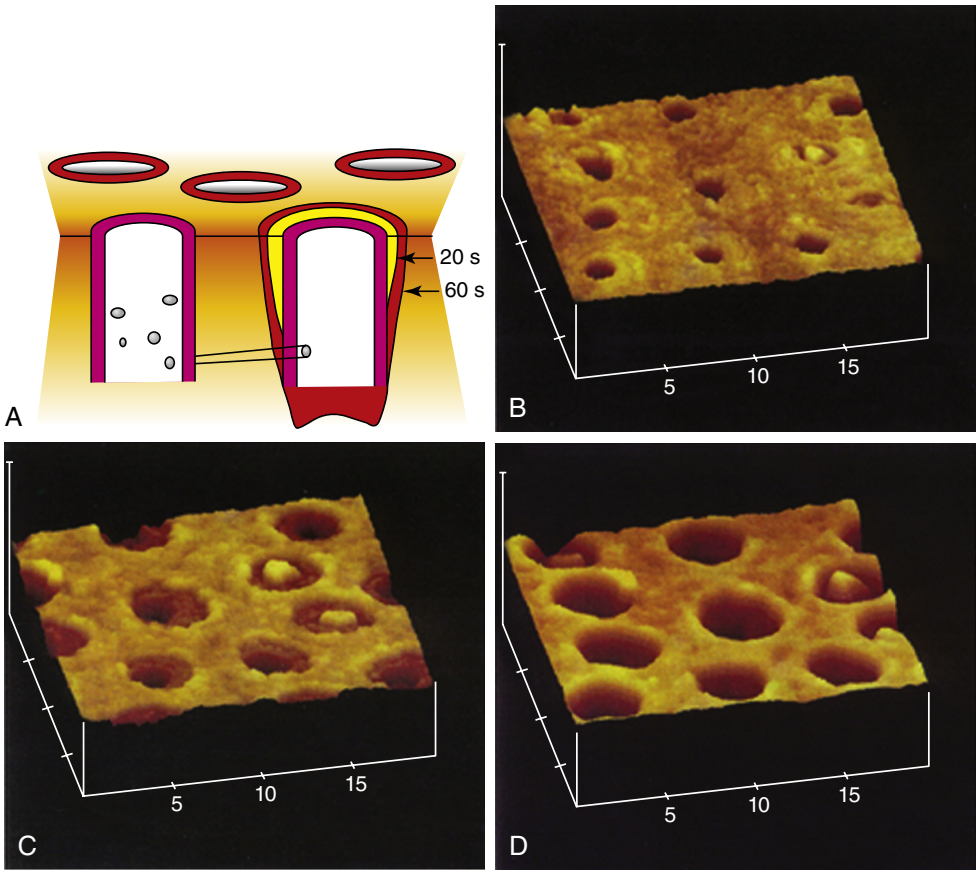
Fig. 2.9 shows these effects in a slightly different way. Unetched dentin in Fig. 2.9A *(top)* has small tubules and peritubular dentin, which is removed from the treated dentin at the exposed surface after etching *(bottom).* The two-dimensional network of collagen type I fibers is shown after treatment in Fig. 2.9A. Fig. 2.9B shows progressive demineralization of a dentin collagen fibril in which the external minerals and proteins are slowly removed to reveal the typical banded pattern of type I collagen. In Fig. 2.9C, this pattern is seen at high magnification of the treated dentin shown in Fig. 2.9A.

If the demineralized dentin is dried, the remaining dentin matrix shrinks, and the collagen fibrils become matted and difficult to penetrate by the liquid bonding agents used in restorative procedures. This is shown in Fig. 2.10, which compares demineralized and dried dentin with demineralized and hydrated dentin.

Most restorative procedures involve dentin that has been altered in some way. Common alterations include formation of carious lesions that form various zones and include transparent dentin that forms under the caries-infected dentin layer. Transparent dentin results when the dentin tubules become filled with minerals, which changes the refractive index of the tubules and produces a translucent or transparent zone.

Fig. 2.11 shows a section through a tooth with a carious lesion, which has been stained to reveal its zones. The gray zone under the stained and severely demineralized dentin is the transparent layer (Fig. 2.11A). Fig. 2.11B shows the transparent dentin in which most of the tubule lumens are filled with minerals. After etching, as shown in Fig. 2.11C, the peritubular dentin is etched away, but the tubules retain plugs of the precipitated mineral, which is more resistant to etching. This resistance to etching makes bonding more difficult.

Several other forms of transparent dentin are formed as a result of different processes. A second form of transparent dentin results from bruxism. An additional form of transparent dentin results from aging as the root dentin gradually becomes transparent. In addition, noncarious cervical lesions, often called *abfraction* or *notch* lesions, form at the enamel–cementum or enamel–dentin junction, usually on facial or buccal surfaces. Their etiology is not clear at this point; their formation has been attributed to abrasion, tooth flexure, and erosion, and most likely some combination of these processes. Nonetheless, these lesions occur with increasing frequency with age, and the exposed dentin becomes transparent as the tubules are filled. Fig. 2.12 shows examples of transparent dentin in which the tubule lumens are completely filled.



• **Fig. 2.8** Stages of dentin demineralization. (A) Schematic showing progressive stages of dentin demineralization. (B–D) Atomic force microscopy images showing stages of etching. The etching leads to wider lumens once the peritubular dentin is dissolved and funnel-shaped openings are formed. (B–D, from Marshall GW. Dentin: microstructure and characterization. *Quintessence Int*. 1993;24:606–617.)

The properties of the transparent dentin may differ from one to another depending on the processes that lead to the deposit of the mineral in the tubules. Several studies have shown that elastic properties of the intertubular dentin are not altered by aging, although the structure may become more susceptible to fracture. Similarly, arrested caries will contain transparent dentin, which has often been called *sclerotic dentin*, a term that implies it may be harder than normal dentin. However, other studies have shown that the elastic properties of the intertubular dentin may actually be unaltered or lower than normal dentin.

Physical and Mechanical Properties

The marked variations in the structural elements of dentin when located within the tooth imply that the properties of dentin will vary considerably with location. That is, variable structure leads to variable properties.

Because one major function of tooth structure is to resist deformation without fracture, it is useful to have knowledge of the forces that are experienced by teeth during mastication. Measurements have given values on cusp tips of about 77 kg distributed over the cusp tip area of 0.039 cm^2, suggesting a stress of about 200 MPa.

