Sturdevant's

ART and SCIENCE of OPERATIVE DENTISTRY

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EIGHTH EDITION

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Foreword

It is indeed an honor to write the foreword for the eighth edition of a textbook that first appeared in 1968 and has since served as a valuable resource for generations of educators and students in Operative Dentistry. Times and materials have changed greatly since 1968. Dental amalgam, cast gold and gold foil, silicate cement, calcium hydroxide, cavity varnishes, zinc phosphate cement, and polysulfide impression material have given way to composite resin, glass ionomer restorative materials, CAD/CAM ceramics, calcium silicate and glass ionomer liners, resin bonding agents, glass ionomer and resin cements, and polyvinylsiloxane and polyether impression materials. And yet, the basic principles of Operative Dentistry—attention to detail and meticulous preparation and restoration procedures—have remained the same. Those principles are as critical now as they have ever been, and this book continues to emphasize the importance of excellent clinical technique.

Chapter 1 of the first edition was titled "Operative Dentistry: Scope and Objective of Service" and included this definition: "Operative dentistry is that branch of dentistry which relates to diagnosis, prognosis, or treatment of teeth with vital or nonvital pulps, to the maintenance or restoration of the functional and physiologic integrity of the teeth as this applies to the adjacent hard and soft tissue structures of the oral cavity; and to all of the latter considerations as they apply to the general health and welfare of the patient."

This definition still applies more than 50 years later; Operative Dentistry continues to focus on diagnosis and treatment of teeth, restoring them to optimal function. But advances in the discipline and materials science allow contemporary clinicians to restore teeth more efficiently, more conservatively, and more esthetically than our predecessors were able to do in 1968.

In preparing to write this foreword, I pulled out my own copy of the landscape format first edition, which was still around during my dental school years. The pages have yellowed and the binding has started to break but my highlights in the text, particularly in the chapters on rubber dam, amalgam, and cast gold inlays have survived the years. The first and eighth editions remain similar in some respects, with the new edition continuing to describe fundamental concepts of treatment planning, tooth preparation, pulp protection, instrumentation, placement and finishing of restorative materials, and isolation. But in many ways, they are quite different, reflecting the enormous progress and developments that have occurred over the years. The eighth edition provides a remarkably broad overview of the art and science of contemporary Operative Dentistry, but it continues in the tradition of the original editor, Dr. Clifford Sturdevant, and multiple editions of this textbook by exploring each topic in great depth and detail.

At the time of this writing, "contemporary" has evolved and expanded into techniques and materials that could have hardly been imagined in 1968. Dr. Sturdevant and his colleagues were great visionaries, but who among them would have predicted that we could predictably bond resin-based materials to dentin, polymerize composite resins using visible light, imperceptibly match composite to adjacent tooth structure, or use computer-controlled machines to design and fabricate restorations? We can and do all of those routinely, and various chapters in this book provide the reader with what they need to know about each topic.

In closing, a few words about the title of the book.... *Sturdevant's Art and Science of Operative Dentistry*. Operative Dentistry is indeed a **science**. Look no further than Chapters 7 and 8 of this new edition to understand how much of what we do *is* based on science. But Operative Dentistry is also an **art**, as evidenced by what you will read and see in Chapters 10 and 11. And finally, **Sturdevant**. In looking back at previous editions of this textbook, the list of authors and editors, beginning with Dr. Cliff Sturdevant, reads like a *Who's Who* of Operative Dentistry. It's a trite metaphor, but the authors and editors of this edition truly "stand on the shoulders of giants."

For students and teachers of Operative Dentistry, I am confident that you will find this new edition to be an excellent resource as you learn and grow in the **art and science** of this discipline. And always remember, as the book and its authors have emphasized over these many years, that excellent clinical technique is absolutely critical to success.

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Preface

Sturdevant's Art and Science of Operative Dentistry was originally developed as a practical manual to assist teachers in the preclinical education of students in the then emerging discipline of Operative Dentistry. Since the publication of the first edition of this textbook in 1968, the Operative Dentistry evidence base has grown in depth and breadth, primarily through laboratory and clinical research, demanding a broader understanding of both the art and the science of this ever-evolving discipline. Consequently, the original laboratory manual was required to grow and expand. The eighth edition of this decades-long textbook series represents our next effort in the distillation of time-tested and proven concepts as well as the consideration and application of more recent advances in Operative Dentistry.

In this edition, we attempted to better sequence chapters, following a logical progression such that, when viewed as a whole, all necessary aspects of restorative clinical care are supported with basic knowledge and its application in the specific management of various dental disease states. At the request of the publisher, and following what has been done in previous recent editions, we also had to make the difficult decision to make a few chapters available only online. We sincerely hope that this will not compromise the reader's experience. Authorship has been expanded to include content experts able to enhance and enable more comprehensive understanding for the reader. As with previous editions, adequate information of various biomaterials and instruments is included to ensure proper handling based on clinical circumstances such that optimal outcomes are more predictable. Text organization, content, color images, and line drawings have been written/revised to support Operative Dentistry educational efforts with clear explanation and supporting research. Every attempt to ensure usefulness for all readers—teachers, students, and practitioners/colleagues—has been made.

The new edition also features an ebook+ website that includes a full online version of the print text, as well as three supplemental online-only chapters and technique videos. See the inside front cover for a complete listing of the chapters and videos available.

This textbook is designed to be a useful tool for guiding both critical thought and precise technique in the discipline of Operative Dentistry. It is our honor and considered privilege to have had the opportunity to generate the eighth edition.

The Editors

Acknowledgements

The editors would like to thank our spouses and families for their love, understanding, and support during this revision; the many colleagues who contributed with illustrations—their names are referenced throughout the textbook—and the entire editorial team at Elsevier for the support, encouragement, and expertise during the revision process. Their professionalism and guidance are reflected in every page of this work.

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Clinical Significance of Dental Anatomy, Histology, Physiology, and Occlusion

LEE W. BOUSHELL, SAULO GERALDELI, KARINA IRUSA, JOHN R. STURDEVANT

A thorough understanding of the histology, physiology, anatomy, and occlusal interactions of the dentition and supporting tissues is essential in operative dentistry. Knowledge of the structures of teeth (enamel, dentin, cementum, and pulp) and their relationships to each other and to the supporting structures is necessary, especially when diagnosing and treating dental caries. The protective function of the tooth composition and anatomy is revealed by its impact on masticatory muscle activity, the supporting tissues (osseous and mucosal), and the pulp. Proper tooth anatomic form contributes to healthy supporting tissues. The contour and contact relationships of teeth with adjacent and opposing teeth are major determinants of muscle function in mastication, esthetics, speech, and protection. Esthetic form of the dentition compliments facial esthetics. The relationships of form to function are especially noteworthy when considering the shape of the dental arch, proximal contacts, occlusal contacts, and mandibular movement.

Teeth and Supporting Tissues

Dentitions

Humans have primary and permanent dentitions. The primary dentition consists of 10 maxillary and 10 mandibular teeth. Primary teeth exfoliate and are replaced by the permanent dentition, which consists of 16 maxillary and 16 mandibular teeth.

Classes of Human Teeth: Form and Function

Human teeth are divided into classes based on form and function. The primary and permanent dentitions include the incisor, canine, and molar classes. The fourth class, the premolar, is found only in the permanent dentition (Fig. 1.1). Tooth form predicts the function, and class traits are the characteristics that place teeth into functional categories. Because the diet of humans consists of animal and plant foods, the human dentition is called *omnivorous*.

Incisors

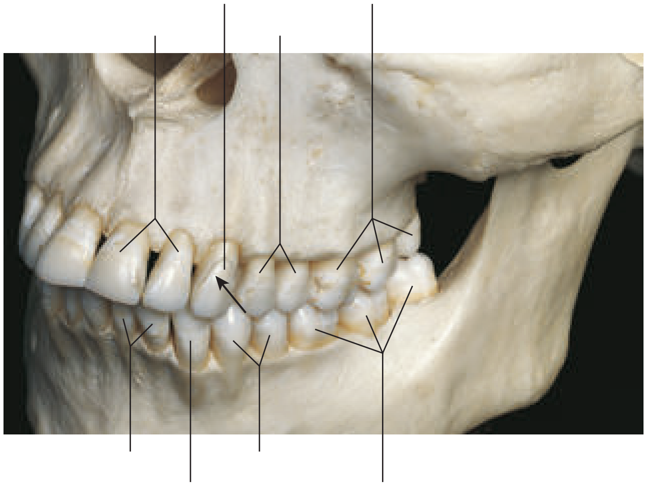
Incisors are located near the entrance of the oral cavity and function as cutting or shearing instruments for food (Fig. 1.1). In a normal dentition, there are two central incisors and two lateral incisors in each arch; each hemi-arch has a central incisor and a lateral incisor. From a proximal view, the crowns of these teeth have a relatively triangular shape, with a narrow incisal surface and a broad cervical base (Fig. 1.2). During mastication, incisors are used to shear (cut through) food. Mandibular central incisors are the smallest teeth in the human dentition. Maxillary lateral incisors vary in form more than any tooth in the mouth, second only to third molars. A common morphological variation of maxillary lateral incisors is peg-shaped lateral incisors (Fig. 1.3). Maxillary lateral incisors may have a palato-radicular groove (PAG) that may serve as a predisposing factor for localized periodontal disease (PD). Incisors are essential for proper facial soft tissue contours (e.g., lip support), speech (phonetics), and esthetics of the smile. Key anatomical features of incisors that play an important role in smile esthetics include the incisal edges, the mesio- and distoincisal angles, the mesio- and distofacial line angles, associated embrasure spaces, and cervical heights of contour. The position, orientation, and prominence of these form features simultaneously contribute to the function of the mandible.

Canines

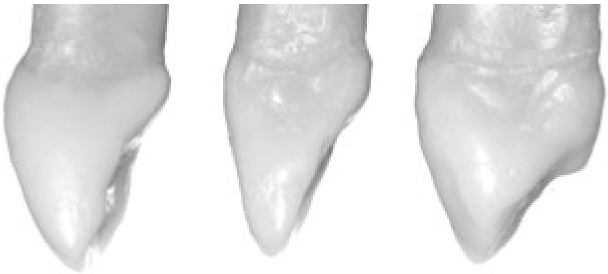
Canines possess the longest roots of all teeth and are located at the corners of the dental arches. In a normal dentition, there are two canines in each arch; each hemi-arch has one canine. They function in the seizing, piercing, tearing, and cutting of food. From a proximal view, the crown also has a triangular shape, with a thick incisal ridge (Fig. 1.2). The anatomic form of the crown and the length of the root make canine teeth strong, stable abutments for fixed or removable prostheses. Canines not only serve as important guides in occlusion because of their anchorage and position in the dental arches, but also play a crucial role (along with the incisors) in the esthetics of the smile and lip support. Additional lip support is provided by the presence of a bony prominence over the labial aspect of the canines, referred to as the canine eminence (Fig. 1.1). The arrow in Fig. 1.1 is pointing to the canine eminence.

Premolars

Premolars serve a dual role: (1) they are similar to canines in the tearing of food, and (2) they are similar to molars in the grinding of food. In a normal dentition, there are four premolars in each arch; each hemi-arch has a first premolar and a second premolar. Although first premolars are angular, with their facial cusps resembling canines, the lingual (or palatal) cusps of the maxillary premolars and molars have a more rounded anatomic form (Fig. 1.4). The occlusal surfaces present a series of curves in the form of concavities and convexities that should be maintained throughout



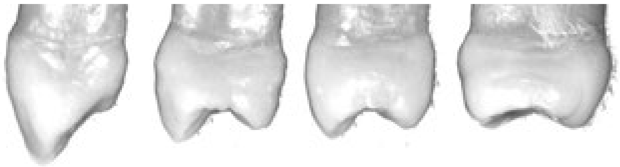
• **Fig. 1.1** Maxillary and mandibular teeth in maximum intercuspal position. The classes of teeth are incisors, canines, premolars, and molars. Cusps of mandibular teeth are one half-cusp anterior of corresponding cusps of teeth in the maxillary arch. (From Logan BM, Reynolds P, Hutchings RT: *McMinn's color atlas of head and neck anatomy*, ed 4, Edinburgh, 2010, Mosby.)



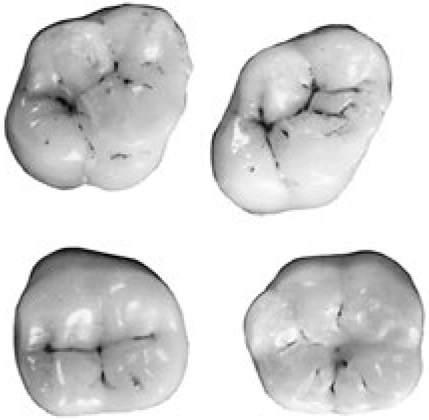
• **Fig. 1.2** Mesioproximal view of maxillary anteriors. From left to right: central incisor, lateral incisor and canine.

• **Fig. 1.3** Peg-shaped maxillary lateral incisors.

life for correct occlusal contacts and function. Although less visible than incisors and canines, premolars still play an important role in esthetics. The maxillary first premolar frequently has a marked mesial developmental depression, which typically spans from immediately apical to the proximal contact area all the way into the root bifurcation. Biofilm retention in this area may



• **Fig. 1.4** Mesioproximal view of maxillary canine, premolars, and first molar showing variations in facial and lingual cusp anatomy.



• **Fig. 1.5** Occlusal surfaces of maxillary and mandibular first and second molars after several years of use, showing rounded curved surfaces and minimal wear.

increase the risk of developing caries and PD. The presence of the concavity also complicates efforts to restore tooth contours after caries-related cavitation has occurred.

