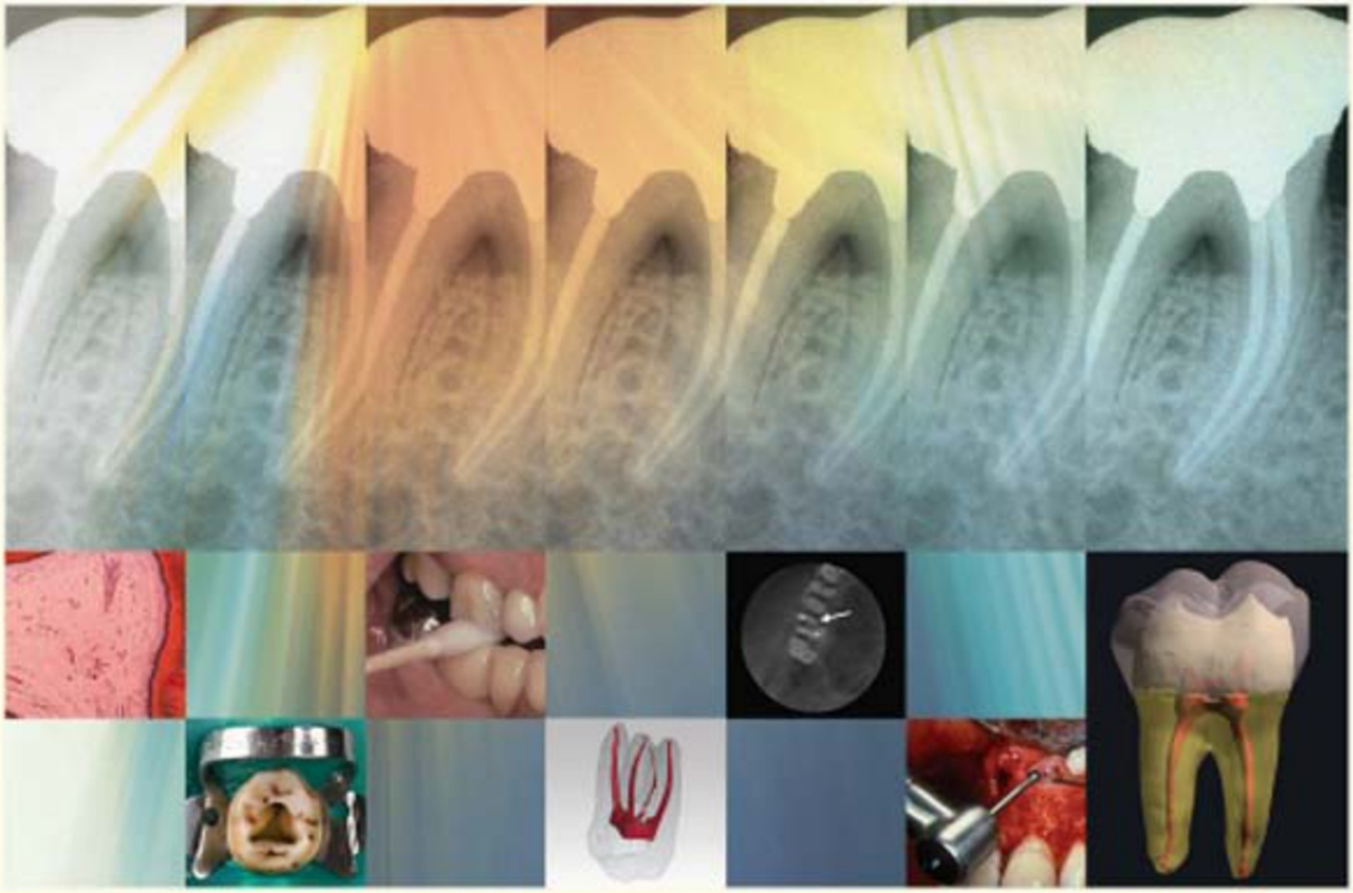
Mahmoud Torabinejad • Richard E. Walton • Ashraf F. Fouad