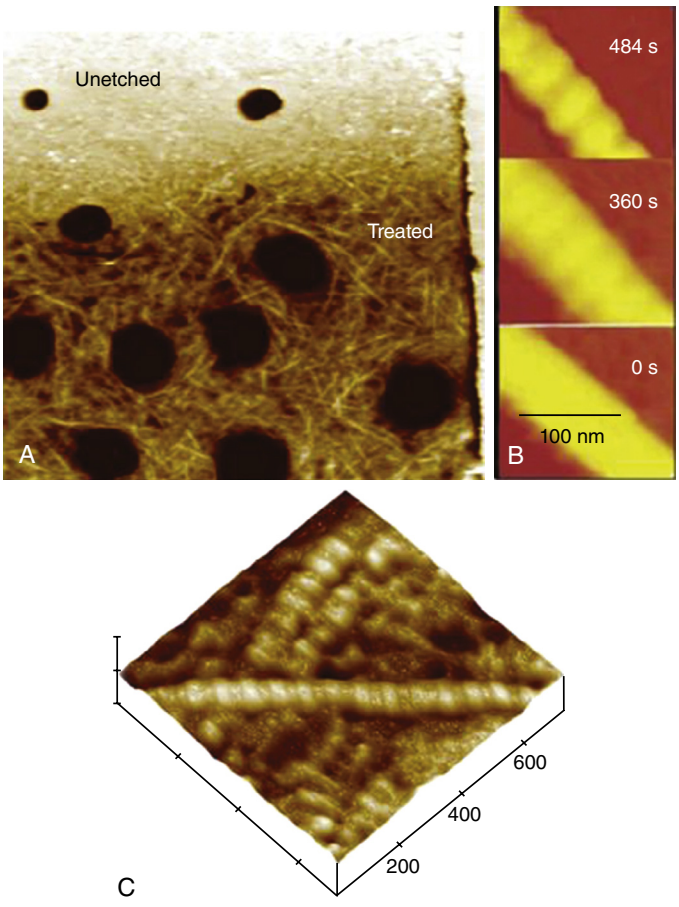
Difficulties in Testing

In Table 2.2, values are presented for some important properties of enamel and dentin. The wide spread of values reported in the literature is remarkable. Some of the reasons for these discrepancies should be appreciated and considered in practice or when reading the literature.

First, human teeth are small, which can create difficulties in obtaining and holding specimens for standard mechanical tests, such as tensile, compressive, or shear tests. When testing bonded teeth, the problem is even more complicated, and special tests have been developed to obtain insights into these properties. From the previous discussion of structural variations, it is also evident that testing such small heterogeneous specimens can lead to high variability.

Another problem is the great variation in structure in both tissues. Enamel prisms are aligned generally perpendicular to the DEJ, whereas dentin tubules change their number density with depth as they course toward the pulp chamber. Consequently, it can be challenging to prepare a uniform sample for testing with the structures running all in one direction. In addition, properties generally vary with direction and location, and the material is not isotropic; therefore a single value can only reveal an average value for the material at best.

Storage and time elapsed since extraction are also important considerations. Properties that exist in situ are of greatest interest. Clearly, this condition is almost impossible to achieve in most routine testing, so changes that have occurred as a result of storage conditions prior to testing must be considered. It is also important to consider biological hazards because extracted teeth must be treated as potentially infectious. How does one sterilize the teeth



• **Fig. 2.9** Etching of dentin removes mineral from the intertubular dentin matrix leaving a collagen-rich layer and widening the dentin tubule orifices. (A) After etching, the tubule lumens are enlarged and the collagen network surrounding the tubules can be seen after further treatment. (B) Isolated dentin collagen fiber is slowly demineralized revealing the typical 67-nm repeat pattern of type I collagen. (C) High-magnification view of collagen fibers is shown in (A). (A and C, from Marshall GW, Yucel N, Balooch M, et al. Sodium hypochlorite alterations of dentin and dentin collagen. *Surf Sci*. 2001;491:444–455; B, modified from Balooch M, Habelitz S, Kinney JH, et al. Mechanical properties of mineralized collagen fibrils as influenced by demineralization. *J Struct Biol*. 2008;162:404–410.)

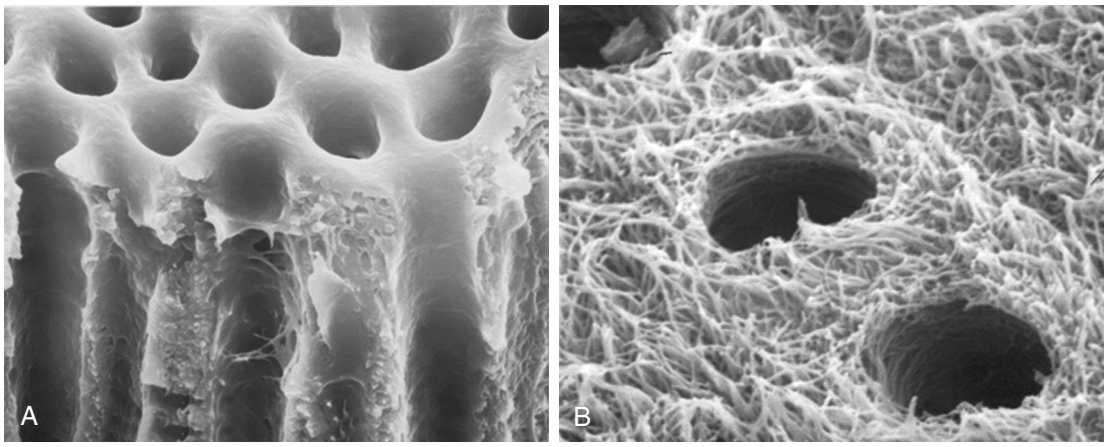
without altering their properties? The high heat used in autoclaving undoubtedly denatures proteins within teeth and is therefore highly inappropriate for dentin. It might impact enamel as well.

Finally, the fluid content of these tissues must be considered. Moisture is a vital component of both tissues and in vivo conditions cannot be replicated if the tissues have been desiccated (see Fig. 2.10). This becomes a critically important consideration when bonding to these tissues, as is discussed further in Chapter 7. In contrast to the importance of this issue, there is the issue of convenience. It is much more difficult to test the tissues in a fully hydrated condition than in a dry condition. All of these factors and a number of others, such as testing temperature, will influence the results and contribute to a spread in the values reported for the measured properties.