Molars

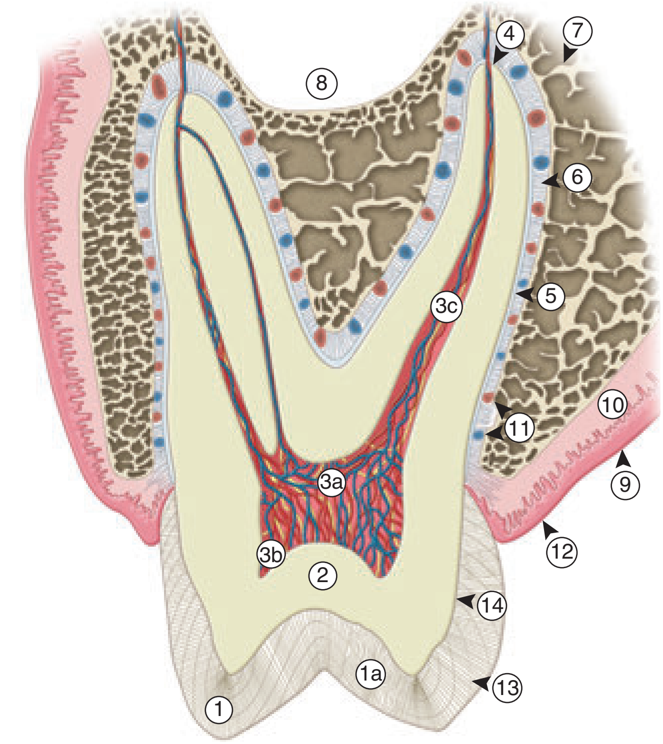
Molars are large, multicusped teeth with multiple roots located nearest the temporomandibular joint (TMJ), which serves as the fulcrum during function. In a normal dentition, there are six molars in each arch; each hemi-arch has a first molar, a second molar, and a third molar. These teeth have a major role in the crushing, grinding, and chewing of food to dimensions suitable for swallowing. They are well suited for this task because they have broad occlusal surfaces and anchorage (Figs. 1.5 and 1.6). Premolars and molars are important in maintaining the vertical dimension of the face (Fig. 1.1). Third molars (referred to as "wisdom teeth" because of the timing of their eruption around the beginning of the third decade of life) reveal the greatest amount of variation in size and shape as compared with all other teeth in the human dentition.

Structures of Teeth

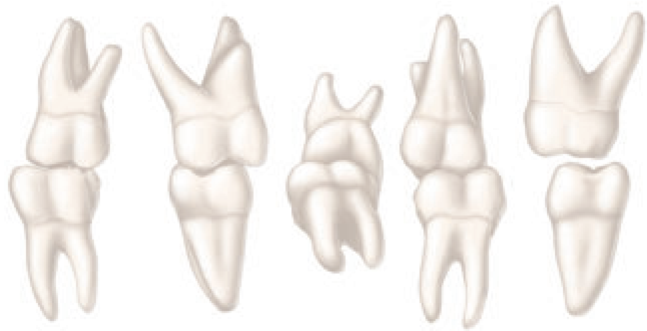
Teeth are composed of enamel, the pulp–dentin complex (PDC), and cementum (Fig. 1.6). Each of these structures is discussed individually.

Enamel

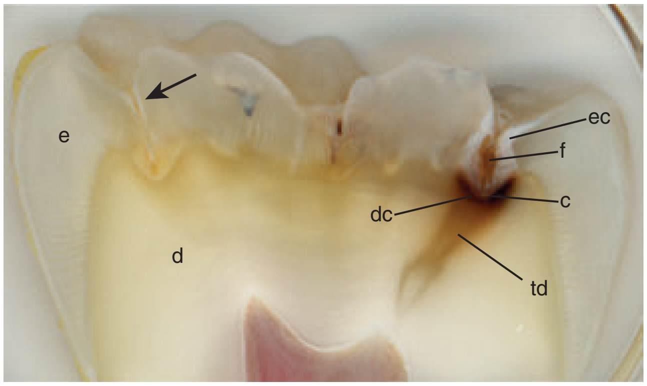
Enamel is formed by *ameloblast* cells in a process called *amelogenesis*. Ameloblasts originate from the embryonic germ layer known as *ectoderm*. Enamel covers the anatomic crown of the tooth, varies in thickness in different areas, and is securely attached to the dentin by the dentinoenamel junction (DEJ) (Fig. 1.6). It is



• **Fig. 1.6** Cross-section of the maxillary molar and its supporting structures. *1*, Enamel; *1a*, gnarled enamel; *2*, dentin; *3a*, pulp chamber; *3b*, pulp horn; *3c*, pulp canal; *4*, apical foramen; *5*, cementum; *6*, periodontal fibers in periodontal ligament; *7*, alveolar bone; *8*, maxillary sinus; *9*, mucosa; *10*, submucosa; *11*, blood vessels; *12*, gingiva; *13*, lines of Retzius; *14*, dentinoenamel junction (DEJ).



• **Fig. 1.7** Maxillary and mandibular first molars in maximum intercuspal contact. Note the grooves for escape of food.



• **Fig. 1.8** Fissure *(f)* at junction of lobes allows accumulation of food and bacteria predisposing the tooth to dental caries *(c).* Enamel *(e)*, dentin *(d)*, enamel caries lesion *(ec)*, dentin caries lesion *(dc)*, transparent dentin *(td)*; early enamel demineralization *(arrow).*

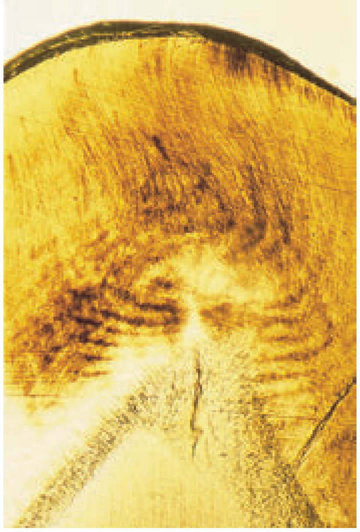
thicker at the incisal and occlusal areas of the crown and becomes progressively thinner until it terminates at the cementoenamel junction (CEJ). The thickness also varies from one class of tooth to another, averaging 2 mm at the incisal ridges of incisors, 2.3 mm–2.5 mm at the cusps of premolars, and 2.5 mm–3 mm at the cusps of molars.

Cusps on the occlusal surfaces of posterior teeth begin as separate ossification centers, which form into developmental lobes. Adjacent developmental lobes increase in size until they begin to coalesce. Grooves and fossae result in the areas of coalescence (at the junction of the developmental lobes of enamel) as cusp formation nears completion. The strategic placement of the grooves and fossae complements the position of the opposing cusps to allow movement of food to the facial and lingual surfaces during mastication. A functional cusp that opposes a groove (or fossa) occludes on enamel inclines on each side of the groove and not in the depth of the groove. This arrangement leaves a V-shaped escape path between the cusp and its opposing groove for the movement of food during chewing (Fig. 1.7).

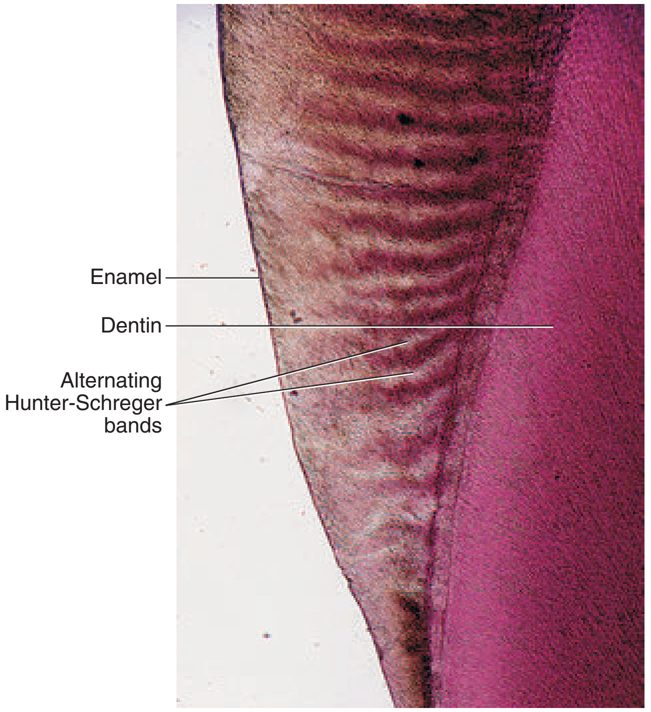
Enamel thickness varies in the area of these developmental features and may approach zero, depending on the effectiveness of adjacent cusp coalescence. Failure or compromised coalescence of the enamel of the developmental lobes results in a deep invagination in the groove area of the enamel surface and is termed *fissure*. Noncoalesced enamel at the deepest point of a fossa is termed *pit*. Fissures and/or pits represent non–self-cleansing areas where acidogenic biofilm accumulation may predispose the tooth to dental caries (Fig. 1.8).

Chemically, enamel is a highly mineralized crystalline structure. Hydroxyapatite (HA), in the form of a crystalline lattice, is the largest mineral constituent (90%–92% by volume). Other minerals and trace elements are present in smaller amounts. The remaining constituents of tooth enamel include organic matrix proteins (1%–2%) that "glue" the apatite crystals together and water (4%–12%) by volume.

Structurally, enamel is composed of millions of enamel rods (or "prisms"), rod sheaths, and a cementing interrod substance. Enamel rods, which are the largest structural components, are formed linearly by successive apposition of enamel in discrete increments. The resulting variations in structure and mineralization are called *incremental striae of Retzius* (SR) and may be considered "growth rings" that form during amelogenesis (Fig. 1.6). Histologically, the SR appear as concentric circles in horizontal sections of a tooth. In vertical sections, the SR are positioned transversely at the cuspal and incisal areas in a symmetric pattern, descending obliquely to the cervical region and terminating at the DEJ. When these circles are incomplete at the enamel surface, a series of alternating grooves, called *imbrication lines of Pickerill,* are formed. Elevations between the grooves are called *perikymata;* they are continuous around a tooth and usually lie parallel to the CEJ and each other. Enamel rods vary in number from approximately 5 million for a mandibular incisor to about 12 million for a maxillary molar. In general, the rods are aligned perpendicularly to the DEJ and the tooth surface in the primary and permanent dentitions, except in the cervical region of permanent teeth, where they are oriented outward in a



• **Fig. 1.9** Gnarled enamel. (From Berkovitz BKB, Holland GR, Moxham BJ: *Oral anatomy, histology and embryology*, ed 4, Edinburgh, 2009, Mosby.)



• **Fig. 1.10** Photomicrograph of enamel Hunter–Schreger bands. Photographed obtained by reflected light. (Modified from Chiego DJ Jr: *Essentials of oral histology and embryology: A clinical approach*, ed 4, St Louis, 2014, Mosby.)

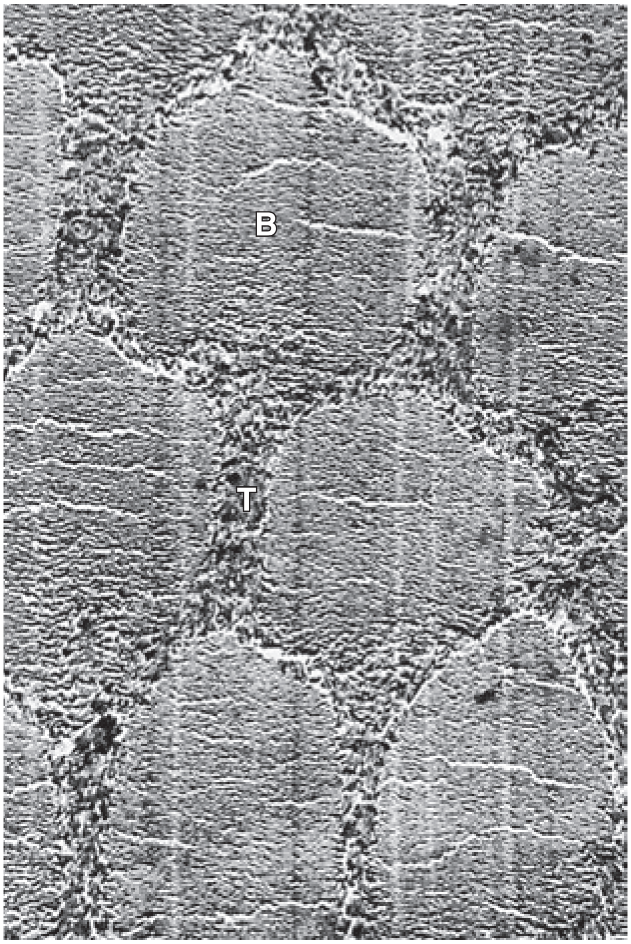
slightly apical direction. Microscopically, the enamel surface initially has circular depressions indicating where the enamel rods end. These concavities vary in depth and shape and gradually wear smooth with age. Additionally, a structureless outer layer of enamel about 30 μm thick may be commonly identified toward the cervical area of the tooth crown and less commonly on cusp tips. There are no visible rod (prism) outlines in this area and the apatite crystals are parallel to one another and perpendicular to the SR. This layer, referred to as *prismless enamel,* may be more heavily mineralized.

Each ameloblast forms an individual enamel rod with a specific length based on the specific type of tooth and the specific coronal location within that tooth. Enamel rods follow a wavy, spiraling course, producing an alternating clockwise and counterclockwise arrangement for each group or layer of rods as they progress radially from the dentin toward the enamel surface. They initially follow a curving path through one-third of the enamel next to the DEJ. After that, the rods usually follow a more direct path through the remaining two-thirds of the enamel to the enamel surface. Groups of enamel rods may entwine with adjacent groups of rods and follow a curving irregular path toward the tooth surface. These constitute *gnarled enamel,* which occurs near the cervical regions and also in incisal and occlusal areas (Fig. 1.9). Intuitively, it may be that gnarled enamel is not subject to fracture as much as is regular enamel though no research studies have assessed this assertion. This type of enamel formation does not yield readily to the pressure of bladed, hand-cutting instruments in tooth preparation. The orientation of the enamel rod heads and tails and the gnarling of enamel rods provides strength by resisting, distributing, and dissipating impact forces.