Endodontics

PRINCIPLES AND PRACTICE



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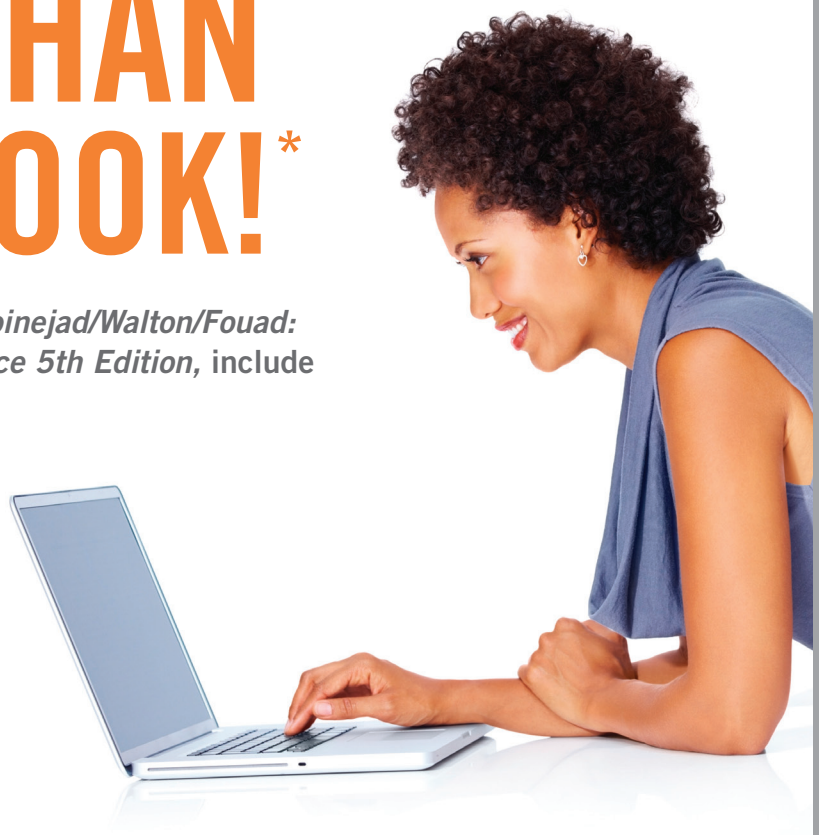

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PRINCIPLES AND PRACTICE

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Preface

The primary objective of dentists has always been to relieve dental pain and prevent tooth loss. Despite this effort, many teeth develop caries, suffer traumatic injury, or are impacted by other diseases and disorders, often requiring endodontic care. Endodontics is a discipline of dentistry that deals with the morphology, physiology, and pathology of the human dental pulp and periapical tissues, as well as the prevention and treatment of diseases and injuries related to these tissues. Its scope is wide and includes diagnosis and treatment of pain of pulpal and/or periapical origin, vital pulp therapy, regenerative endodontic procedures, nonsurgical root canal treatment, retreatment of unsuccessful treatment, internal bleaching, and endodontic surgery. Ultimately, the primary goal in endodontics is to preserve the natural dentition. Root canal treatment is a well-tested procedure that has provided pain relief and has restored function and esthetics to patients. Millions of patients expect preservation of their natural dentition; if root canal treatment is necessary, they should be aware that the procedure is safe and has a high success rate if properly performed.

As with other dental specialties, the practice of endodontics requires two inseparable components: art and science. The *art* consists of executing technical procedures during root canal treatment. The *science* includes the basic and clinical sciences related to biological and pathological conditions that guide the art of endodontics through the principles and methods of evidence-based treatment. Evidence-based treatment integrates the best clinical evidence with the practitioner's clinical expertise and the patient's treatment needs and preferences. A principal objective of our textbook is to incorporate evidence-based information when available and when appropriate.

Because there are not enough endodontists to manage the endodontic needs of the public, general dentists must assist endodontists to preserve natural dentition. Their responsibility is to diagnose pulpal and periapical diseases and to perform noncomplicated root canal treatments. In fact, most of the endodontic procedures are performed by generalists. Our textbook, written specifically for dental students and general dentists, contains the information necessary for those who would like to incorporate endodontics in their practice. This includes diagnosis and treatment planning as well as management of pulpal and periapical diseases. In addition, the general dentist must be able to determine the case complexity and whether she or he can perform the necessary treatment or if referral is the better option.

Although many advances have been made in endodontics in the past decade, the main objectives of root canal therapy continue to be the removal of diseased tissue, the elimination of microorganisms, and the prevention of recontamination after treatment. This new edition of *Endodontics: Principles and Practice* has been systematically organized to simulate the order of procedures performed in a clinical setting. It contains information regarding normal structures, etiology of disease, diagnosis and treatment planning, local anesthesia, emergency treatment, root canal instruments, access preparations, cleaning and shaping, obturation, and temporization. In addition, it covers etiology, prevention, and treatment of accidental procedural errors, as well as treatment of inadequate root canal–treated teeth using nonsurgical and surgical approaches. A chapter is dedicated to the endodontic outcomes that provide guidelines regarding the assessment of outcomes of these procedures. In this edition we've included information on pulp and periapical stem cells, regenerative endodontic procedures, novel analyses of endodontic microflora, the use of cone beam CT in endodontics, the interaction of general dentists and endodontists, and systemic considerations in endodontics. Furthermore, a chapter discusses single tooth implant.