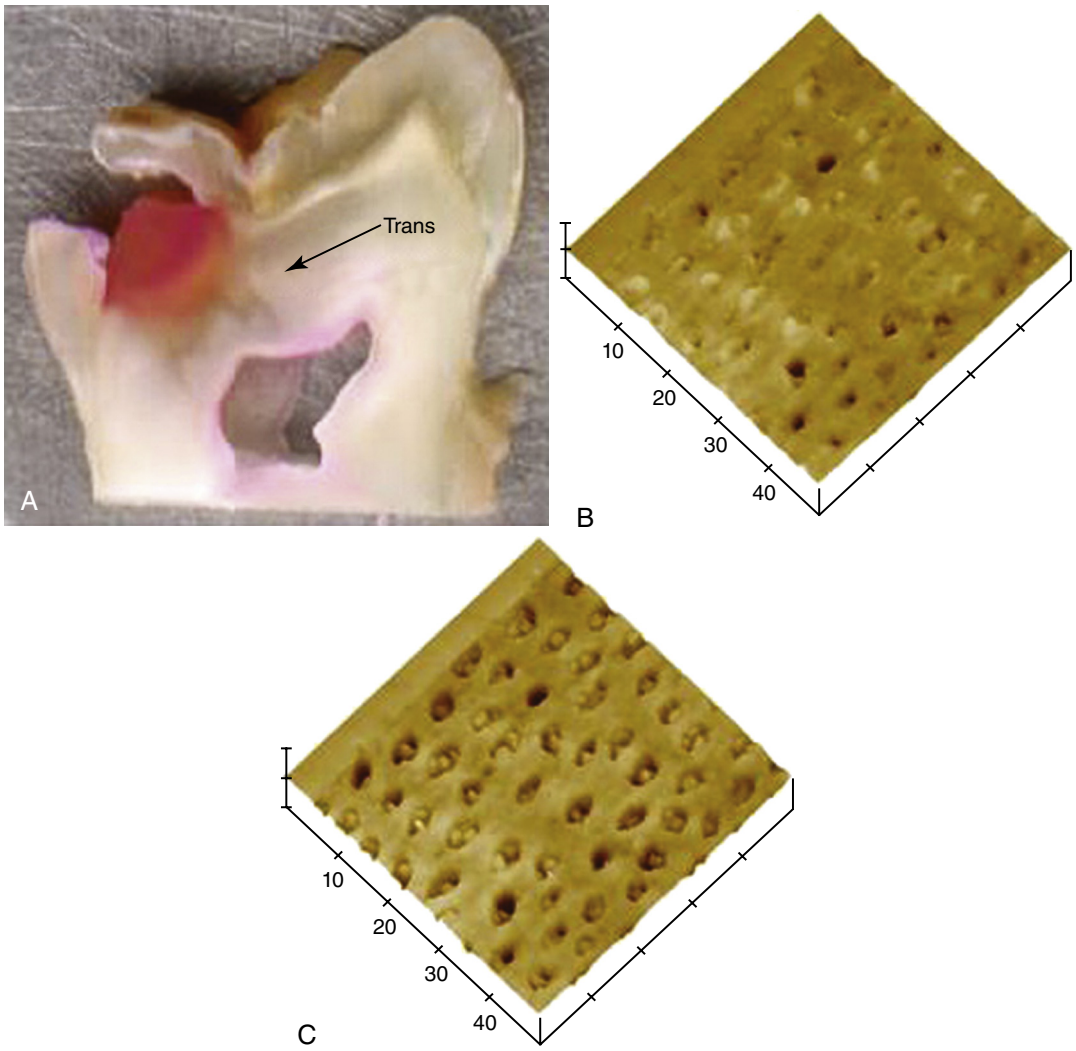
Despite these limitations, some generalizations about the properties of these tissues are useful (see Table 2.1). Root dentin is generally weaker and softer than coronal dentin. Enamel also appears to vary in its properties, with cuspal enamel being stronger and harder than other areas, presumably as an adaptation to masticatory forces. Dentin is less stiff than enamel (i.e., it has a lower elastic modulus) but has higher fracture toughness. This may be counterintuitive, but it will become clearer when these terms are defined in Chapter 4. In addition, dentin is viscoelastic, meaning its mechanical deformation characteristics are time dependent, and its elastic recovery is not instantaneous. Thus dentin may be sensitive to how rapidly it is deformed or strained, a phenomenon called *strain rate sensitivity*. Strain rate sensitivity is characteristic of polymeric materials; the collagen matrix imparts this property to tissues such as dentin. Under normal circumstances, ceramic materials do not exhibit this characteristic in their mechanical properties and are typically stiff, brittle, and fracture elastically (i.e., without permanent deformation). Pure HA shows this typical brittle characteristic, but when formed in enamel, it exhibits greater toughness (see Chapter 4), though it remains slightly less tough than dentin. This higher toughness of enamel versus pure HA is associated with the microstructure and the small protein component of enamel.

The Dentin–Enamel Junction

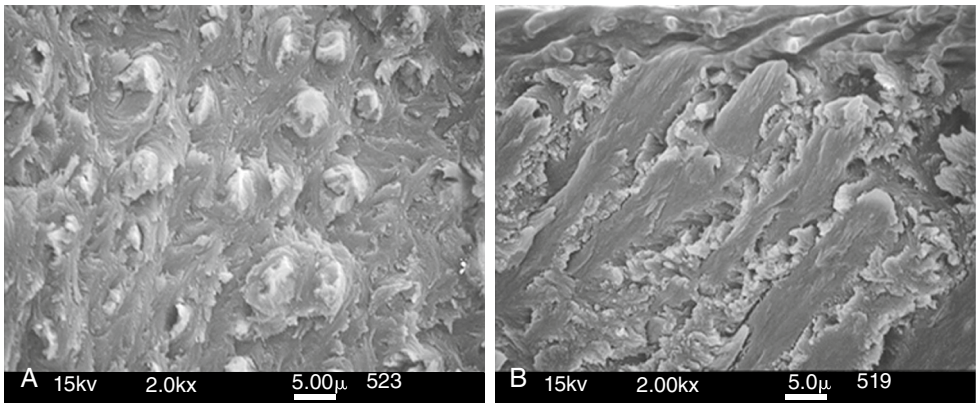
The DEJ is much more than the boundary between enamel and dentin. Because enamel is very hard and dentin is softer but



• **Fig. 2.10** Demineralized dentin is sensitive to moisture and shrinks on drying. (A) Demineralized dentin undergoes shrinkage when air dried, forming a collapsed layer of collagen that is difficult to infiltrate with resin-bonding agents. (B) When kept moist, the collagen network is open and can be penetrated by bonding agents. (From Marshall GW, Marshall SJ, Kinney JH, et al. The dentin substrate: structure and properties related to bonding. *J Dent*. 1997;25:441–458.)