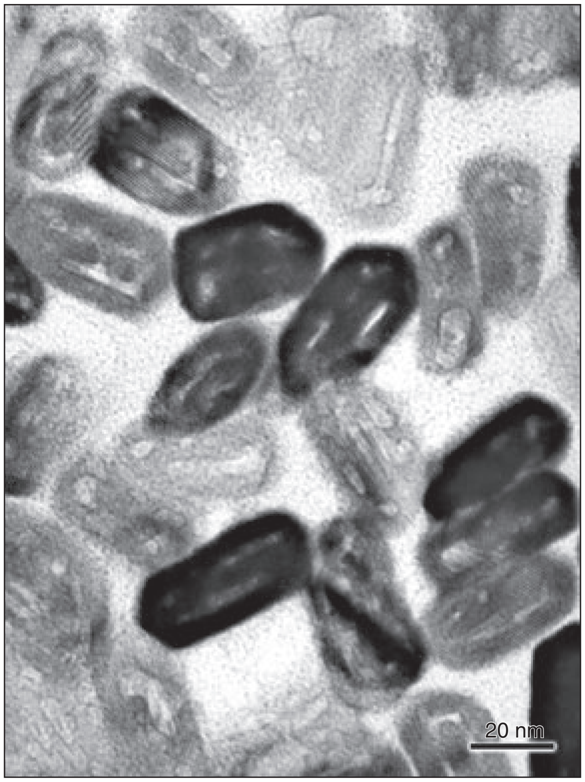
Changes in the direction of enamel rods in the axial direction (which may minimize the potential for attrition, abrasion, and fracture) produce an optical appearance called *Hunter–Schreger bands* (HSB) (Fig. 1.10).[1] These bands are found in different areas of each class of teeth and appear to be composed of alternate light and dark zones of varying widths that have slightly different permeability and organic content. Because the enamel rod orientation varies in each tooth, HSBs also have a variation in the number present in each tooth. In anterior teeth, they are located near the incisal surfaces. They increase in numbers and areas of teeth, from canines to premolars. In molars, the bands occur from near the cervical region to the cusp tips. In the primary dentition, the enamel rods in the cervical and central parts of the crown are nearly perpendicular to the long axis of the tooth and are similar in their direction to permanent teeth in the occlusal two-thirds of the crown.

Enamel rod diameter is about 8 μm at the exterior surface and narrows to about 4 μm near the DEJ. This diameter difference accommodates the larger outer surface of the enamel crown compared with the dentinal surface at the DEJ. Enamel rods, in transverse section, have a rounded head (or body) section and a tail section, which enable interlocking with adjacent rods. Microscopic (~5000×) cross-sectional evaluation of enamel reveals that the rounded body section of each rod lies between the narrow tail sections of two adjacent prisms (Fig. 1.11). Generally, the rounded head portion is oriented in the incisal or occlusal direction; the tail section is oriented cervically. The final act of the ameloblasts, upon the completion of enamel rod formation, is the secretion of a membrane layer that covers the ends of the enamel rods. This layer is referred to as *Nasmyth membrane (REE),* or *primary enamel cuticle*. Ameloblasts degenerate upon completion of the REE, which covers the newly erupted tooth and is worn away by mastication and cleaning. The membrane is replaced by a thin layer of organic salivary proteins, called the *pellicle,* that precipitate on the enamel surface. Microorganisms may attach to the pellicle to form a biofilm (bacterial plaque), which, if acidogenic in nature, may become a precursor to dental disease.

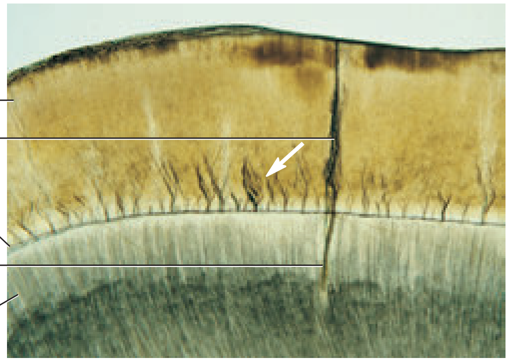
Each enamel rod contains millions of small, elongated apatite crystallites that vary in size and shape. The crystallites are tightly packed in a distinct pattern of orientation that gives strength and structural identity to the enamel rod. The long axis of the



• **Fig. 1.11** Electron micrograph of cross section of rods in mature human enamel. Crystal orientation is different in "bodies" *(B)* than in "tails" *(T).* Approximate level of magnification ×5000.(From Meckel AH, Griebstein WJ, Neal RJ: Structure of mature human dental enamel as observed by electron microscopy, *Arch Oral Biol* 10(5):775–783, 1965.)



• **Fig. 1.12** Electron micrograph of mature, hexagon-shaped enamel crystallites. (From Nanci A: *Ten Cate's oral histology: development, structure, and function*, ed 7, St Louis, 2008, Mosby.)

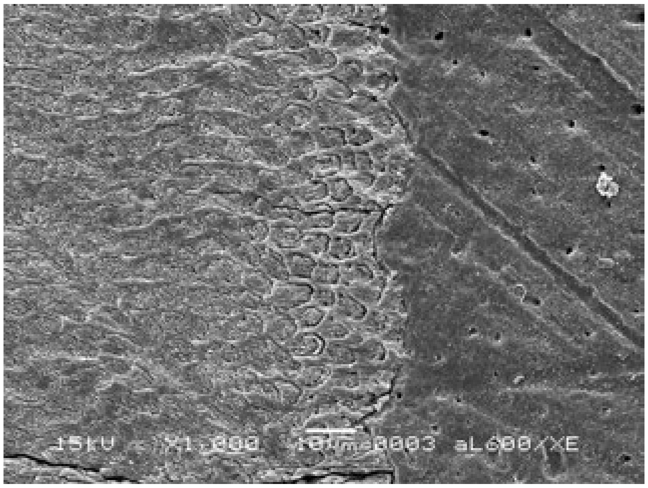


• **Fig. 1.13** Microscopic view through lamella that goes from enamel surface into dentin. Note the enamel tufts *(arrow).* (From Fehrenbach MJ, Popowics T: *Illustrated dental embryology, histology, and anatomy*, ed 4, St. Louis, 2016, Saunders. Courtesy James McIntosh, PhD, Assistant Professor Emeritus, Department of Biomedical Sciences, Baylor College of Dentistry, Dallas, TX.)

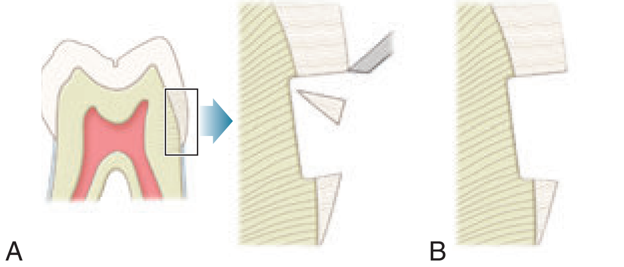
apatite crystallites within the central region of the head (body) is aligned almost parallel to the rod long axis, and the crystallites incline with increasing angles (65 degrees) to the rod axis in the tail region.

The susceptibility of these crystallites to acidic conditions, from the caries process or as a result of an etching procedure, may be correlated with their orientation. Acid-induced mineral dissolution (demineralization) occurs more in the head region of each rod. The tail region and the periphery of the head region are relatively resistant to acidic demineralization. The crystallites are irregular in shape, with an average length of 160 nm and an average width of 20 nm–40 nm. Each apatite crystallite is composed of thousands of unit cells that have a highly ordered arrangement of atoms. A crystallite may be 300 unit cells long, 40 cells wide, and 20 cells thick in a hexagonal configuration (Fig. 1.12). An organic matrix surrounds individual crystals that supports maintenance of the hierarchical structure that enables enamel to bear mechanical loads during masticatory function.

Although enamel is a hard, dense structure, it is permeable to certain ions and molecules. The route of passage may be through structural units such as rod sheaths, enamel cracks, and other defects that are hypomineralized and rich in organic content. Water plays an important role as a transporting medium through the small intercrystalline spaces. Enamel tufts are hypomineralized structures of interrod substance between adjacent groups of enamel rods that project from the DEJ (Fig. 1.13). These projections arise in dentin, extend into enamel in the direction of the long axis of the crown, and may play a role in the spread of dental caries. Enamel lamellae are thin, leaf-like faults between the enamel rod groups that extend from the enamel surface toward the DEJ, sometimes extending into dentin (Fig. 1.13). They contain mostly organic material and may predispose the tooth to the entry of bacteria and subsequent development of dental caries.



• **Fig. 1.14** Scanning electron microscope view of scalloped dentoenamel junction (DEJ; *arrow*). *E*, Enamel; *D*, dentin.



• **Fig. 1.15** (A) Enamel rods unsupported by dentin base are fractured away readily by pressure from hand instrument. (B) Cervical preparation showing enamel rods supported by dentin base.

Enamel permeability decreases with age because of changes in the enamel matrix, a decrease referred to as *enamel maturation*.

Enamel is soluble when exposed to acidic conditions, but the dissolution is not uniform. Solubility of enamel increases from the enamel surface to the DEJ. When fluoride ions are present during enamel formation or are topically applied to the enamel surface, the solubility of surface enamel is decreased. Fluoride concentration decreases toward the DEJ. Trace amounts of fluoride can affect surface hardness and stabilize enamel crystallites by lowering acid solubility, decreasing the rate of demineralization and enhancing the rate of remineralization.

Enamel is the hardest tissue of the human body. Hardness, that is, the surface resistance of a material to plastic deformation, may vary over the external tooth surface according to the location; also, it decreases inward, with hardness lowest near to the DEJ. The density of enamel also decreases from the surface to the DEJ. Enamel is a rigid structure that is both strong (high elastic modulus, high compressive strength) and brittle (inability to deform plastically under tensile stress). The ability of the enamel to withstand masticatory forces depends on a stable attachment to the dentin by means of the DEJ. Dentin is a biocomposite. In comparison with enamel, dentin is a more flexible substance (low elastic modulus) that is both strong (high compressive strength) and resilient (high tensile strength). These characteristics increase the fracture toughness (i.e., fracture resistance of a brittle material to catastrophic propagation of flaws under an applied stress) of the more superficial enamel if the DEJ is intact. The junction of enamel and dentin (DEJ) is scalloped or wavy in outline, with the crest of the waves penetrating toward enamel (Fig. 1.14). The rounded projections of enamel fit into the shallow depressions of dentin. This interdigitation may contribute to the durable connection of enamel to dentin. The DEJ is approximately 2 μm wide and comprises a mineralized complex of interwoven dentin, apatite crystals, and enamel matrix proteins. In addition to the physical, scalloped relationship between the enamel and dentin, an interphase matrix layer (made primarily of a fibrillary collagen network) extends 100 μm–400 μm from the DEJ into the enamel. This matrix-modified interphase layer is considered to provide fracture propagation-limiting properties to the interface between the enamel and the DEJ and thus the overall structural stability of the enamel attachment to dentin.[2] Enamel rods that lack a dentin base because of caries or improper preparation design are easily fractured away from neighboring rods if stressed by occlusal loads. For optimal strength in tooth preparation, all enamel rods should be supported by dentin (Fig. 1.15).

Pulp–Dentin Complex

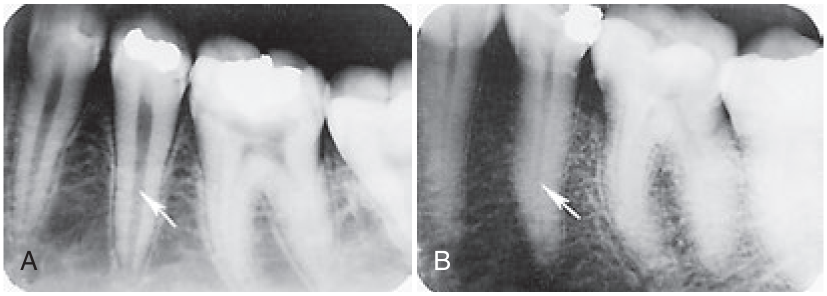
Pulp and dentin tissues are specialized connective tissues of mesodermal origin, formed from the dental papilla of the tooth bud. Many investigators consider these two tissues as a single tissue, which forms the DPC, with mineralized dentin constituting the mature end product of cell differentiation and maturation.

Dental pulp occupies the pulp cavity in the tooth and is a unique, specialized organ of the human body that serves four functions: (1) formative (developmental), (2) nutritive, (3) sensory (protective), and (4) reparative (defensive). The formative function is the production of primary and secondary dentin by odontoblasts. The nutritive function supplies mineral ions, proteins, and water to dentin through the blood supply to odontoblasts and their processes (which create dentinal tubular fluid [DTF]). The sensory function is provided by nerve fibers within the pulp that mediate the sensation of pain. Dentin nervous nociceptors are unique because various stimuli elicit only pain as a response. The pulp usually does not differentiate between heat, touch, pressure, or chemicals. Motor nerve fibers initiate reflexes in the muscles of the blood vessel walls for the control of circulation in the pulp. The defensive/reparative function is discussed in the subsequent section, The PDC: Response to Pathologic Challenge.

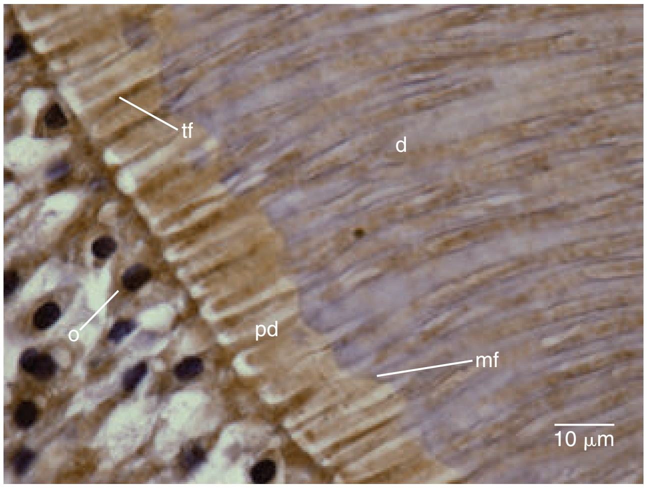
The pulp is circumscribed by dentin and is lined peripherally by a cellular layer of *odontoblasts* (which created the dentin), the cell-free zone, and the cell-rich zone. The pulp contains nerves, arterioles, venules, capillaries, lymph channels, connective tissue cells, intercellular substance, odontoblasts, fibroblasts, macrophages, collagen, and fine fibers.[3]

Anatomically, the pulp is divided into (1) coronal pulp located in the pulp chamber in the crown portion of the tooth, including the pulp horns that are located beneath the incisal ridges and cusp tips, and (2) radicular pulp located in the pulp canals in the root portion of the tooth. The radicular pulp is continuous with the periapical tissues through the apical foramen (AF) or foramina of the root. Accessory canals may extend from the pulp canals laterally through the root dentin to periodontal tissue.