The other distinctive features of the new edition are (1) updated relevant and recent references, (2) information regarding new scientific and technological advances in the field of endodontics, (3) information regarding single tooth implant, and (4) a revised contents with new authors. The appendix provides colorized illustrations that depict the size, shape, and location of the pulp space within each tooth. There is also a website with video clips for selected procedures and an interactive version of the self-assessment questions. These features provide the reader with a textbook that is concise, current, and easy to follow in an interactive manner.

This textbook is not intended to include all background information on the art and science of endodontics. At the same time, it is not designed to be a "cookbook" or a preclinical laboratory technique manual. We have tried to provide the reader with the basic information to perform root canal treatment and to give the reader background knowledge in related areas. This textbook should be used as a building block for understanding the etiology and treatment of teeth with pulpal and periapical diseases; then the reader can expand her or his endodontic experiences with more challenging cases. Providing the best quality of care is the guiding light for treatment planning and performing appropriate treatment.

We thank the contributing authors for sharing their materials and experiences with our readers and with us. Their contributions improve the quality of life for millions of patients. We also express our appreciation to the editorial staff of Elsevier, whose collaboration and dedication made this project possible and Mohammad Torabinejad for editing and

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proofreading the manuscripts. In addition, we acknowledge our colleagues and students who provided cases and gave us constructive suggestions to improve the quality of our textbook. Because much of their material is incorporated into the new edition, we also would like to acknowledge the contributors to the fourth edition: Leif K. Bakland, Marie Therese Flores, Gerald N. Glickman, Gary R. Hartwell, Karl Keiser, Keith V. Krell, Ronald R. Lemon, Neville J. McDonald, Mary Rafter, Isabela N. Rôças, Asgeir Sigurdsson, James H.S. Simon, Henry O. Trowbridge, and Frank J. Vertucci.

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CHAPTER 1

The biology of dental pulp and periradicular tissues

Graham Rex Holland, Mahmoud Torabinejad

CHAPTER OUTLINE

LEARNING OBJECTIVES

After reading this chapter, the student should be able to:

1. Describe the development of pulp.
2. Describe the process of root development.
3. Recognize the anatomic regions of pulp.
4. List all cell types in the pulp and describe their function.
5. Describe both fibrous and non-fibrous components of the extracellular matrix of pulp.
6. Describe the blood vessels and lymphatics of pulp.
7. List the neural components of pulp and describe their distribution and function.
8. Discuss theories of dentin sensitivity.
9. Describe the pathway of efferent nerves from pulp to the central nervous system.
10. Describe the changes in pulp morphology that occur with age.
11. Describe the structure and function of the periradicular tissues.

1-1

The dental pulp is the loose connective tissue in the center of the tooth. The primary function of the pulp is to form and support the dentin that surrounds it and forms the bulk of the tooth. The pulp contains odontoblasts that not only form dentin, but also interact with dental epithelium early in tooth development to initiate the formation of enamel. The pulp remains vital throughout life and is able to respond to external stimuli. Both dentin and pulp contain nociceptive nerve fibers. Autonomic nerve fibers occur only in the pulp. When needed for repair, more dentin can be laid down and new odontoblasts differentiated.

The pulp is equipped with all the necessary peripheral components of the immune system and will react to foreign antigens, such as those presented by dental caries. Injury and foreign antigens lead to inflammation and pain. The good health of the pulp is important to the successful completion of restorative and prosthetic dental procedures. In restorative dentistry, for example, the size and shape of the pulp must be considered in determining cavity depth. The size and shape of the pulp depend on the tooth type (e.g., incisor, molar), the degree of tooth development related to the age of the patient, and any restorative procedures that may have been carried out on the tooth. When a tooth is injured, the stage of development the pulp influences the type of treatment rendered. Procedures routinely undertaken on a fully developed tooth are not always practicable for a tooth that is only partially developed, and special procedures are applied.

Because endodontics involves the diagnosis and treatment of diseases of the pulp and their sequelae, a knowledge of the biology of the pulp is essential for the development of an evidence-based treatment plan. This chapter presents an overview of the biology of the pulp and the periodontium as a fundamental component of the evidential base.

DEVELOPMENT OF THE DENTAL PULP

Early Development of Pulp

The tooth originates as a band of epithelial cells, the dental lamina (Fig. 1.1, *A*), on the surface of the embryonic jaws. Downgrowths from this band ultimately form the teeth. The stages of tooth formation are described by the shapes of these downgrowths. Initially, they look like the bud of a forming flower (bud stage, Fig. 1.1, *B*). The bud becomes invaginated at the cap stage (Fig. 1.1, *C*). The invagination deepens, and the bell stage is reached (Fig. 1.1, *D*). The bell-shaped downgrowth is the enamel organ. It is ectodermal in origin and will be responsible for amelogenesis. The tissue within the invagination ultimately becomes the dental pulp, known as the *dental papilla,* during the early stages of development. Before