• **Fig. 2.11** Transparent dentin associated with carious lesions. (A) Carious lesion showing dentin carious zones revealed by staining, including the grayish transparent zone. (B) Atomic force microscopy of carious transparent dentin before etching. (C) After etching, the tubule lumens remain filled even as the peritubular dentin is etched away. (A, from Zheng L, Hilton JF, Habelitz S, et al. Dentin caries activity status related to hardness and elasticity. *Eur J Oral Sci*. 2003;111(3):243–252; B and C, from Marshall GW, Chang JY, Gansky SA, et al. Demineralization of caries-affected transparent dentin by citric acid: an atomic force microscopy study. *Dent Mater*. 2001;17:45–52.)



• **Fig. 2.12** Transparent dentin. (A) Viewed from the facial direction. (B) Viewed longitudinally. The transparent dentin results from filling of the tubules with mineral deposits that alter the optical properties of the tooth. (Courtesy G.W. Marshall.)

TABLE 2.2 Properties of Enamel and Dentin

Property	Enamel	Dentin
Density (g/cm³)	2.96	2.1
Compressive		
Modulus of elasticity (GPa)	60–120	18–24
Proportional limit (MPa)	70–353	100–190
Strength (MPa)	94–450	230–370
Tensile		
Modulus of elasticity (GPa)		11–19
Strength (MPa)	8–35	30–65
Shear strength (MPa)	90	138
Flexural strength (MPa)	60–90	245–280
Hardness (GPa)	3–6	0.13–0.51

tougher, they need to be joined together to provide a biomechanically compatible system. Joining such dissimilar materials is a challenge, and it is not completely clear how nature has accomplished this. However, the DEJ not only joins these two tissues but also appears to resist cracks in the enamel from penetrating into dentin, cracks that would lead to tooth fracture, as shown in Fig. 2.13A. Many such cracks exist in the enamel but do not seem to propagate into the dentin. If the DEJ is intact, it is unusual to have tooth fracture, except in response to severe trauma. In Fig. 2.13B, microhardness indentations have been placed to drive cracks toward the DEJ *(orange)*. The crack stops at or just beyond the interface. This image also shows that the DEJ is scalloped, with its concavity directed toward the enamel. This means that most cracks approach the DEJ at an angle, and this may lead to the arrest of many of the cracks. The scalloped structure actually has three levels: scallops, microscallops within the scallops, and a finer structure. Fig. 2.13C–D shows images of larger scallops in molars (~24 µm across) and smaller scallops (~15 µm across) in anterior teeth after the removal of the enamel. Mathematical (finite element) models suggest that the scallops reduce stress concentrations at the interface, but it is not known whether the larger scallop size in posterior teeth is an adaptation to higher masticatory loads or a developmental variation. In Fig. 2.13E, the crystals of dentin are almost in contact with those of the enamel, so that the anatomical DEJ is said to be optically thin. However, measurements of property variations across the DEJ show that this is a graded interface with properties varying from those of the enamel to the adjacent mantle dentin over a considerable distance. This gradient, which is due in part to the scalloped nature of the DEJ, makes the functional width of the DEJ much larger than its anatomical appearance and further reduces stresses. In addition, although collagen is generally absent from enamel, collagen fibers cross the DEJ from dentin into enamel to further integrate the two tissues. Recent work suggests that other proteins that could be remnants of the basement membrane at the DEJ may include collagen types IV and VII and perhaps other proteins that could help stabilize the DEJ structure and contribute to its fracture resistance.

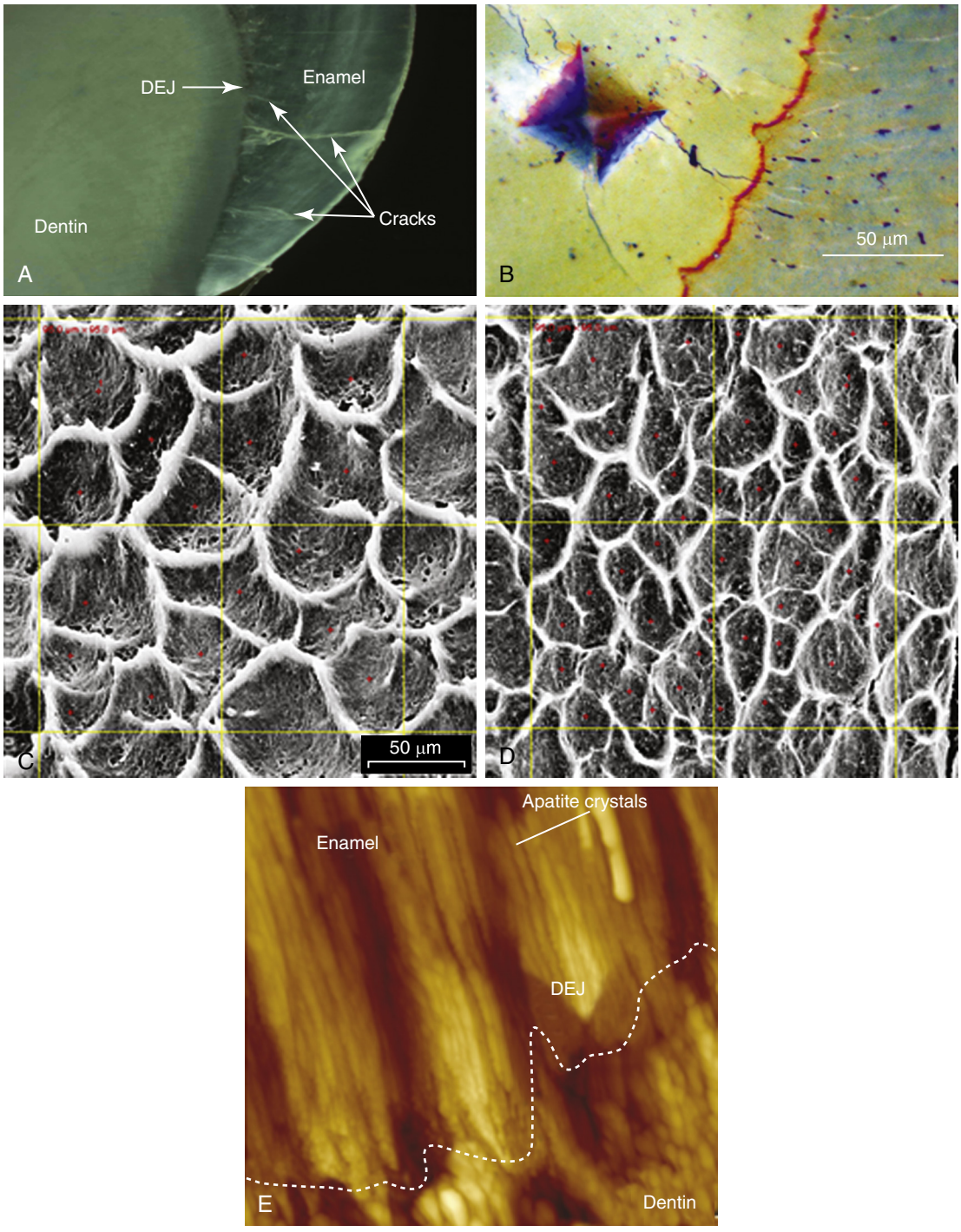
The enamel, dentin, and DEJ are highly complex structures that have varied physical and chemical properties. Their ability to work together to resist mechanical forces is critical for the survival of the tooth. In addition, they are constantly exposed to chemical insults within the oral environment. The main concern for teeth is their exposure to acids, including those present within imbibed foods and drinks, but especially from organic acids produced by the resident oral microbiome. Under certain conditions, the oral microbiota can form destructive biofilms that promote extensive demineralization of otherwise sound tooth structure, ultimately leading to caries lesions that require surgical interventions with dental restorative materials.