Knowledge of the contour and size of the pulp cavity is essential during tooth preparation. In general, the pulp cavity is a miniature contour of the external surface of the tooth (Fig. 1.6). Pulp cavity size varies with tooth size in the same person and among individuals.



• **Fig. 1.16** Pulp cavity size. (A) Premolar radiograph of young person. (B) Premolar radiograph of older person. Note the difference in the size of the pulp cavity *(arrows).*



• **Fig. 1.17** Odontoblasts *(o)* have cell processes (Tomes fibers [tf]) that extend through the predentin *(pd)* into dentin *(d)*. *mf*, Mineralization front.

• **Fig. 1.18** Longitudinal section of enamel. Odontoblastic processes extend into enamel as enamel spindles *(A).* (From Berkovitz BKB, Holland GR, Moxham BJ: *Oral anatomy, histology and embryology*, ed 4, Edinburgh, 2009, Mosby. Courtesy Dr. R. Sprinz.)

With advancing age, the pulp cavity usually decreases in size. Radiographs are an invaluable aid in determining the size of the pulp cavity and any existing pathologic condition (Fig. 1.16). A primary clinical objective during operative procedures must be the preservation of the health of the pulp.

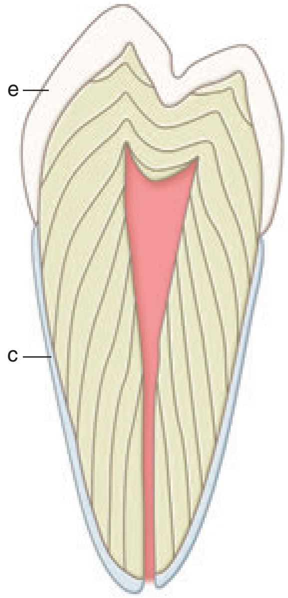
Dentin formation, *dentinogenesis,* is accomplished by the odontoblasts. These cells are considered part of both pulp and dentin tissues because their cell bodies are in the pulp cavity, and their long, slender cytoplasmic cell processes (Tomes fibers) extend well (100 µm–200 µm) into the tubules in the mineralized dentin (Fig. 1.17).

Dentin is considered a living tissue, with the capability of reacting to physiologic and pathologic stimuli because of the odontoblastic cell processes. Odontoblastic processes occasionally cross the DEJ into enamel; these are termed *enamel spindles* when their ends are thickened (Fig. 1.18). Enamel spindles may serve as pain receptors, explaining the sensitivity experienced by some patients during tooth preparation that is limited to enamel only.

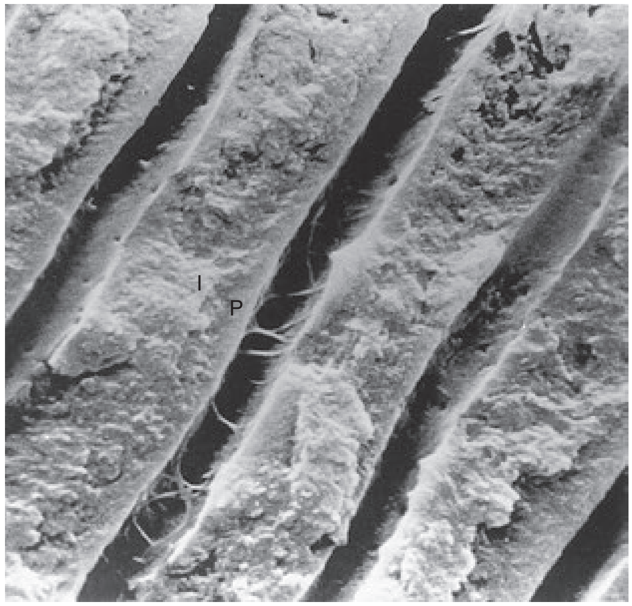
Dentin forms the largest portion of the tooth structure, extending almost the full length of the tooth. Externally, dentin is covered by enamel on the anatomic crown and cementum on the anatomic root. Internally, dentin forms the walls of the pulp cavity (pulp chamber and pulp canals) (Fig. 1.19). Dentin formation begins immediately before enamel formation. Odontoblasts generate an extracellular collagen matrix (ECM) as they begin to move away from adjacent ameloblasts. Mineralization of the ECM, facilitated by modification of the ECM by various noncollagenous proteins, gradually follows its secretion and self-assembly/organization. The most recently formed layer of dentin is always on the pulpal surface. This unmineralized zone of dentin is immediately next to the cell bodies of odontoblasts and is called *predentin* (Fig. 1.17). Dentin formation begins at areas subjacent to the cusp tip or incisal ridge and gradually spreads, at the rate of ~4 µm/day, to the apex of the root (Fig. 1.19). In contrast to enamel formation, dentin formation continues after tooth eruption and throughout the life of the pulp. The dentin forming the initial shape of the tooth is called *primary dentin* and is usually completed three years after tooth eruption (in the case of permanent teeth).

The dentinal tubules are small canals that remain from the process of dentinogenesis and extend through the entire width of dentin, from the pulp to the DEJ (Figs. 1.20 and 1.21). Each tubule contains the cytoplasmic cell process (Tomes fiber) of an odontoblast and is lined with a layer of peritubular dentin, which is much more mineralized than the surrounding intertubular dentin (Fig. 1.21).

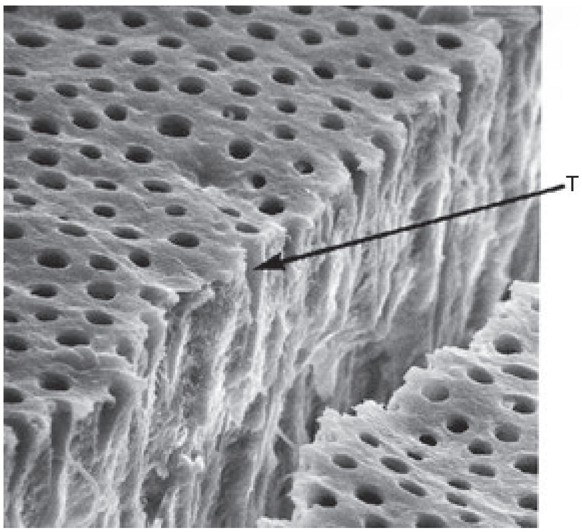
The surface area of dentin is much larger at the DEJ and dentinocemental junction (DCJ) than it is on the pulp cavity side.



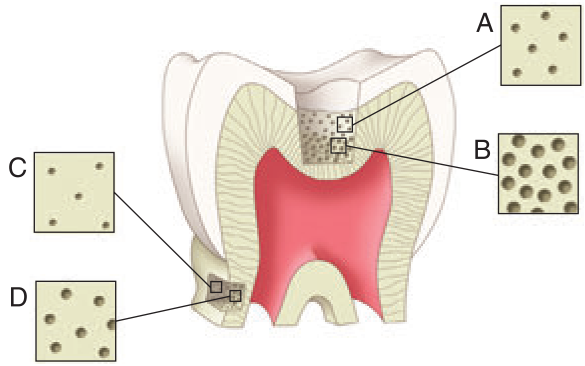
• **Fig. 1.19** Pattern of formation of primary dentin. This figure also shows enamel *(e)* covering the anatomic crown of the tooth and cementum *(c)* covering the anatomic root.



• **Fig. 1.21** Dentinal tubules in cross section, 1.2 mm from pulp. Peritubular dentin *(P)* is more mineralized than intertubular dentin *(I).* (From Brännström M: *Dentin and pulp in restorative dentistry*, London, 1982, Wolfe Medical.)



• **Fig. 1.20** Ground dentinal surface, acid-etched with 37% phosphoric acid. The artificial crack shows part of the dentinal tubules *(T).* The tubule apertures are opened and widened by acid application. (From Brännström M: *Dentin and pulp in restorative dentistry*, London, 1982, Wolfe Medical.)



• **Fig. 1.22** Tubules in superficial dentin close to the dentoenamel junction (DEJ) *(A)* are smaller and more sparsely distributed compared with deep dentin *(B).* The tubules in superficial root dentin *(C)* and deep root dentin *(D)* are smaller and less numerous than those in comparable depths of coronal dentin.

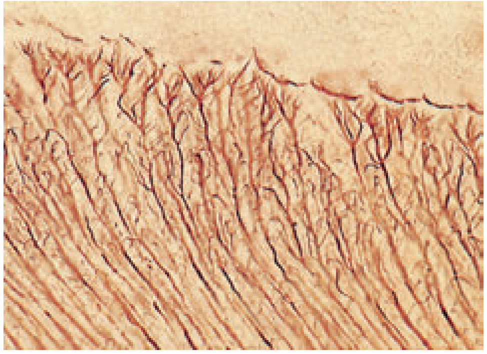
Because odontoblasts form dentin while progressing inward toward the pulp, the tubules are forced closer together. The number of tubules increases from 15,000 mm–20,000/mm^2 at the DEJ to 45,000 mm–65,000/mm^2 at the pulp.[4] The lumen of the tubules also varies from the DEJ to the pulp surface. In coronal dentin, the average diameter of tubules at the DEJ is 0.5 μm–0.9 μm, but this increases to 2 μm–3 μm near the pulp (Fig. 1.22).

The course of the dentinal tubules is a slight S-curve in the tooth crown, but the tubules are straighter in the incisal ridges, cusps, and root areas (Fig. 1.23). Tubules are generally oriented perpendicular to the DEJ. Along the tubule walls are small lateral openings called *canaliculi* or lateral canals. The lateral canals are formed as a result of the presence of secondary (lateral) branches of adjacent odontoblastic processes during dentinogenesis. Near the DEJ, the tubules are divided into several branches, forming an intercommunicating and anastomosing network (Fig. 1.24).

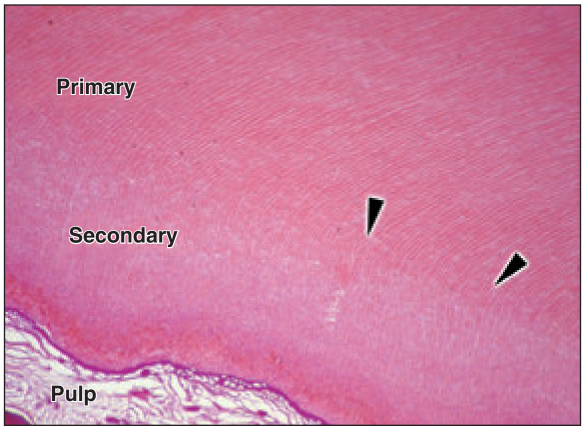
After the primary dentin is formed, dentin deposition continues at a reduced rate (~0.4 μm/day) even without obvious external stimuli, although the rate and amount of physiologic secondary dentin may vary considerably among individuals. In contrast to the primary dentin, the tubules take a slightly different directional pattern in the secondary dentin (Fig. 1.25). The secondary dentin forms on all internal aspects of the pulp cavity, but in the pulp chamber, in multirooted teeth, it tends to be thicker on the roof and floor than on the side walls.[5]

The walls of the dentinal tubules (peritubular dentin) in the primary dentin gradually thicken, through ongoing mineral deposition, with age. The dentin therefore becomes harder, denser,

• **Fig. 1.23** Ground section of human incisor. Course of dentinal tubules is in a slight S-curve in the crown, but straight at the incisal tip and in the root. (From Young B, Lowe JS, Stevens A, Heath JW: *Wheater's functional histology: a text and colour atlas*, ed 5, Edinburgh, 2006, Churchill Livingstone.)



• **Fig. 1.24** Ground section showing dentinal tubules and their lateral branching close to the dentoenamel junction (DEJ). (From Berkovitz BKB, Holland GR, Moxham BJ: *Oral anatomy, histology, and embryology*, ed 4, Edinburgh, 2010, Mosby.)



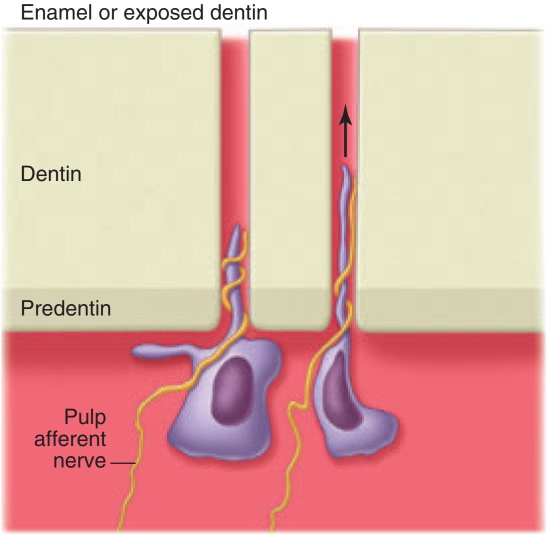
• **Fig. 1.25** Ground section of dentin with pulpal surface at right. Dentinal tubules curve sharply as they move from primary to secondary dentin. Dentinal tubules are more irregular in shape in secondary dentin. (From Nanci A: *Ten Cate's oral histology: development, structure, and function*, ed 8, St. Louis, 2013, Mosby.)

and, because tubular fluid flow becomes more restricted as the lumen spaces become smaller, less sensitive. The increased amount of mineral in the primary dentin is defined as *dentin sclerosis (DS)*. Dentin sclerosis resulting from aging is called *physiologic dentin sclerosis.*

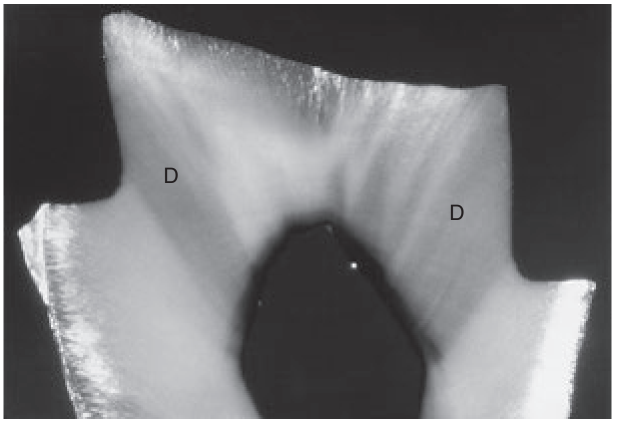
Human dentin is a natural biocomposite containing approximately 50% inorganic material and 30% organic material by volume. The organic material is approximately 90% type I collagen and 10% noncollagenous proteins. Dentin is less mineralized than enamel but more mineralized than cementum or bone. The mineral content of dentin increases with age. The mineral phase is composed primarily of (HA) crystallites, which are arranged in a less systematic manner than enamel crystallites. Dentinal crystallites are smaller than enamel crystallites, having a length of 20 nm–100 nm and a width of about 3 nm, which is similar to the size seen in bone and cementum.[5] Dentin is significantly softer than enamel but harder than bone or cementum. The hardness of dentin averages one-fifth to that of enamel, and its hardness near the DEJ is about three times greater than near the pulp. Although dentin is a hard, mineralized tissue, it is flexible, with a modulus of elasticity of approximately 18 gigapascals (GPa).[6] This flexibility helps support the more brittle, less-resilient enamel. Dentin is not as prone to fracture as is the enamel rod structure. Often small "craze lines" are seen in enamel, indicating minute fractures of that structure. The craze lines usually are not clinically significant unless associated with cracks in the underlying dentin (Fig 1.26). The ultimate tensile strength of dentin is approximately 98 megapascals (MPa), whereas the ultimate tensile strength of enamel is approximately 10 MPa. The compressive strength of dentin and enamel are approximately 297 MPa and 384 MPa, respectively.[6]

During tooth preparation, dentin usually is distinguished from enamel by (1) color and opacity, (2) reflectance, and (3) hardness.