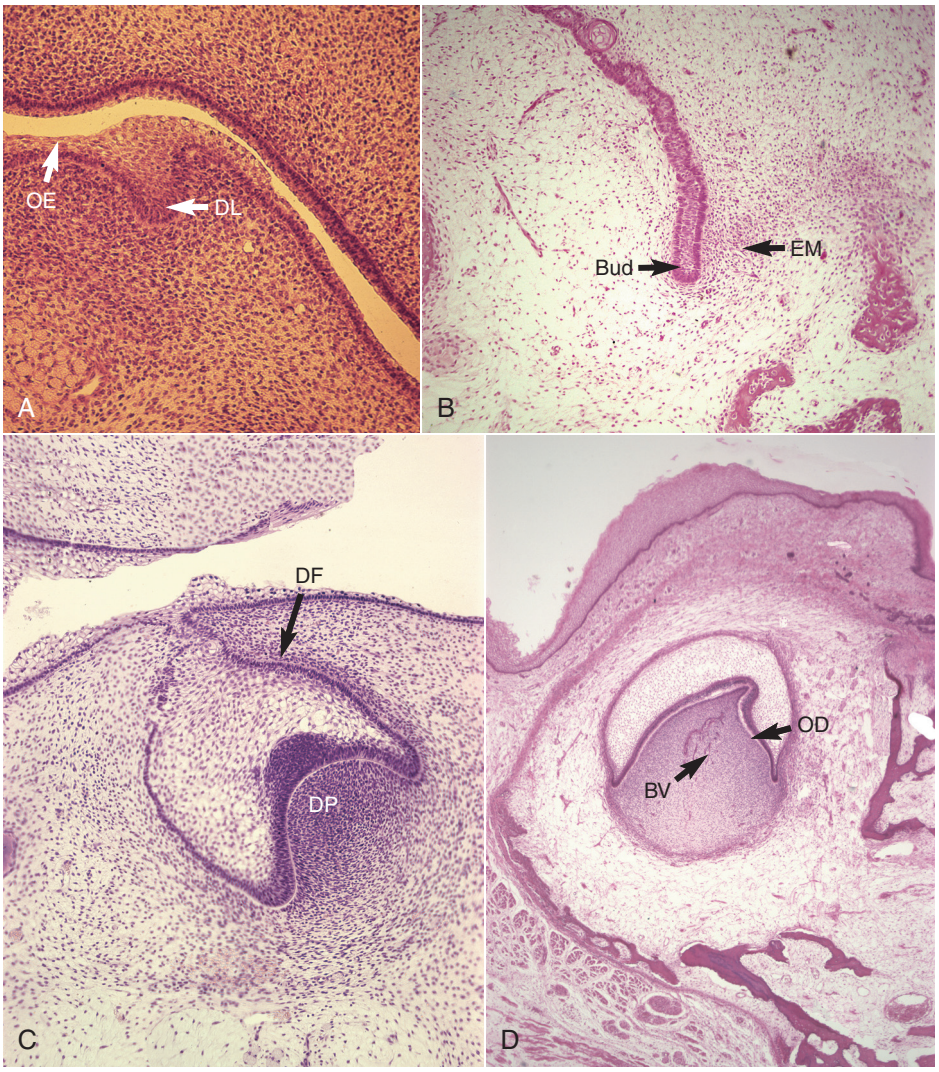

Fig. 1.1 **A,** Earliest stage of tooth development. The dental lamina *(DL)* invaginates from the oral epithelium *(OE).* **B,** Bud stage of tooth development. Ectomesenchyme *(EM)* is beginning to condense around the tooth germ. **C,** The cap stage of tooth development. The condensed ectomesenchyme within the invagination is the dental papilla *(DP).* The dental follicle *(DF)* is beginning to develop around the tooth germ. **D,** Early bell stage. The odontoblast layer *(OD)* and blood vessels *(BV)* are visible in the dental pulp. (Courtesy Dr. H. Trowbridge.)

that, the cells it contains differentiate. The papilla (and thus the pulp) is derived from cells that have migrated from the neural crest (ectomesenchymal cells) and mingled with cells of local mesenchymal origin.

During the bell stage, the inner layer of cells of the enamel organ differentiate into ameloblasts (Fig. 1.2, *A*). This is followed by the outer layer of cells of the dental papilla differentiating into odontoblasts (Fig. 1.2, *B*), which begin to lay down dentin in the late bell (or crown) stage (Fig. 1.2, *C*). From this point on, the tissue within the invagination is known as the *dental pulp.* A layer of tissue begins to differentiate around the enamel organ and dental papilla and forms the dental follicle, which later becomes the periodontal attachment. The combination of the enamel organ dental papilla/pulp and dental follicle is the tooth germ.