Oral Biofilms and Oral Health

Biofilms are complex, surface-adherent, spatially organized microbial communities encased within a hydrated matrix composed primarily of polysaccharides and extracellular DNA (eDNA), as well as various proteins and lipids. The biofilm matrix is typically referred to as extracellular polymeric substance (EPS). Oral biofilms that form on the surfaces of teeth and restorative biomaterials are also known as *dental plaque*. The microbes found within oral biofilms are directly derived from the oral microbiome, which includes both oral biofilm species as well as numerous additional organisms that normally reside on various mucosal surfaces of the oral cavity. The human oral microbiome is primarily composed of a diverse collection of bacterial species, but it is worth noting that fungi, protozoans, and viruses are all typically found in the oral microbiome as well. The overall microbial diversity in the oral cavity is second only to that in the human colon, with >700 different oral microbial species possible, making the oral cavity one of the most ecologically diverse environments of the entire human mucosa. The microbial communities present within dental plaque are highly dynamic, being subject to major compositional changes in response to both host genetics and behaviors. In oral health, the oral biofilm is primarily composed of commensal organisms that exhibit low pathogenic potential. Such a biofilm is sometimes referred to as eubiotic. In contrast, an oral biofilm enriched for pathogenic species is referred to as dysbiotic. The two most common dysbiotic oral diseases are caries and periodontitis. When the human diet is rich in fermentable carbohydrates, this can lead to the development of a dysbiotic oral biofilm containing an overabundance of cariogenic organisms (capable of producing or promoting caries). Such organisms tend to be both acidogenic (acid-producing) and aciduric (acid-tolerant) and can be found among certain species of *Streptococcus*, *Lactobacillus*, and even fungal *Candida* species. In addition, long-term oral biofilm accumulation can lead to mucosal inflammation and trigger a dysbiotic remodeling of oral biofilm ecology to favor the growth of highly inflammatory, tissue-invasive, proteolytic species associated with periodontal disease and periimplantitis (inflammation of the soft and hard tissues surrounding an implant). Dysbiotic diseases of the oral cavity exhibit a polymicrobial etiology, meaning there are no specific pathogens singularly responsible for diseases like caries and periodontitis; rather, disease results from the development of pathogenic synergistic *communities* containing multiple organisms. Thus oral disease susceptibility is a direct reflection of the underlying microbial ecology in the oral cavity.

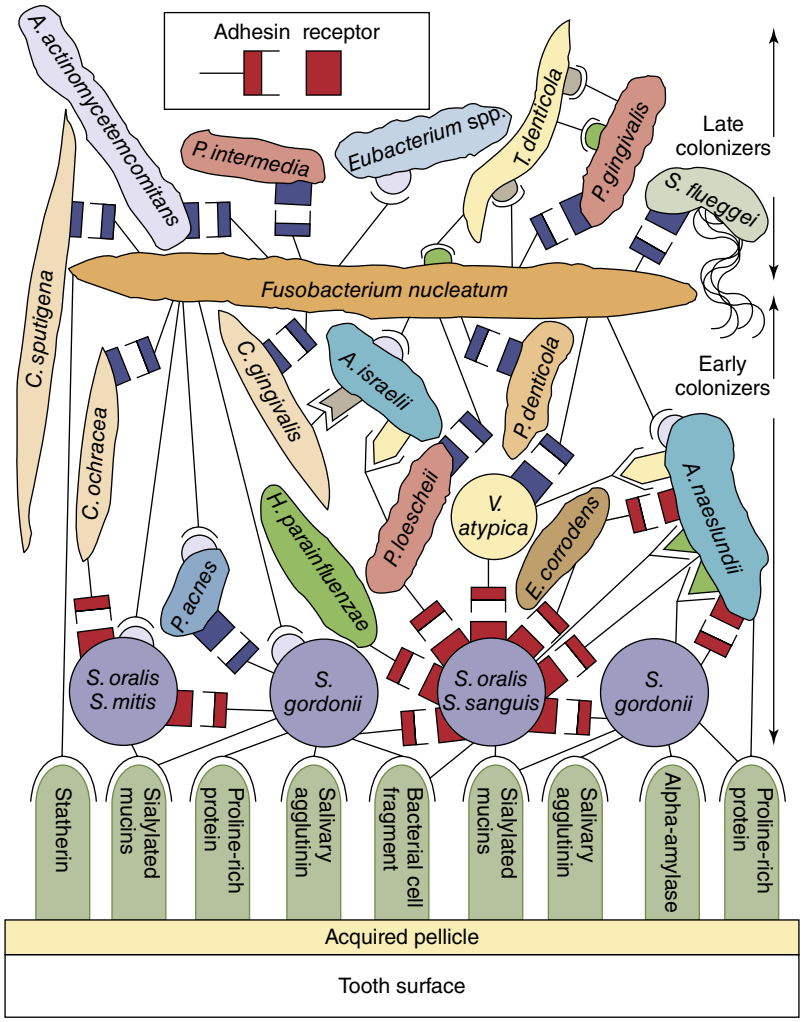
Early Oral Biofilm Development on Enamel