• **Fig. 1.26** Enamel craze lines that form secondary to heavy occlusal loading during mastication and/or parafunctional activity.



• **Fig. 1.27** Stimuli that induce rapid fluid movements in dentinal tubules distort odontoblasts and afferent nerves *(arrow)*, leading to a sensation of pain. Many operative procedures such as cutting or air-drying induce rapid fluid movement.



• **Fig. 1.28** Ground section of MOD (mesio-occluso-distal) tooth preparation of a third molar. Dark blue dye was placed in the pulp chamber under pressure after tooth preparation. Dark areas of dye penetration *(D)* show that the dentinal tubules of axial walls are much more permeable than those of the pulpal floor of preparation.

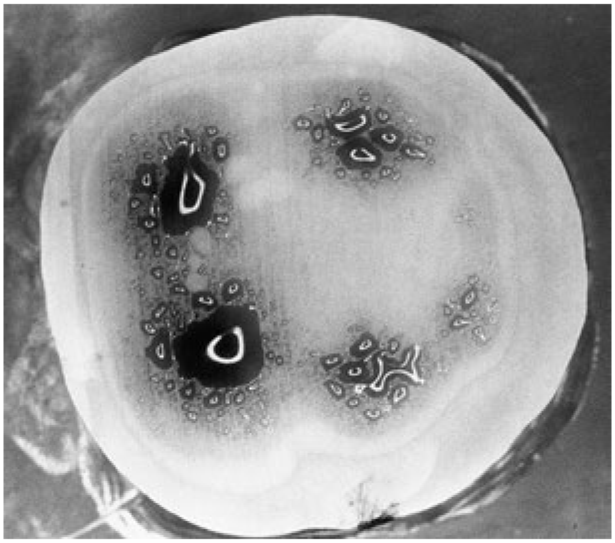
Dentin is normally yellow-white and slightly darker than enamel. In older patients, dentin is darker, and it can become brown or black when it has been exposed to oral fluids, old restorative materials, or slowly advancing caries. Dentin surfaces are more porous, which makes them appear opaque and dull (less reflective to light) as compared with enamel surfaces, which appear translucent and shiny. Dentin is generally softer than enamel and provides greater yield to the pressure of a sharp explorer tip, but this is region-specific. Dentin in close proximity to the pulp is softer than in more peripheral areas.

Dentin sensitivity is perceived whenever nociceptor afferent nerve endings, in close proximity to odontoblastic processes within the dental tubules, are depolarized. The nerve transduction is most often interpreted by the central nervous system (CNS) as pain. Physical, thermal, chemical, bacterial, and traumatic stimuli are remote from the nerve fibers and are detected through the fluid-filled dentinal tubules (i.e., the dentinal fluid), although the precise mechanism of detection has not been conclusively established. The most accepted theory of stimulus detection is the *hydrodynamic theory,* which suggests that stimulus-initiated rapid dentinal fluid movement within the tubules accounts for nerve depolarization.[7] Operative procedures that involve cutting, drying, pressure changes, osmotic shifts, or changes in temperature result in rapid dentinal fluid movement, which is perceived as pain (Fig. 1.27).

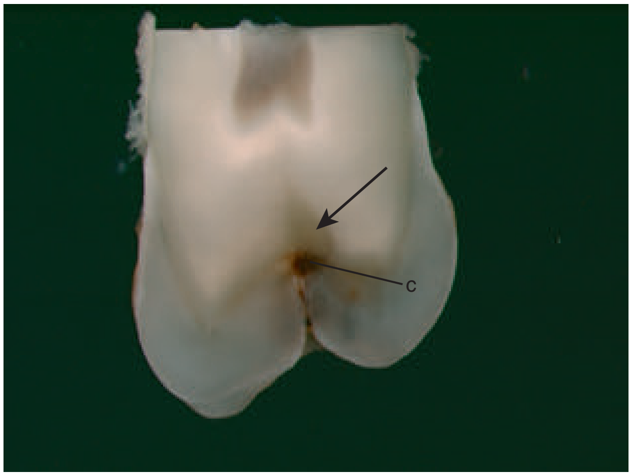
Dentinal tubules are filled with dentinal fluid, a transudate of plasma that contains all components necessary for mineralization to occur and provide protective responses. These components include water, matrix proteins, matrix-modifying proteins, mineral ions, and immunoglobulins.[8,9] The vital dental pulp has a slight positive pressure that results in continual dentinal fluid flow toward the external surface of the tooth. Enamel and cementum, though semipermeable, provide an effective layer serving to protect the underlying dentin and limit tubular fluid flow. When enamel or cementum is removed during tooth preparation, the protective layer is lost, allowing increased tubular fluid movement toward the cut surface. Permeability studies of dentin indicate that tubules are functionally much smaller than would be indicated by their measured microscopic dimensions as a result of numerous constrictions along their paths (Fig. 1.21).[10] Dentin permeability is not uniform throughout the tooth. Coronal dentin is much more permeable than root dentin. There also are differences within coronal dentin (Figs. 1.22 and 1.28).[11] Dentin permeability primarily depends on the remaining dentin thickness (i.e., length of the tubules) and the diameter of the tubules. Because the tubules are shorter, more numerous, and larger in diameter closer to the pulp, deep dentin is a less effective pulpal barrier compared with superficial dentin (Figs. 1.22 and 1.29).

The Pulp–Dentin Complex: Response to Pathologic Challenge

The PDC responds to tooth pathology through pulpal immune-inflammation defense systems and dentin repair/formation.



• **Fig. 1.29** Horizontal section in the occlusal third of a molar crown. Dark blue dye was placed in the pulp chamber under pressure. Deep dentin areas (over pulp horns) are much more permeable than superficial dentin. (From Pashley DH, Andringa HJ, Derkson GD, Derkson ME, Kalathoor SR: Regional variability in the permeability of human dentin, *Arch Oral Biol* 32:519–523, 1987, with permission from Pergamon, Oxford, UK.)



• **Fig. 1.30** Transparent dentin *(arrow)* beneath a caries lesion *(c).*

The defensive and reparative functions of the pulp are mediated by an extremely complex host-defense response to bacterial, chemical, mechanical, and/or thermal irritation.[12] Primary odontoblasts are the first to respond to lesion formation and communicate with the deeper pulp tissue (via cytokines and chemokines) such that an adaptive and innate inflammatory reaction begins. Mild to moderate injury normally causes a reversible inflammatory response in the pulp, referred to as *reversible pulpitis,* which resolves when the pathology is removed. Moderate to severe injury (e.g., deep caries) may cause the degeneration of the affected odontoblastic processes and death of the corresponding primary odontoblasts. Toxic bacterial products, molecules released from the demineralized dentin matrix, and/or high concentrations of inflammatory response mediators may signal death of the primary odontoblasts. In cases of severe injury, an irreversible inflammatory response of the pulp *(irreversible pulpitis)* will ultimately result in capillary dilation, local edema, stagnation of blood flow, anoxia, and ultimately pulpal necrosis (see Chapter 2).

Very early host-defense processes in primary dentin seek to block the advancement of a caries lesion by means of the precipitation of mineral in the lumens of the dentinal tubules of the affected area. The physical occlusion of the tubular lumens increases the ability of light to pass through this localized region (i.e., increases its transparency). This dentin is referred to as *transparent dentin* (Fig. 1.30).[13] Dentin in this area is not as hard as normal primary dentin because of mineral loss in the intertubular dentin (see Chapter 2). Successful host-defense repair processes result in the remineralization of the intertubular dentin, in addition to the mineral occlusion of the dentinal tubules, such that the final hardness of the dentin in this affected area is greater than normal primary dentin. The increased overall mineralization of this caries-affected primary dentin is referred to as *reactive dentin sclerosis*.

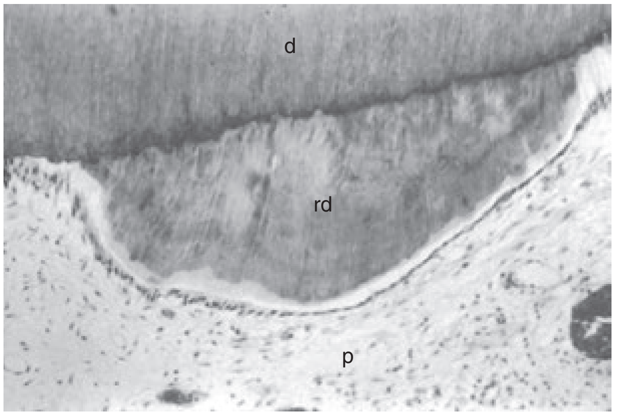
Deep dentin formation processes occur simultaneously with the pulpal inflammatory response and result in the generation of *tertiary dentin* at the pulp–dentin interface. The net effect of these processes is to increase the thickness/effectiveness of the dentin as a protective barrier for the pulp tissue. Two types of tertiary dentin form in response to lesion formation. In the case of mild injury (e.g., a shallow caries lesion), primary odontoblasts initiate increased formation of dentin along the internal aspect of the dentin beneath the affected area through secretion of *reactionary tertiary dentin* (or "reactionary dentin"). Reactionary dentin is tubular in nature and is continuous with primary and secondary dentin.

More severe injury (e.g., a deep caries lesion) causes the death of the primary odontoblasts. When therapeutic steps successfully resolve the injury, replacement cells (variously referred to as *secondary odontoblasts, odontoblast-like cells,* or *odontoblastoid cells*) differentiate from pulpal mesenchymal stem cells (MSCs). The secondary odontoblasts subsequently generate *reparative tertiary dentin* (or "reparative dentin") as a part of the ongoing host defense. Reparative dentin usually appears as a localized dentin deposit on the wall of the pulp cavity immediately subjacent to the area on the tooth that had received the injury (Fig. 1.31). Reparative dentin is generally atubular and therefore structurally different from the primary and secondary dentin.

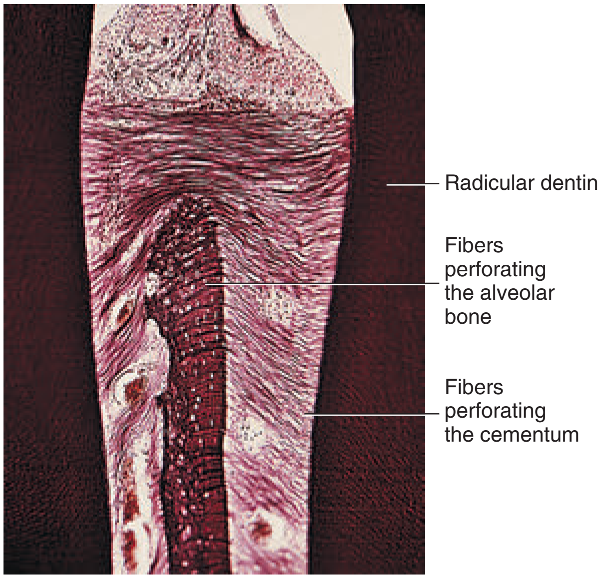
Cementum

Cementum is a thin layer of hard dental tissue covering the anatomic roots of teeth. It is formed by cells known as *cementoblasts,* which develop from undifferentiated MSCs in the connective tissue of the dental follicle. Cementum is slightly softer than dentin and consists of about 45%–50% inorganic material (hydroxyapatite) by weight and 50%–55% organic matter and water by weight. The organic portion is composed primarily of collagen and protein polysaccharides (PC). *Sharpey fibers* are portions of the principal collagen fibers of the periodontal ligament (PDL) embedded in cementum and alveolar bone to attach the tooth to the alveolus (Fig. 1.32). Cementum is avascular.

Cementum is yellow and slightly lighter in color than dentin. It is formed continuously throughout life because, as the superficial layer of cementum ages, a new layer of cementum is deposited to keep the attachment intact. *Acellular cementum* (i.e., there are no cementoblasts) is predominately associated with the coronal half of the root. *Cellular cementum* is more frequently associated with the apical half of the root. Cementum on the root end surrounds the AF and may extend slightly onto the inner wall of the pulp canal. Cementum thickness may increase on the root end to



• Fig. 1.31 Reparative dentin in response to a caries lesion. *d*, Dentin; *rd*, reparative dentin; *p*, pulp. (From Trowbridge HO: Pulp biology: Progress during the past 25 years, *Aust Endo J* 29(1):5–12, 2003.)

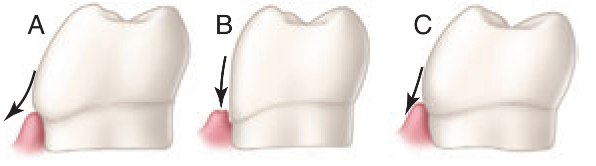


• Fig. 1.32 Principal fibers of periodontal ligament continue into surface layer of cementum as Sharpey fibers. (Modified from Chiego DJ Jr: *Essentials of oral histology and embryology: A clinical approach*, ed 4, St Louis, 2014, Mosby.)

compensate for attritional wear of the occlusal or incisal surface and passive eruption of the tooth.