The histodifferentiation and morphodifferentiation of the tooth germ are genetically determined and executed by a group of growth factors, transcription factors, and other signaling molecules. Several of the genes controlling this process have been identified. Disorder at this stage can lead to anodontia, amelogenesis imperfecta, odontogenesis imperfecta, and related defects. A substantial research effort has been underway for some years, with a long-term goal of using these molecules therapeutically in procedures such as apexogenesis and pulpal regeneration.

The differentiation of odontoblasts from undifferentiated ectomesenchymal cells is initiated and controlled by the ectodermal cells of the inner dental epithelium of the enamel organ. The ameloblasts synthesize growth factors and signaling molecules that pass into the basal lamina of the epithelium and from there to the preodontoblast. The cells beneath the forming odontoblasts remain as undifferentiated stem cells and retain the potential to differentiate.

Once the odontoblast layer has differentiated, the basal lamina of the inner dental epithelium that contained the signaling molecules disappears, and the odontoblasts, now linked to each other by tight junctions, desmosomal junctions, and gap junctions, begin to lay down dentin (see Fig. 1.2, *C*).[1]

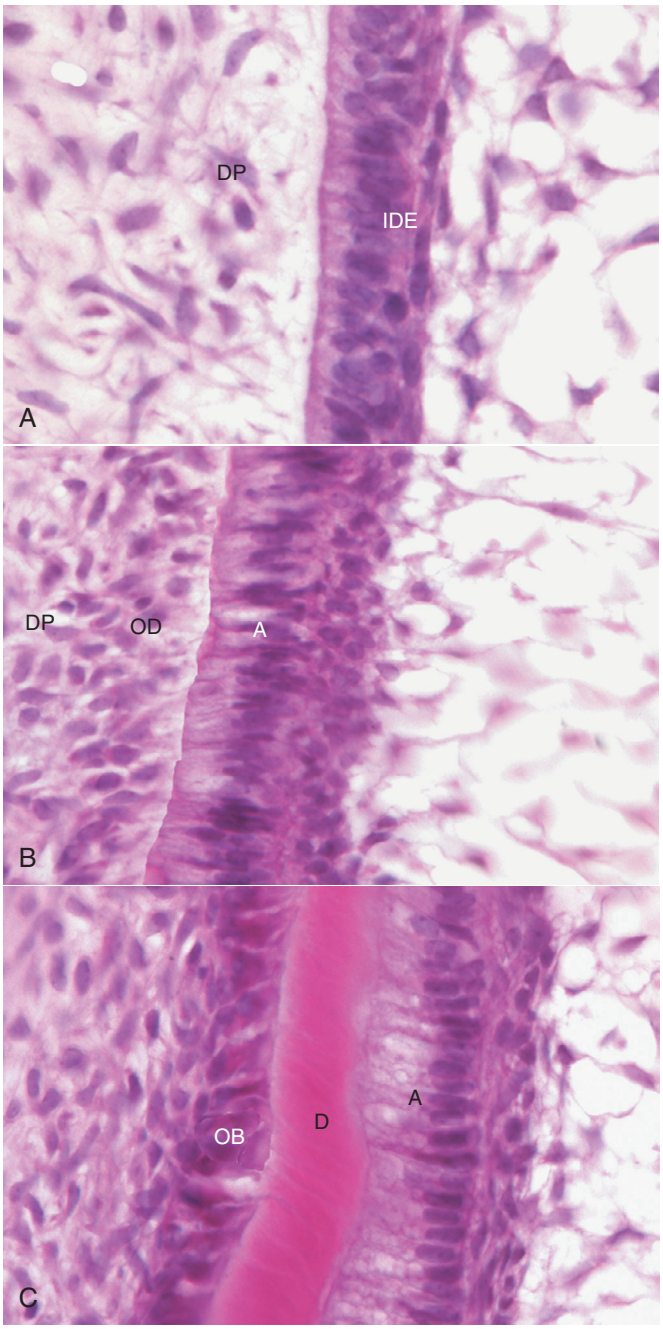

Fig. 1.2 **A,** At the late cap stage the internal dental epithelium *(IDE)* has differentiated into a layer of ameloblasts but has not laid down enamel. The outer layer of the dental papilla *(DP)* has not yet differentiated into odontoblasts. **B,** Slightly later than in Fig. 1.2, *A,* the outer cells of the dental papilla are beginning to become odontoblasts *(OD)* at the periphery of what now is the dental pulp *(DP).* The ameloblasts *(A)* are fully differentiated, but no enamel has formed yet. **C,** In the bell stage, the odontoblasts *(OB)* are laying down dentin *(D),* but the ameloblasts *(A)* have laid down little, if any, enamel. (Courtesy Dr. H. Trowbridge.)