Oral biofilm formation on tooth surfaces occurs through a highly reproducible and sequential process. The first step begins with the formation of a proteinaceous conditioning film on the tooth surface known as the salivary pellicle (also referred to as the acquired enamel pellicle). The salivary pellicle contains a diverse assortment of adsorbed phosphoproteins and glycoproteins derived from saliva, as well as adsorbed bacterial proteins derived from the oral



• **Fig. 2.13** Cracks in enamel appear to stop at the dentin–enamel junction (DEJ). (A) Low-magnification view of cracks in enamel. (B) Indentation-generated cracks stop near or at the scalloped DEJ *(orange)*. (C) Large scallops in molars. (D) Smaller scallops in anterior teeth. (E) Crystals of the enamel are nearly in contact with dentin crystals at the DEJ forming an optically thin, but functionally wide union. (A, C–E, from Marshall SJ, Balooch M, Habelitz S, et al. The dentin-enamel junction—a natural, multilevel interface. *J Eur Ceram Soc*. 2003;23:2897–2904; B, from Imbeni V, Kruzic JJ, Marshall GW, et al. The dentin-enamel junction and the fracture of human teeth. *Nat Mater*. 2005;4:229–232.)

microbiome. Salivary pellicle formation on the teeth occurs rapidly and spontaneously as a consequence of saliva exposure. The pellicle layer is normally stably attached to the teeth and generally survives tooth brushing but can be removed during professional cleaning. However, it reforms within minutes upon saliva exposure. The pellicle layer is quite thin, typically ranging from hundreds of nanometers to about 1 μm in thickness. The proper formation of a salivary pellicle is critical for maintaining the integrity of teeth as both a lubricating layer protecting from mastication-induced tooth wear as well as a mediator of tooth remineralization. The



• **Fig. 2.14** Spatiotemporal model of oral bacterial colonization, showing recognition of salivary pellicle receptors by early colonizing bacteria and coaggregations between early colonizers, fusobacteria, and late colonizers of the tooth surface. Starting at the bottom, primary colonizers bind via adhesins *(round-tipped black line symbols)* to complementary receptors *(blue-green vertical round-topped columns)* in the salivary pellicle coating the tooth surface. Secondary colonizers bind to previously bound bacteria. Sequential binding results in the appearance of nascent surfaces that bridge with the next coaggregating partner cell. The bacterial strains shown are *Aggregatibacter actinomycetemcomitans, Actinomyces israelii, Actinomyces naeslundii, Capnocytophaga gingivalis, Capnocytophaga ochracea, Capnocytophaga sputigena, Eikenella corrodens, Eubacterium* spp., *Fusobacterium nucleatum, Haemophilus parainfluenzae, Porphyromonas gingivalis, Prevotella denticola, Prevotella intermedia, Prevotella loescheii, Propionibacterium acnes, Selenomonas flueggei, Streptococcus gordonii, Streptococcus mitis, Streptococcus oralis, Streptococcus sanguinis*, *Treponema* spp., and *Veillonella atypica*. (From Kolenbrander PE, Andersen RN, Blehert DS, et al. Communication among oral bacteria. *Microbiol Mol Biol Rev*. 2002;66(3):486–505.)

salivary pellicle also serves as the initial attachment substrate during oral biofilm development. A distinct subset of species from the oral microbiome produces cell surface receptors that bind to different proteins found in the salivary pellicle, allowing free-floating (planktonic) organisms to attach to uncolonized sites and initiate biofilm formation. These "pioneer colonizers" primarily comprise oral *Streptococcus* species and, to a lesser extent, *Actinomyces* (Fig. 2.14). The ability to bind to nonshedding surfaces, such as enamel, gives oral streptococci a tremendous colonization advantage over most other microbiome species. This also explains observations from clinical studies that have revealed streptococci to constitute 60% to 90% of the initial bacterial flora found on newly colonized enamel. Subsequent growth and cell division of the pellicle-attached organisms yield microcolonies that begin producing biofilm EPS to protect and house the developing community. Because the pioneer colonizers are almost exclusively oxygen-tolerant facultative anaerobes, their metabolic activity within the biofilm community eventually depletes the local oxygen concentration, subsequently creating an increasingly anaerobic environment within the developing biofilm that supports the growth of later colonizing obligate anaerobic species, including those often associated with gingivitis and periodontitis.

Oral Biofilm Maturation

Interactions among human oral bacteria are pivotal for the maturation and ecological diversification of developing oral biofilm communities. Of particular importance are genetically encoded

coaggregation interactions (receptor/ligand-mediated adherence between genetically distinct cell types), which allow many later colonizing organisms to join the established biofilm communities initiated by the pioneer colonizers (see Fig. 2.14). In the first 4 hours of biofilm formation, Gram-positive cocci from the Mitis group of streptococci predominate. Even after 8 hours of growth, the majority of the bacterial population remains largely coccoid, but the appearance of rod-shaped organisms can also be observed. By 24 to 48 hours, thick deposits of cells with various morphologies can be detected, including coccoid, coccobacillary, rod-shaped, and filamentous bacteria. Within 4 days of biofilm growth, there is a major increase in the proportion of Gram-negative obligate anaerobes, with various *Prevotella* species and *Fusobacterium nucleatum* being particularly abundant. The latter organism is especially noteworthy due to its unique ability to coaggregate with an exceptionally wide variety of both Gram-positive and Gram-negative bacteria (Fig. 2.14). This ability is believed to play a pivotal role in the maturation of oral biofilms because it creates an extensive network of coaggregation bridges with both early and late colonizers, which results in increased mechanical stability of the biofilm as well as much greater microbial diversity within the community. Consequently, *F. nucleatum* is often referred to as a "bridge species." As the biofilm reaches maturity, all of the major bacterial morphotypes can be identified in the community, while the community composition skews in favor of Gram-negative obligate anaerobes. These ecological shifts in the microbial composition of the oral biofilm are important because they correlate with the development of gingivitis (inflammation of gingival tissues), which can subsequently lead to the further development of periodontitis.