The cementodentinal junction (CDJ) is relatively smooth in the permanent tooth. The attachment of cementum to dentin, although not completely understood, is very durable. Cementum joins enamel to form the CEJ. In about 10% of teeth, enamel and cementum do not meet, and this can result in a sensitive area as the openings of the dentinal tubules are not covered. Abrasion, erosion, caries, scaling, and restoration finishing/polishing procedures may denude dentin of its cementum covering. This may lead to sensitivity to various stimuli (e.g., heat, cold, sweet substances, sour substances). Limited cementum remodeling ("turnover") is possible though this is poorly understood.[14] Resorption of the apical portion of the root cementum and dentin may occur, however, if orthodontic forces result in tooth movement that is faster than alveolar bone remodeling processes will allow (Fig. 1.33).

• Fig. 1.33 Radiograph showing root resorption on lateral incisor after orthodontic tooth movement.



• Fig. 1.34 Contours. Arrows show pathways of food passing over facial surface of mandibular molar during mastication. (A) Overcontour deflects food from gingiva and results in understimulation of supporting tissues. (B) Undercontour of tooth may result in irritation of soft tissue. (C) Correct contour permits adequate stimulation and protection of supporting tissue.

Physiology of Tooth Form

Function

Teeth serve four main functions: (1) mastication, (2) esthetics, (3) speech, and (4) protection of supporting tissues. Normal tooth form and proper alignment ensure efficiency in the incising and reduction of food. The various tooth classes—incisors, canines, premolars, and molars—perform specific functions in the masticatory process and in the coordination of the various muscles of mastication. The form and alignment of anterior teeth contribute to the esthetics of personal physical appearance. The form and alignment of anterior and posterior teeth assist in the articulation of certain sounds so as to effect proper speech. Finally, the form and alignment of teeth assist in the development and protection of supporting gingival tissue and alveolar bone.

Contours

Facial and lingual surfaces possess a degree of convexity that affords protection and stimulation of supporting tissues during mastication. The convexity generally is located at the cervical third of the crown on the facial surfaces of all teeth and the lingual surfaces of incisors and canines. Lingual surfaces of posterior teeth usually have their height of contour in the middle third of the crown. Normal tooth contours act in deflecting food only to the extent that the passing food stimulates (by gentle massage) and does not irritate (abrade) supporting soft tissues. If these curvatures are too great, tissues usually receive inadequate stimulation by the passage of food. Too little contour may result in trauma to the attachment apparatus. Normal tooth contours must be recreated during restorative dental procedures. Improper location and degree of facial or lingual convexities may result in iatrogenic injury, as illustrated in Fig. 1.34, in which the proper facial contour is disregarded in the design of the cervical area of a mandibular molar restoration. Overcontouring is the worst offender, usually resulting in an increased plaque retention that leads to a chronic inflammatory state of the gingiva. Evidence shows that overhanging restorations result in a shift of the subgingival microflora resembling what is typically found in chronic periodontitis.[15]

Proper form of the proximal surfaces of teeth is just as important to the maintenance of periodontal tissue health as is the proper form of facial and lingual surfaces. The proximal height of contour serves to provide (1) contacts with the proximal surfaces of adjacent teeth, thus preventing food impaction; and (2) adequate embrasure space (immediately apical to the contacts) for gingival tissue, supporting bone, blood vessels, and nerves that serve the supporting structures (Fig. 1.35).

• **Fig. 1.35** Portion of skull showing triangular spaces beneath the proximal contact areas that are normally filled with soft tissue. See Fig. 1.38.

Proximal Contact Area

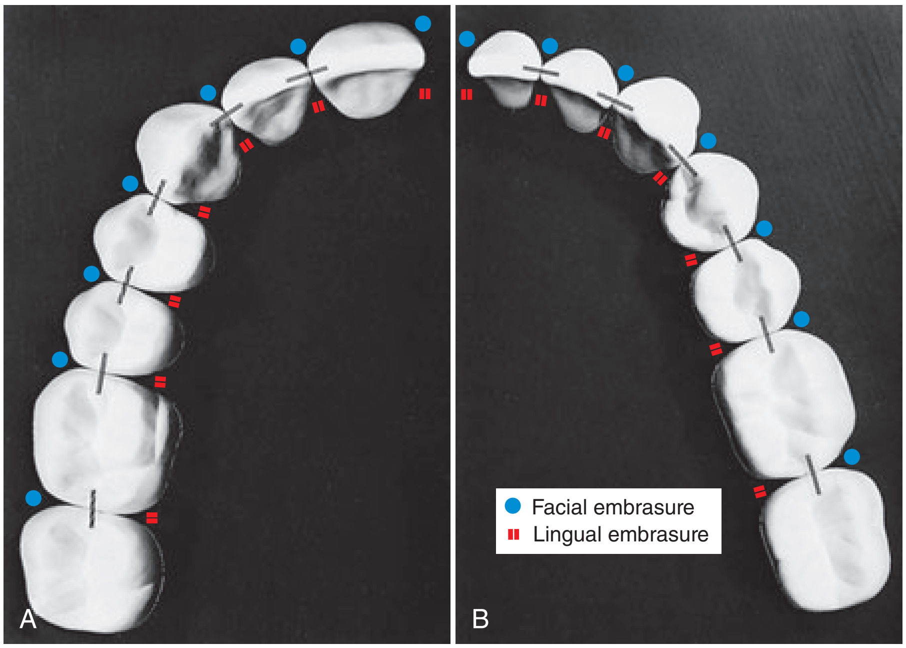
When teeth initially erupt to make proximal contact with previously erupted teeth, a contact *point* is present. The contact point increases in size to become a proximal contact *area* as the two adjacent tooth surfaces abrade each other during physiologic tooth movement (Figs. 1.36 and 1.37).

The physiologic significance of properly formed and located proximal contacts cannot be overemphasized; they promote normal healthy interdental papillae filling the interproximal spaces. Improper contacts may result in pathogenic biofilm formation and/or food impaction between teeth, potentially increasing the risk of PD, caries, and tooth movement. In addition, retention of food is objectionable because of its physical presence and the halitosis that results from food decomposition. Proximal contacts and interdigitation of maxillary and mandibular teeth, through occlusal contact areas, stabilize and maintain the integrity of the dental arches.

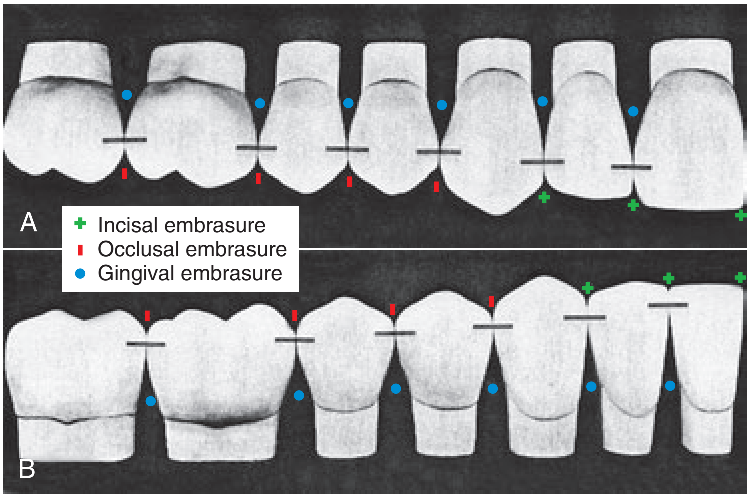
The proximal contact area is located in the incisal third of the approximating surfaces of maxillary and mandibular central incisors (Fig. 1.37). It is positioned slightly facial to the center of the proximal surface faciolingually (Fig. 1.36). Proceeding posteriorly from the incisor region through all the remaining teeth, the contact area is located near the junction of the incisal (or occlusal) and middle thirds or in the middle third. Proximal contact areas typically are larger in the molar region, which helps prevent gingival food impaction during mastication. Adjacent surfaces near the proximal contacts (embrasures) usually have remarkable symmetry.

Embrasures

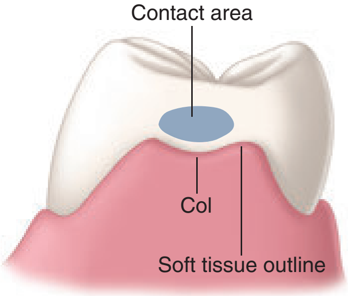
Embrasures are V-shaped spaces that originate at the proximal contact areas between adjacent teeth and are named for the direction toward which they radiate. These embrasures are (1) facial, (2) lingual, (3) incisal or occlusal, and (4) gingival (Figs. 1.36 and 1.37).



• **Fig. 1.36** Proximal contact areas. Black lines show positions of contact faciolingually. (A) Maxillary teeth. (B) Mandibular teeth. Facial and lingual embrasures are indicated.



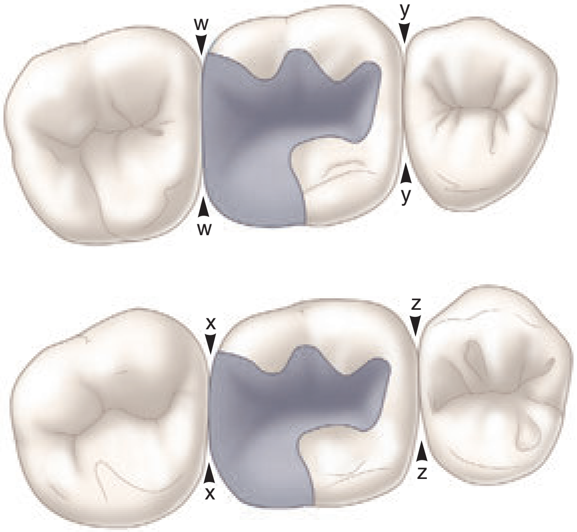
• **Fig. 1.37** Proximal contact areas. Black lines show positions of contact incisogingivally and occlusogingivally. Incisal, occlusal, and gingival embrasures are indicated. (A) Maxillary teeth. (B) Mandibular teeth.



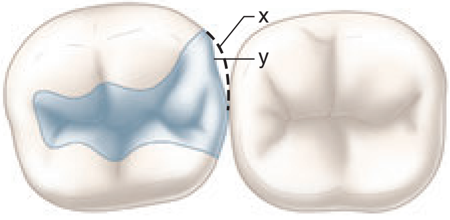
• **Fig. 1.38** Relationship of ideal interdental papilla to molar contact area.

Initially, the interdental papilla fills the gingival embrasure. When the form and function of teeth are ideal and optimal oral health is maintained, the interdental papilla may continue in this position throughout life. When the gingival embrasure is filled by the papilla, trapping of food in this region is prevented. In a faciolingual vertical section, the papilla is seen to have a triangular shape between anterior teeth, whereas in posterior teeth, the papilla may be shaped like a mountain range, with facial and lingual peaks and the col ("valley") lying beneath the contact area (Fig. 1.38). This col, a central faciolingual concave area beneath the contact, is more vulnerable to PD from incorrect contact and embrasure form because it is covered by nonkeratinized epithelium.

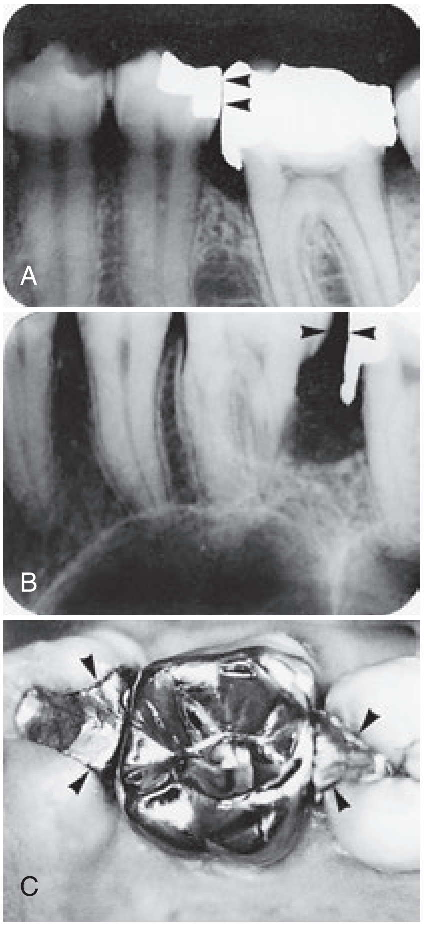
The correct relationships of embrasures, cusps to sulci, marginal ridges, and grooves of adjacent and opposing teeth provide for the escape of food from the occlusal surfaces during mastication. When an embrasure is decreased in size or absent, additional stress is created on teeth and the supporting structures during mastication. Embrasures that are too large provide little protection to the supporting structures as food is forced into the interproximal space by an opposing cusp (Fig. 1.39). A prime example is the failure to restore the distal cusp of a mandibular first molar when placing a restoration (Fig. 1.40). Lingual embrasures are usually larger than facial embrasures; this allows more food to be displaced lingually because the tongue can return the food to the occlusal surface more easily than if the food is displaced facially into the buccal vestibule (Fig. 1.36). The marginal ridges of adja-



• **Fig. 1.39** Embrasure form. *w*, Improper embrasure form caused by overcontouring of restoration resulting in unhealthy gingiva from lack of stimulation. *x*, Good embrasure form. *y*, Frictional wear of contact area has resulted in decrease of embrasure dimension. *z*, When the embrasure form is good, supporting tissues receive adequate stimulation from foods during mastication.



• **Fig. 1.40** Embrasure form. *x*, Portion of tooth that offers protection to underlying supporting tissue during mastication. *y*, Restoration fails to establish adequate contour for good embrasure form.



• **Fig. 1.41** Poor anatomic restorative form. (A) Radiograph of flat contact/amalgam gingival excess and resultant vertical osseous loss. (B) Radiograph of restoration with amalgam gingival excess and absence of contact resulting in osseous loss, adjacent root caries. (C) Poor embrasure form and restoration margins.

cent posterior teeth should be at the same height to have proper contact and embrasure forms. When this relationship is absent, it may cause an increase in the problems associated with inadequate proximal contacts and faulty embrasure forms.