Once dentin formation has begun, the cells of the inner dental epithelium begin responding to a signal from the odontoblasts and start to deposit enamel. This back-and-forth signal control is an example of epithelial-mesenchymal interaction, a key developmental process that has been heavily studied in the tooth germ model. Deposition of unmineralized dentin matrix begins at the cusp tip and progresses in a cervical (apical) direction in a regular rhythm at an average of 4.5 µm/day.[2] Crown shape is genetically predetermined by the proliferative pattern of the cells of the inner dental epithelium. The first thin layer of dentin formed is called *mantle dentin.* The direction and size of the collagen fibers in mantle dentin, together with the mineralization pattern, differ from those in the subsequently formed circumpulpal dentin. Processes from the odontoblasts remain at least in the inner part of the dentinal tubules. A pattern of matrix formation followed by mineralization continues throughout dentin deposition. Between 10 and 50 µm of the dentin matrix immediately adjacent to the odontoblast layer remains unmineralized at all times and is known as *predentin.*

As crown formation occurs, nerves and blood vessels begin migrating into the pulp from the future root apex in a coronal direction. Both undergo branching and narrowing toward the odontoblast layer, and at a late stage, each forms plexuses beneath the layer with the nerves extending branches into the odontoblast layer and some of the dentinal tubules. Dentin formation continues throughout life in an incremental pattern marked by lines in the matrix and changes in direction of the tubules. The rate of deposition slows in adulthood but never completely stops. The rate can increase if the odontoblasts are stimulated by toxin molecules penetrating the dentin.

Root Formation

In the developing tooth, cells of the inner and outer dental epithelia meet at a point known as the *cervical loop.* This delineates the end of the anatomic crown and the site where root formation begins. Root formation is initiated by the apical proliferation of the two fused epithelia, now known as *Hertwig's epithelial root sheath.*[3] The function of the sheath is similar to that of the inner enamel epithelium during crown formation. It provides signals for the differentiation of odontoblasts and thus acts as a template for the root (Fig. 1.3, *A*). Cell proliferation in the root sheath is genetically determined; its pattern regulates whether the root will be wide or narrow, straight or curved, long or short, or single or multiple. Multiple roots result when opposing parts of the root sheath proliferate both horizontally and vertically. As horizontal segments of Hertwig's epithelial root sheath join to form the "epithelial diaphragm," the pattern for multiple root formation is laid down. This pattern is readily discernible when the developing root end is viewed microscopically (Fig. 1.3, *B*).

After the first dentin in the root has formed, the basement membrane beneath Hertwig's sheath breaks up and the innermost root sheath cells secrete a hyaline material over the newly formed dentin. After mineralization has occurred, this becomes the *hyaline layer of Hopewell-Smith,* which helps bind the soon-to-be-formed cementum to dentin. Fragmentation of Hertwig's epithelial root sheath occurs shortly afterward. This fragmentation allows cells of the surrounding dental follicle (the future periodontium) to migrate and contact the newly formed dentin surface, where they differentiate into cementoblasts and initiate acellular cementum formation (Fig. 1.4).[4] This cementum ultimately serves as an anchor for the developing principal fibers of the periodontal ligament (PDL). In many teeth, cell remnants of the root sheath persist in the periodontium in close proximity to the root after root development has been completed. These are the *epithelial cell rests of Malassez.*[5] Normally functionless, in the presence of