Oral Biofilm Development on Restorative and Implant Materials

Though biofilms accumulate on restorative, orthodontic, endodontic, and implant biomaterials, the remainder of this section will specifically focus on biofilms that accumulate on the surfaces of restorative and implant materials. The precise mechanisms of bacterial adhesion and biofilm formation on dental materials have yet to be fully elucidated, but it is evident that it is a complex process analogous to that described for enamel surfaces. In vitro studies have demonstrated that the adhesion of salivary proteins and bacteria at small distances (5–100 nm) from the surfaces of biomaterials is influenced by a combination of Lifshitz–van der Waals forces, electrostatic interactions, and acid-base bonding. Other properties, such as substrate hydrophobicity, surface free energy, surface charge, and surface roughness, have been commonly investigated in vitro for their correlation to the number of adhering bacteria. Many of the aforementioned surface properties are described in later chapters.

The role of surface roughness in biofilm formation has been the subject of a number of detailed investigations. Smooth surfaces have been shown in vivo to support less biofilm development than rough surfaces. Similarly, hydrophobic supragingival surfaces develop less biofilm in vivo over a 9-day period compared to more hydrophilic surfaces. Conversely, an increase in the mean surface roughness parameter (R_a) above a threshold value of 0.2 μm or an increase in surface free energy were both found to result in more biofilm accumulation on dental materials. When both of those surface properties interact, surface roughness was observed to exert the more dominant effect upon biofilm accumulation. The creation of a rough restoration surface caused by abrasion, erosion, air polishing/ultrasonic instrumentation, or a lack of polishing after the fabrication of a restoration has been associated with enhanced biofilm formation.

Surfaces having a low surface energy were observed to retain the smallest amount of adherent biofilm because of the lower binding forces between bacteria and substrata, even after several days of exposure in the oral cavity. Reciprocally, the higher surface energy of many restorative materials compared with that of the tooth surface could result in a greater tendency for the surface and margins of the restoration to accumulate debris, saliva, and bacteria. This may partially account for the relatively high incidence of secondary (recurrent) carious lesions seen in enamel at the margins of resin composite and amalgam restorations. Salivary pellicle formation has also been shown to exert a masking effect on certain surface characteristics of biomaterials, which is an especially important consideration when developing novel bioactive dental materials.

Interactions of Oral Biofilms With Common Restorative Materials

Investigations of oral biofilms on restorative materials can generally be divided into in vivo, in situ, and in vitro studies, with the latter comprising both monospecies and multispecies investigations. Biofilms that are formed on restorative materials can vary in thickness and viability. In vivo and in situ studies of biofilm formation on dental materials have produced inconsistent results thus far. Therefore there is no widely accepted consensus regarding biofilm accumulation on commonly employed dental materials. Studies suggest that the levels of specific cariogenic organisms like *Streptococcus mutans* are higher in biofilms adjacent to posterior resin restorations compared to amalgam or glass ionomer restorations. Furthermore, the formation of cariogenic oral biofilms is associated with an increase in the surface roughness of resin composites, degradation of the material due to acid production by cariogenic organisms, hydrolysis of the resin matrix, and a decrease in microhardness of the restoration surface. Esterases of salivary and bacterial origin have also been implicated as sources of methacrylate resin degradation. In addition, it has been theorized that planktonic bacteria can enter gaps at the adhesive interface between the restorative material and the tooth, leading to secondary caries and pulp pathology. By contrast, trace amounts of unpolymerized resin, resin monomers, and the products of resin biodegradation, such as 2,2-bis[4(2,3-hydroxypropoxy) phenyl]propane (BisHPPP), triethylene glycol monomethacrylate (TEGMA), triethylene glycol (TEG), and methacrylic acid (MA), have been shown to modulate the growth of oral bacteria in the vicinity of resin restorations. All of these factors likely create a damaging positive feedback cycle of bacteria-surface interaction that further increases surface roughness and encourages additional bacterial attachment to the surface, thereby placing the adjacent enamel at a greater risk for secondary caries.

Like other restorative materials, glass ionomer and resin-modified glass ionomer biomaterials support oral biofilm formation, and bacterial metabolism on these materials can increase their surface roughness. Fluoride-releasing materials and glass ionomers (compomers in particular) can neutralize acids produced by biofilm bacteria. Released fluoride ions can also provide cariostatic benefits and have been demonstrated to interfere with bacterial metabolism in vitro. Presumably, the volume of saliva present in the oral cavity is too large for glass ionomer and resin-modified glass ionomer restorations to provide oral cavity-wide antibacterial protection via fluoride release. However, it could still be theoretically sufficient to minimize demineralization of the tooth structure

directly adjacent to these restorations. In addition, glass ionomer materials can be recharged by daily exposure to fluoride-containing dentifrices, thereby compensating for the significant decrease in fluoride release that occurs over time. Interestingly, clinical studies have yet to clearly demonstrate that fluoride-releasing restorative materials significantly reduce the incidence of secondary caries compared to fluoride-free biomaterials. Thus the actual clinical efficacy of these materials remains an open question.

Bacterial adhesion to casting alloys and dental amalgams has received limited attention in recent years, as the use of dental amalgam is being phased down in response to global concerns about mercury (Hg) in the environment. However, biofilms formed on amalgam are reported to have low viability, which could be attributed to the presence of the Hg(II) form of mercury in dental amalgam. Interestingly, amalgam restorations have been shown to bolster the levels of Hg-resistant bacteria in vitro and in vivo. Resistance to antibiotics, particularly tetracycline, was observed to be concurrent with Hg resistance in oral bacteria. It is worth noting that Hg-resistant bacteria were also found in children without amalgam fillings or previous exposure to amalgam. Like amalgams, biofilms formed on gold-based casting alloys are also reported to be of low viability, possibly because of the bacteriostatic effect of elements in the gold alloy.

Information regarding the morphology of biofilms formed on ceramic restorations is limited, although it is generally accepted that ceramic crowns accumulate less biofilm than the adjacent tooth structure. However, the recent in vitro demonstration of increased surface roughness of zirconia surfaces following the use of hand and ultrasonic scaling instruments suggests that dental prophylaxis procedures could potentially result in increased biofilm accumulation on zirconia restorations.