Preservation of the curvatures of opposing cusps and surfaces in function maintains masticatory efficiency throughout life (Fig. 1.5). Correct anatomic form renders teeth more self-cleansing because of the smoothly rounded contours that are more exposed to the cleansing action of foods and fluids and the frictional movement of the tongue, lips, and cheeks. Failure to understand and adhere to correct anatomic form may contribute to the breakdown of the restored system (Fig. 1.41).

Coronal Exposure

The amount of coronal tooth structure exposed to the oral environment influences the esthetics of the smile (see Chapter 12). The *anatomic crown* is the part of the tooth crown that is covered by enamel. Tooth eruption typically does not result in exposure of the complete anatomic crown, particularly in the early lifecycle of the tooth. The visible part of the enamel present after eruption is termed the *clinical crown.* The visible amount of the clinical crown continues to change over time. Initially, the clinical crown is less than the anatomic crown. When root exposure occurs due to gingival recession or due to compensatory eruption in response to tooth wear, the clinical crown is greater than the anatomic crown. The American Academy of Periodontology (AAP) Glossary of Periodontal Terms defines *active eruption* as the process by which a tooth moves from its germinative position to its functional position in occlusion with the opposing arch and *passive eruption* as tooth exposure secondary to apical migration of the gingival margin to a location at or slightly coronal to the CEJ.[16] Disruption of any of these processes is known as *altered active eruption* (AAE) and *altered passive eruption* (APE). Both AAE and APE may result in a short clinical crown. When evaluating patients for esthetic dental procedures, the amount of gingival display (i.e., the amount of clinical crown) is noted with excessive display of the gingiva being described as a "gummy smile." Other causes of a "gummy smile" include vertical maxillary excess, dento-alveolar extrusion, lip hypermobility, and a short upper lip.[17]

Maxilla and Mandible

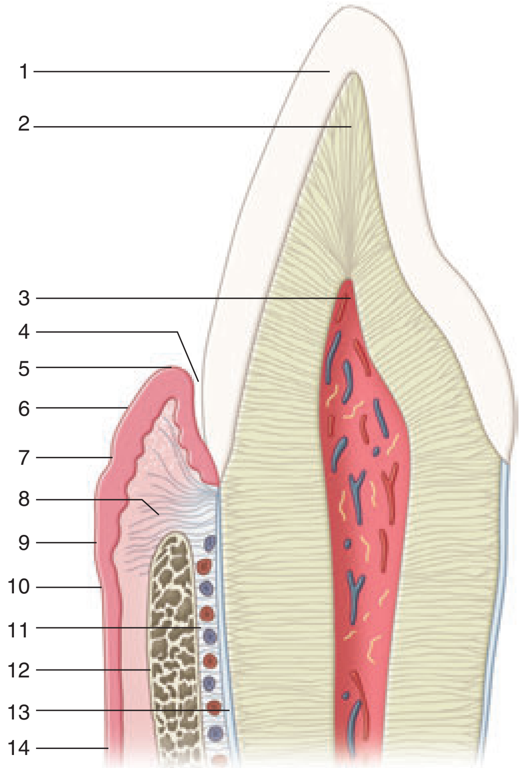
The human maxilla is formed by two bones, the maxilla proper and the premaxilla. These two bones form the bulk of the upper jaw and the major portion of the hard palate and help form the floor of the orbit and the sides and base of the nasal cavity. They contain 10 maxillary primary teeth initially and later contain 16 maxillary permanent teeth in the alveolar process (Figs. 1.1 and 1.6, *label 7*).

The mandible, or the lower jaw, is horseshoe-shaped and relates to the skull on either side via the TMJs. The mandible is composed of a body of two horizontal portions joined at the midline symphysis mandibulae and the rami, the vertical parts. The coronoid process and the condyle make up the superior border of each ramus. The mandible initially contains 10 mandibular primary teeth and later 16 mandibular permanent teeth in the alveolar process. Maxillary and mandibular bones comprise approximately 38%–43% inorganic material and 34% organic material by volume. The inorganic material is HA, and the organic material is primarily type I collagen, which is surrounded by a ground substance of glycoproteins and proteoglycans. Vitality of these structures is maintained via vascularity and innervation.

Oral Mucosa

The oral mucosa is the mucous membrane that covers all oral structures except the clinical crowns of teeth. It is composed of two layers: (1) the stratified squamous epithelium (SSE) and (2) the supporting connective tissue, called *lamina propria (LP)* (see the LP of the gingiva in Fig. 1.42, *indicator 8*). The epithelium may be keratinized, parakeratinized, or nonkeratinized, depending on its location. The LP varies in thickness and supports the epithelium. It may be attached to the periosteum of alveolar bone, or it may be interposed over the submucosa, which may vary in different regions of the mouth (e.g., the floor of the mouth, the soft palate). The submucosa, consisting of connective tissues varying in density and thickness, attaches the mucous membrane to the underlying bony structures. The submucosa contains glands, blood vessels, nerves, and adipose tissue.

Oral mucosa is classified into three major functional types: (1) masticatory mucosa, (2) lining or reflective mucosa, and (3) specialized mucosa. The masticatory mucosa comprises the free and attached gingiva (Fig. 1.42, *indicators 6 and 9*) and the mucosa of the hard palate. The epithelium of these tissues is keratinized, and



• **Fig. 1.42** Vertical section of a mandibular incisor illustrating supporting structures: *1*, enamel; *2*, dentin; *3*, pulp; *4*, gingival sulcus; *5*, free gingival margin; *6*, free gingiva; *7*, free gingival groove; *8*, lamina propria of gingiva; *9*, attached gingiva; *10*, mucogingival junction; *11*, periodontal ligament; *12*, alveolar bone; *13*, cementum; *14*, alveolar mucosa.

the LP is a dense, thick, firm connective tissue containing collagen fibers. The hard palate has a distinct submucosa except for a few narrow specific zones. The dense LP of the attached gingiva is connected to the cementum and periosteum of the bony alveolar process (Fig. 1.42, *indicator 8*).

The lining or reflective mucosa covers the inside of the lips, cheek, and vestibule, the lateral surfaces of the alveolar process (except the mucosa of the hard palate), the floor of the mouth, the soft palate, and the ventral surface of the tongue. The lining mucosa is a thin, movable tissue with a relatively thick, nonkeratinized epithelium and a thin LP. The submucosa comprises mostly thin, loose connective tissue with muscle and collagenous and elastic fibers, with different areas varying from one another in their structures. The junction of the lining mucosa and the masticatory mucosa is the mucogingival junction (MGJ), located at the apical border of the attached gingiva facially and lingually in the mandibular arch and facially in the maxillary arch (Fig. 1.42, *indicator 10*). The specialized mucosa covers the dorsum of the tongue and the taste buds. The epithelium is nonkeratinized except for the covering of the dermal filiform papillae.

Periodontium

The periodontium consists of the oral hard and soft tissues that invest and support teeth. It may be divided into (1) the gingival unit, consisting of free and attached gingiva and the alveolar mucosa, and (2) the attachment apparatus, consisting of cementum, the PDL, and the alveolar process (Fig. 1.42).

Gingival Unit

As mentioned, the free gingiva and the attached gingiva together form the masticatory mucosa. The free gingiva is the gingiva from the marginal crest to the level of the base of the gingival sulcus (Fig. 1.42, *indicators 4 and 6*). The gingival sulcus is the space between the tooth and the free gingiva. The outer wall of the sulcus (inner wall of the free gingiva) is lined with a thin, nonkeratinized epithelium. The outer aspect of the free gingiva in each gingival embrasure is called *gingival* or *interdental papilla*. The free gingival groove is a shallow groove that runs parallel to the marginal crest of the free gingiva and usually indicates the level of the base of the gingival sulcus (Fig. 1.42, *indicator 7*).

The attached gingiva, a dense connective tissue with keratinized, SSE, extends from the depth of the gingival sulcus to the MGJ. A dense network of collagen fibers connects the attached gingiva firmly to cementum and the periosteum of the alveolar process (bone).

The alveolar mucosa is a thin, soft tissue that is loosely attached to the underlying alveolar bone (Fig. 1.42, *indicators 12 and 14*). It is covered by a thin, nonkeratinized epithelial layer. The underlying submucosa contains loosely arranged collagen fibers, elastic tissue, fat, and muscle tissue. The alveolar mucosa is delineated from the attached gingiva by the MCJ and continues apically to the vestibular fornix and the inside of the cheek.

Clinically, the level of the gingival attachment and gingival sulcus is an important factor in restorative dentistry. Soft tissue health must be maintained by teeth having the correct anatomic form and position to prevent recession of the gingiva and possible abrasion and erosion of the root surfaces. The margin of a tooth preparation should not be positioned subgingivally (at levels between the marginal crest of the free gingiva and the base of the sulcus) unless dictated by caries, previous restoration, esthetics, or other preparation requirements (see Chapter 12).

Attachment Apparatus

The tooth root is attached to the alveolus (bony socket) by the PDL (Fig. 1.42, *indicator 11*), which is a complex connective tissue containing numerous cells, blood vessels, nerves, and an extracellular substance consisting of fibers and ground substance. Most of the fibers are collagen, and the ground substance is composed of a variety of proteins and polysaccharides. The PDL serves the following functions: (1) attachment and support, (2) sensory, (3) nutritive, and (4) homeostatic. Bundles of collagen fibers, known as *principal fibers of the ligament,* serve to connect cementum and alveolar bone in order to suspend and support the tooth. Coordination of masticatory muscle function is achieved, through an efficient proprioceptive mechanism, by the sensory nerves located in the PDL. Blood vessels supply the attachment apparatus with nutritive substances. Specialized cells of the ligament function to resorb and replace cementum, the PDL, and alveolar bone.

The alveolar process—a part of the maxilla and the mandible—forms, supports, and lines the sockets into which the roots of teeth fit. Anatomically, no distinct boundary exists between the body of the maxilla or the mandible and the alveolar process. The alveolar process comprises thin, compact bone with many small openings through which blood vessels, lymphatics, and nerves pass. The wall of the bony socket consists of the thin lamella of bone that surrounds the root of the tooth and is termed *alveolar bone proper*. The second part of the bone is called *supporting alveolar bone,* which surrounds and supports the alveolar bone proper. Supporting bone is composed of two parts: (1) the cortical plate, consisting of compact bone and forming the inner (lingual) and outer (facial) plates of the alveolar process, and (2) the spongy base that fills the area between the plates and the alveolar bone proper.

Occlusion

Occlusion literally means "closing." In dentistry, occlusion means the contact of teeth in opposing dental arches when the jaws are closed (static occlusal relationships) and during various jaw movements (dynamic occlusal relationships). The size of the jaw and the arrangement of teeth within the jaw are subject to a wide range of variation. The locations of contacts between opposing teeth (occlusal contacts) vary as a result of differences in the sizes and shapes of teeth and jaws and the relative position of the jaws. A wide variety of occlusal schemes are found in healthy individuals. Consequently, definition of an ideal occlusal scheme is fraught with difficulty.[18] Repeated attempts have been made to describe an ideal occlusal scheme, but these descriptions are so restrictive that few individuals can be found to fit the criteria. Failing to find a single adequate definition of an ideal occlusal scheme has resulted in the conclusion that "in the final analysis, optimal function and the absence of disease is the principal characteristic of a good occlusion."[18] The dental relationships described in this section conform to the concepts of normal, or usual, occlusal schemes and include common variations of tooth-and-jaw relationships. The masticatory system (muscles, TMJs, and teeth) is highly adaptable and usually able to successfully function over a wide range of differences in jaw size and tooth alignment. Despite this great adaptability, however, some patients are highly sensitive to changes in tooth contacts (which influence the masticatory muscles and TMJs), which may be brought about by orthodontic and/or restorative dental procedures.

Occlusal contact patterns vary with the position of the mandible. Static occlusion is defined further by using reference positions that include fully closed, terminal hinge (TH) closure, retruded, protruded, and right and left lateral extremes. The number and location of occlusal contacts between opposing teeth have important effects on the amount and direction of muscle force applied during mastication and other parafunctional activities such as mandibular clenching, tooth grinding, or a combination of both (bruxism). In extreme cases, these forces damage the teeth and/or their supporting tissues. Forceful tooth contact occurs routinely near the limits or borders of mandibular movement, showing the relevance of these reference positions.[19]

Tooth contact during mandibular movement is termed *dynamic occlusal relationship*. Gliding or sliding contacts occur during mastication and other mandibular movements. Gliding contacts may be advantageous or disadvantageous, depending on the teeth involved, the position of the contacts, and the resultant masticatory muscle response. The design of the restored tooth surface will have important effects on the number and location of occlusal contacts, and both static and dynamic relationships must be taken into consideration. The following sections discuss common arrangements and variations of teeth and the masticatory system. Mastication and the contacting relationships of anterior and posterior teeth are described with reference to the potential restorative needs of teeth.