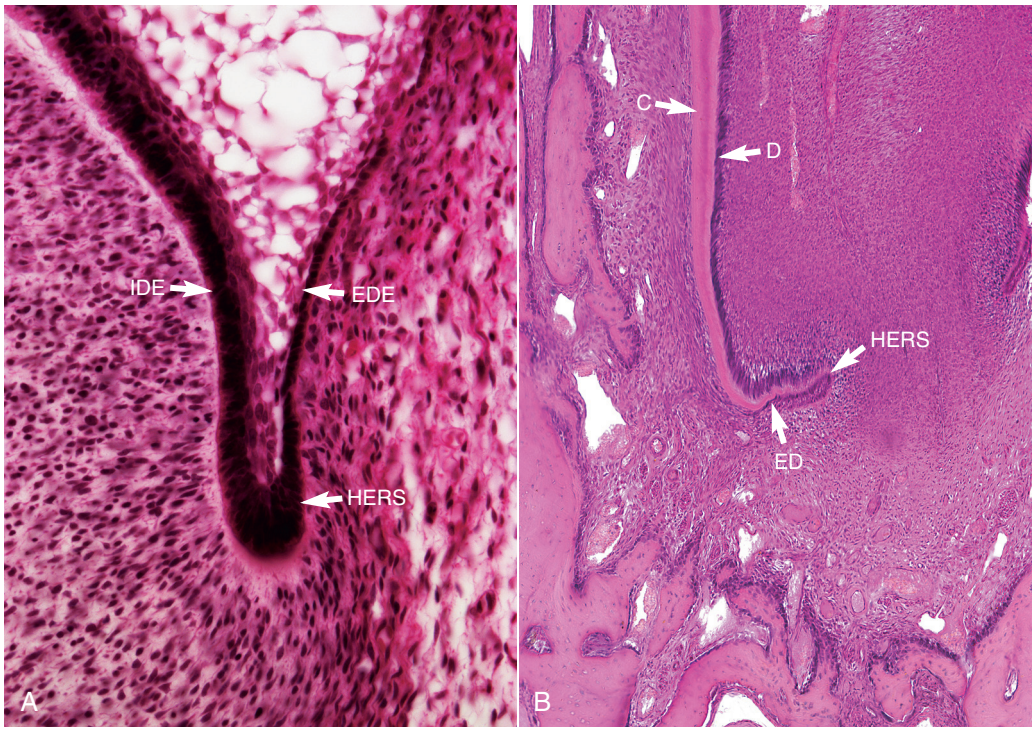

Fig. 1.3 **A,** The formation of Hertwig's epithelial root sheath *(HERS)* from the internal *(IDE)* and external *(EDE)* epithelia. **B,** Hertwig's epithelial root sheath *(HERS)* has extended. Both dentin *(D)* and cementum *(C)* have been deposited. HERS has changed direction to form the epithelial diaphragm *(ED).*

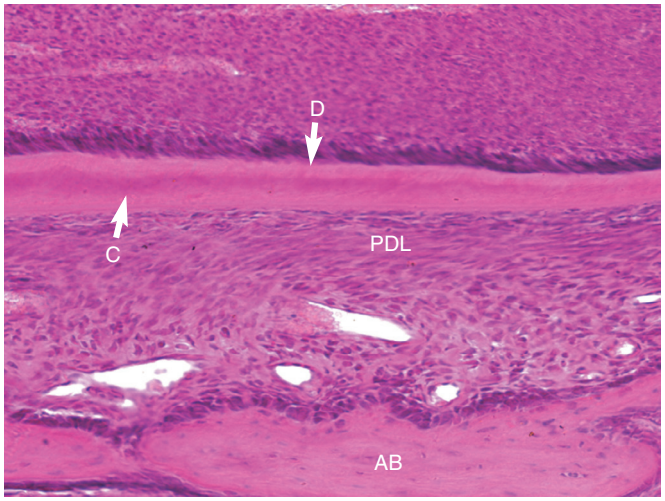

Fig. 1.4 Developing dentin *(D),* cementum *(C),* periodontal ligament *(PDL),* and alveolar bone *(AB).*

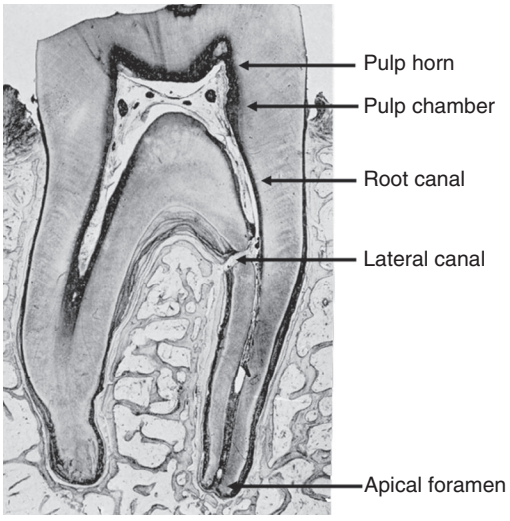

Fig. 1.5 Anatomic regions of the root canal system highlighting the pulp horn(s), pulp chamber, root canal, lateral canal, and apical foramen. The pulp, which is present in the root canal system, communicates with the periodontal ligament primarily through the apical foramen and the lateral canal(s). (Courtesy Orban Collection.)

inflammation they can proliferate and may under certain conditions give rise to a radicular cyst.[6]

Formation of Lateral Canals and Apical Foramen

Lateral Canals

Lateral canals (or, synonymously, accessory canals) are channels of communication between pulp and PDL (Fig. 1.5). They form when a localized area of root sheath is fragmented before dentin formation. The result is direct communication between pulp and the PDL via a channel through the dentin and cementum that carries small blood vessels and, perhaps, nerves. Lateral canals may be single or multiple, large or small. They may occur anywhere along the root but are most common in the apical third. In molars, they may join the pulp chamber PDL in the root furcation. *Lateral canals are*

clinically significant; like the apical foramen, they represent pathways along which disease may extend from the pulp to periradicular tissues and from the periodontium to the pulp.