Interactions Oral Biofilms With Denture and Implant Materials

Biofilms that adhere to denture base resins contain an abundance of fungal *Candida* species. However, initial adhesion to the denture base by pioneer colonizing bacteria like streptococci might be required to occur before *Candida* species can attach and form biofilms. For example, bacteria have been observed to attach to dentures within hours, whereas *Candida* species are only detected after multiple days. Furthermore, *Candida* species have been demonstrated to adhere to specific cell wall proteins of streptococci. Denture biofilms have been commonly associated with denture stomatitis (chronic inflammation of the oral mucosa) in both elderly and immunocompromised patients. The removal of biofilms from dentures typically requires mechanical and/or chemical means due to the avid adherence of biofilms to denture base resins.

The accumulation of biofilms on both titanium and titanium alloy dental implants has received significant attention due to the central role of biofilm formation in determining the success of an implant. The sequence of microbial colonization and biofilm formation on dental implants has been shown to be similar to that of teeth but differs in early colonization patterns. Several in vivo studies have confirmed that a reduction in mean R_a of implant materials below the threshold value of 0.2 μm has no major effect on adhesion, colonization, or microbial composition. Compared with polished titanium surfaces, titanium implant surfaces that were modified with titanium nitride (TiN) showed significantly less bacterial adhesion and biofilm formation in vivo, thereby potentially minimizing biofilm accumulation and subsequent periimplantitis. Other contributing factors, such as the hydrophobicity, surface chemistry, and surface free energy of the implant material, have been found to play critical roles in bacterial adhesion to dental implant materials. In addition, the surface characteristics of the bacteria, the design of the implant and abutment, and the microgap between the implant and abutment have all been demonstrated to influence microbial colonization of dental implants.

Caries Prevention

The most common reason for the replacement of dental restorations is secondary caries at the gingival tooth-restoration margin. It has been estimated that 50% to 80% of resin restorations are replaced annually in the United States alone. The cost of replacing restorations is estimated to be in the billions of dollars worldwide, and the number and cost of replacing restorations are increasing annually. Although bacteriological studies of secondary caries indicate that its etiology is similar to that of primary caries, the mechanisms by which secondary caries occur remain an active area of investigation.

The removal of tenaciously adherent oral biofilms from hard surfaces is crucial for the prevention of oral dysbiotic diseases and is most effectively accomplished by mechanical brushing with dentifrice, especially within interproximal regions and around posterior teeth. The use of adjunctive chemical agents can further improve clinical efficacy. Although tooth brushing has been suggested to increase the surface roughness of restorations over time due to the process of wear, mechanical removal has been shown to be more efficacious than chemical intervention alone. This is likely because biofilm-embedded bacteria are typically highly resistant to environmental insults, which in the oral cavity include the host immune response, antibiotics, and other antibacterial agents. Furthermore, most antimicrobial agents have been benchmarked using planktonic bacteria, which are killed by substantially lower concentrations of antimicrobials than biofilm bacteria. In some cases, this difference in susceptibility has been shown to reach several orders of magnitude. Long-term chemical control of biofilms has also been discouraged due to concerns about inducing antimicrobial resistance following prolonged usage. In addition, it is now widely accepted that the microbiota should not be completely eliminated due to its many important health-protective benefits. The preferred approach is to establish and/or maintain a favorable microbial ecology that prevents oral disease.

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3

Materials-Centered Treatment Design

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CHAPTER OUTLINE

This section presents two concepts in dental treatment design: evidence-based dentistry and materials-centered design. Both concepts are used to develop rational treatment plans that consider the patient's needs and preferences, and materials characteristics appropriate for those needs.

Evidence-Based Dentistry

The American Dental Association (ADA) has defined *evidence-based dentistry* as "an approach to oral healthcare that requires the judicious integration of systematic assessments of clinically relevant scientific evidence, relating to the patient's oral and medical condition and history, with the dentist's clinical expertise and the patient's treatment needs and preferences." This approach is patient-centered and tailored to the patient's needs and preferences. All three elements are used in the decision-making process for patient care (Fig. 3.1).

Patient Evidence

Patient needs, conditions, and preferences are considered throughout the diagnostic and treatment planning process. *Observation* of patient needs and medical/dental history occurs first. In this phase, performance of prior and existing restorations, in terms of success or failure, should be noted. This is often a good indicator of conditions in the oral environment and the prognosis of success of similar materials in this environment. The patient's facial profile and orofacial musculature are good indicators of potential occlusal forces. Wear patterns on occlusal surfaces are indicators of bruxing, clenching, occlusal forces, and mandibular movements. Cervical abfractions may indicate heavy occlusal contact accompanied by bruxing or occlusal interferences and possibly in association with aggressive tooth brushing and acidic conditions. Erosion on anterior teeth typically suggests elevated levels of dietary acids, and generalized wear without occlusal trauma could involve a systemic disorder such as gastroesophageal reflux disease (GERD). Any of these conditions would compromise the longevity of restorative therapy. Unusually harsh environments require careful restoration design and selection of materials, sometimes different from the norm.

Restorative material options then need to be considered with the problems and needs of the patient. The integration of patient data and material characteristics forms a more comprehensive plan for treatment.

Scientific Evidence

When searching for scientific evidence, the best available evidence, usually compiled from a review of the scientific literature, provides objective information to inform the clinician and patient. The highest level of validity is chosen to minimize bias. These studies are typically meta-analyses of randomized controlled trials (RCTs), systematic reviews, or individual RCTs. Lower levels of evidence are found in case studies, cohort studies, and case reports. Laboratory studies are listed as "other evidence" because a clinical correlation can be made only as an extrapolation of the laboratory data. The listing of bench or laboratory research as "other evidence" should not be construed as meaning that bench research is not valid or useful. The hierarchy of evidence as presented for evidence-based data (EBD) is based on human clinical trials, for which laboratory tests are, at best, only a simulation.

Because new material developments that are enhancements to existing products are not required to undergo clinical testing by the Food and Drug Administration (FDA), published laboratory or in vitro studies are often the only forms of scientific evidence available for specific materials. This does not mean that no evidence is available. However, the clinician must recognize the limitations of these data, despite their scientific validity, when translating them to the clinical situation and making treatment decisions for a patient (Table 3.1).

Researchers in dental materials science have analyzed the correlation between one or two physical or mechanical properties of materials and clinical performance. Although it is possible to use laboratory tests to rank the clinical performance of different formulations of the same class of material, there is no one perfect predictor of clinical performance. This is logical, as clinical performance is a multifactorial process. In addition, differences in test configuration, specimen geometry, specimen processing, and environmental conditions make direct comparisons between laboratory tests difficult. However, understanding these tests and the