General Description

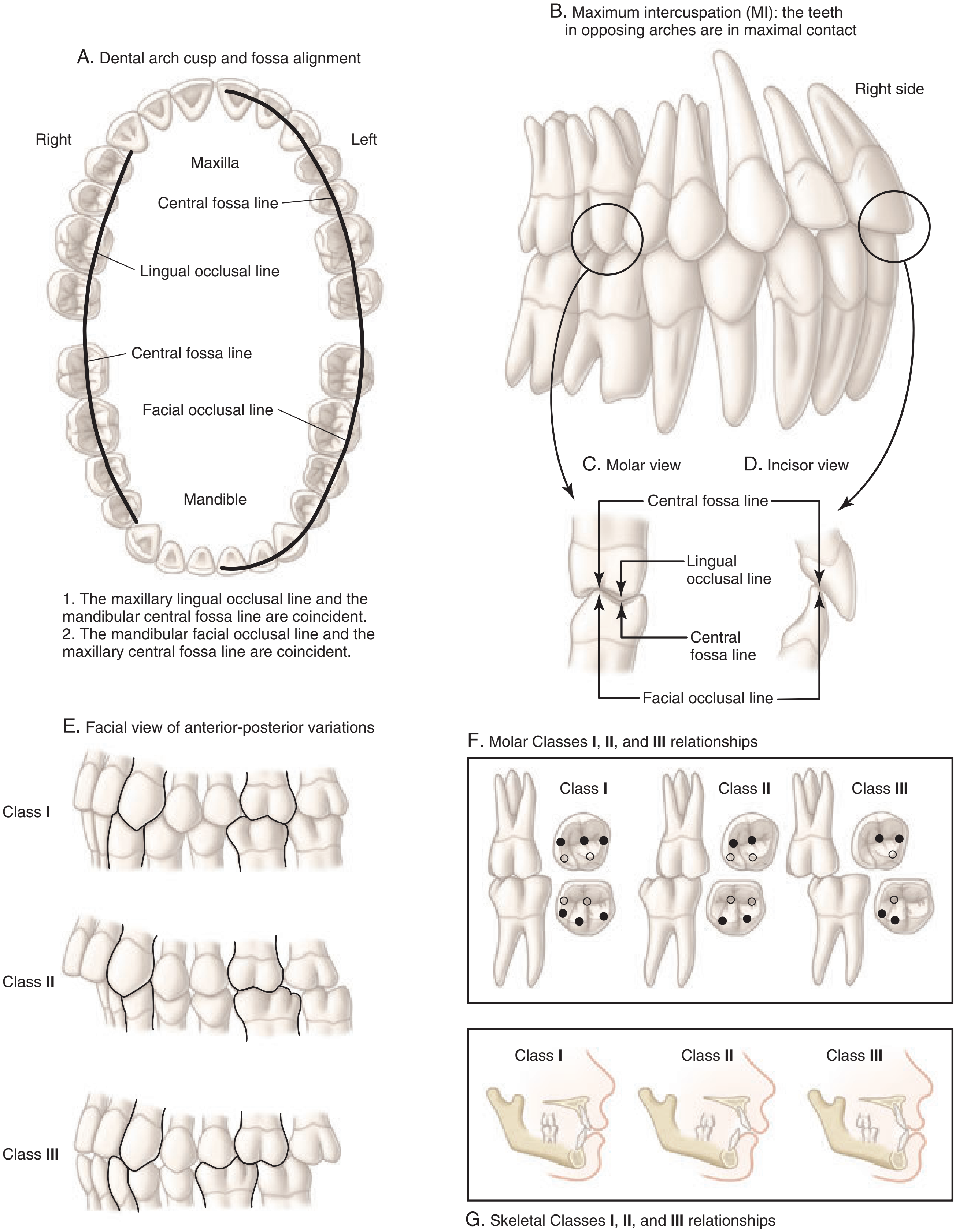
Tooth Alignment and Dental Arches

In Fig. 1.43A, the cusps have been drawn as blunt, rounded, or pointed projections of the crowns of teeth. Posterior teeth have one, two, or three cusps near the facial and lingual surfaces of each tooth. Cusps are separated by distinct developmental grooves and sometimes have additional supplemental grooves on cusp inclines. Facial cusps are separated from the lingual cusps by a deep groove, termed *central groove*. If a tooth has multiple facial cusps or multiple lingual cusps, the cusps are separated by facial or lingual developmental grooves. The depressions between the cusps are termed *fossae* (singular, *fossa*). Cusps in both arches are aligned in a smooth curve. Usually, the maxillary arch is larger than the mandibular arch, which results in maxillary cusps overlapping mandibular cusps when the arches are in maximal occlusal contact (Fig. 1.43B). In Fig. 1.43A, two curved lines have been drawn over the teeth to aid in the visualization of the arch form. These curved lines identify the alignment of similarly functioning cusps or fossae. On the left side of the arches, an imaginary arc connecting the row of facial cusps in the mandibular arch have been drawn and labeled *facial occlusal line*. Above that, an imaginary line connecting the maxillary central fossae is labeled *central fossa occlusal line*. The mandibular facial occlusal line and the maxillary central fossa occlusal line coincide exactly when the mandibular arch is fully closed into the maxillary arch. On the right side of the dental arches, the maxillary lingual occlusal line and mandibular central fossa occlusal line have been drawn and labeled. These lines also coincide when the mandible is fully closed.

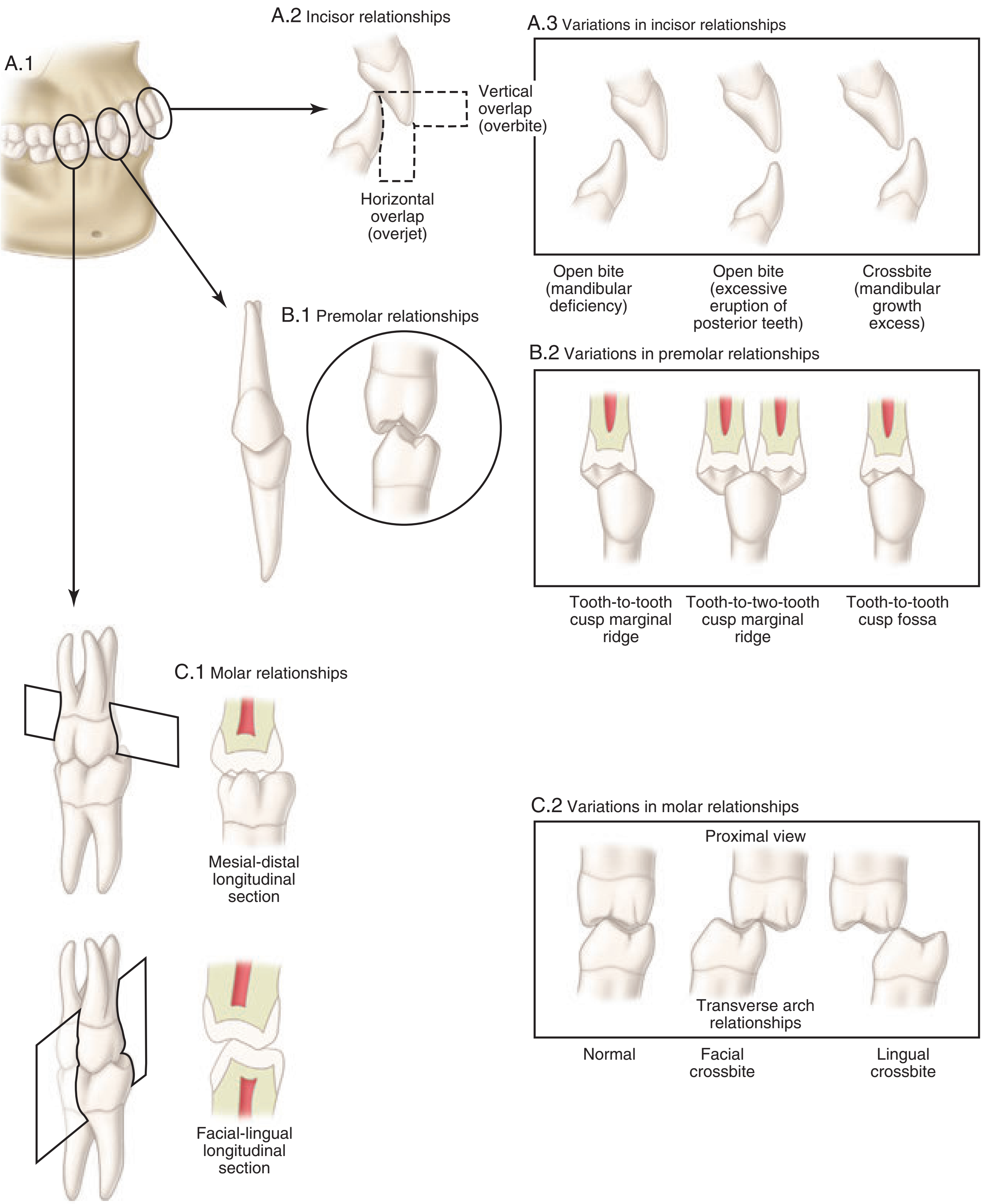
In Fig. 1.43B, the dental arches are fully interdigitated, with maxillary teeth overlapping mandibular teeth. The overlap of the maxillary cusps may be observed directly when the jaws are closed. *Maximum intercuspation (MI)* refers to the position of the mandible when teeth are brought into full interdigitation with the maximal number of teeth contacting. Synonyms for MI include *intercuspal contact, maximum closure,* and *maximum habitual intercuspation (MIP)*.

In Fig. 1.43C (proximal view), the mandibular facial occlusal line and the maxillary central fossa occlusal line coincide exactly. The maxillary lingual occlusal line and the mandibular central fossa occlusal line identified in Fig. 1.43A also are coincidental. The cusps that contact opposing teeth along the central fossa occlusal line are termed *functional cusps* (synonyms include supporting, holding, or stamp cusps); the cusps that overlap opposing teeth are termed *nonfunctional cusps* (synonyms include nonsupporting or nonholding cusps). The mandibular facial occlusal line identifies the mandibular functional cusps, whereas the maxillary facial cusps are nonfunctional cusps. These terms are usually applied only to posterior teeth to distinguish the functions of the two rows of cusps. In some circumstances, the functional role of the cusps may be reversed, as illustrated in Fig. 1.44C.2. Posterior teeth are well suited to crushing food because of the mutual cusp–fossa contacts (Fig. 1.45D).

In Fig. 1.43D, anterior teeth are seen to have a different relationship in MI, but they also show the characteristic maxillary overlap. Incisors are best suited to shearing food because of their overlap and the sliding contact on the lingual surface of maxillary teeth. In MI, mandibular incisors and canines contact the respective lingual surfaces of their maxillary opponents. The amount of horizontal (overjet) and vertical (overbite) overlap (Fig. 1.44A.2) can significantly influence mandibular movement and the cusp design of restorations of posterior teeth. Variations in the growth and development of the jaws and in the positions of anterior teeth may result in open bite, in which vertical or horizontal discrepancies prevent teeth from contacting (Fig. 1.44A.3).



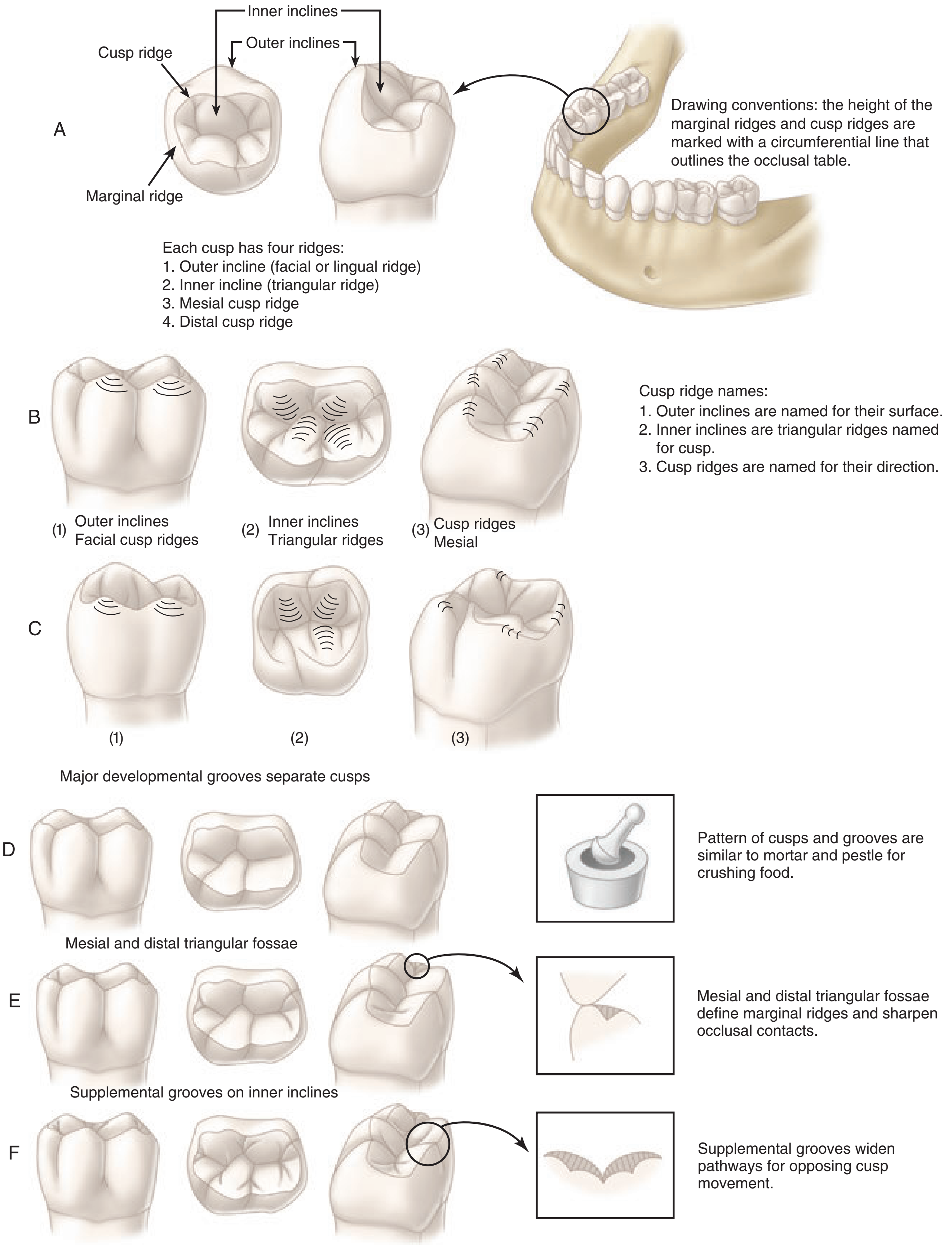
• **Fig. 1.43** Dental arch relationships.



• **Fig. 1.44** Tooth relationships.

Anteroposterior Interarch Relationships

In Fig. 1.43E, the cusp interdigitation pattern of the first molar teeth is used to classify anteroposterior arch relationships using a system developed by Angle.[20] During the eruption of teeth, the tooth cusps and fossae guide the teeth into maximal contact. Three interdigitated relationships of the first molars are commonly observed. See Fig. 1.43F for an illustration of the occlusal contacts that result from different molar positions. The location of the mesiofacial cusp of the maxillary first molar in relation to the mandibular first molar is used as an indicator in the Angle



• **Fig. 1.45** Common features of all posterior teeth.