Apical Foramen

The epithelial root sheath continues to extend until the full, predetermined length of the root is reached. As the epithelial root sheath extends, it encloses more of the dental pulp until only an apical foramen remains, through which pulpal vessels and nerves pass. During root formation, the apical foramen is usually located at the end of the anatomic root. When tooth development has been completed, the apical foramen is smaller and can be found a short distance coronal to the anatomic end of the root.[7] This distance increases later as more apical cementum is formed.

There may be one foramen or multiple foramina at the apex. Multiple foramina occur more often in multirooted teeth. When more than one foramen is present, the largest one is referred to as the *apical foramen* and the smaller ones as *accessory canals.* (Together they constitute the *apical delta*.) The diameter of the apical foramen in a mature tooth usually ranges between 0.3 and 0.6 mm. The largest diameters are found on the distal canal of mandibular molars and the palatal root of maxillary molars. Foramen size is unpredictable, however, and cannot be accurately determined clinically.

Formation of the Periodontium

Tissues of the periodontium develop from ectomesenchyme-derived tissue *(dental follicle)* that surrounds the developing tooth. After the mantle dentin has formed, enamel-like proteins are secreted into the space between the basement membrane and the newly formed collagen by the root sheath cells. This area is not mineralized with the mantle dentin but does mineralize later from the hyaline layer of Hopewell-Smith. After mineralization has occurred, the root sheath breaks down. This fragmentation allows cells from the follicle to proliferate and differentiate into cementoblasts, which lay down cementum over the hyaline layer. Bundles of collagen, produced by fibroblasts in the central region of the follicle *(Sharpey's fibers),* are embedded in the forming cementum and will become the principal fibers of the PDL.

At the same time, cells in the outermost area of the follicle differentiate into osteoblasts to form the bundle bone that will also anchor the periodontal fibers. Later, periodontal fibroblasts produce more collagen that binds the anchored fragments together to form the principal periodontal fibers that suspend the tooth in its socket. Loose, fibrous connective tissue carrying nerves and blood vessels remains between the principal fibers. Undifferentiated mesenchymal cells (tissue-specific stem cells) are plentiful in the periodontium and possess the ability to form new cementoblasts, osteoblasts, or fibroblasts in response to specific stimuli. Cementum formed after the formation of the principal periodontal fibers is cellular and plays a lesser role in tooth support. As with the development of the dental pulp, these processes are genetically predetermined and executed via signaling molecules. There is intense research in this area, because it promises truly biologic approaches to periodontal disease.

The blood supply to the periodontium is derived from the surrounding bone, gingiva, and branches of the pulpal vessels.[8] It is extensive and supports the high level of cellular activity in the area. The pattern of innervation is similar to that of the vasculature. The neural supply consists of small, unmyelinated sensory and autonomic nerves and larger myelinated sensory nerves. Some of the latter terminate as unmyelinated neural structures thought to be nociceptors and mechanoreceptors.

ANATOMIC REGIONS AND THEIR CLINICAL IMPORTANCE

The tooth has two principal anatomic divisions, root and crown, that join at the cervix *(cervical region).* The pulp space is similarly divided into coronal and radicular regions. In general, the shape and the size of the tooth surface reflect the shape and size of the pulp space. The coronal pulp is subdivided into the pulp horn(s) and pulp chamber (see Fig. 1.5). Pulp horns extend from the chamber into the cuspal region. In young teeth, they are extensive and may be inadvertently exposed during routine cavity preparation.

The pulp space becomes asymmetrically smaller after root growth is complete because of the slower production of dentin. There is a pronounced decrease in the height of the pulp horn and a reduction in the overall size of the pulp chamber. In molars, the apical-occlusal dimension is reduced more than the mesial-distal dimension. Excessive reduction of the size of the pulp space is clinically significant and can lead to difficulties in locating, cleaning, and shaping the root canal system (Fig. 1.6).

The anatomy of the root canal varies not only between tooth types, but also within tooth types. Although at least one canal must be present in each root, some roots have multiple canals of varying sizes. *Understanding and appreciating all aspects of root canal anatomy are essential prerequisites to root canal treatment.*

Variation in the size and location of the apical foramen influences the degree to which blood flow to the pulp may be compromised after a traumatic event. *Young, partially developed teeth have a better prognosis for pulp survival than teeth with mature roots* (Fig. 1.7).

Posteruptive deposition of cementum in the region of the apical foramen creates a disparity between the radiographic apex and the apical foramen. It also creates a funnel-shaped opening to the foramen that is often larger in diameter than the intraradicular portion of the foramen. The narrowest portion of the canal is referred to as the *apical constriction.* However, a constriction is not clinically evident in all teeth. The constriction coincides with the *cementodentinal junction* (CDJ). The level of the CDJ varies from root to root. One study estimated the junction to be located 0.5 to 0.75 mm coronal to the apical opening.[7] Theoretically, that is the point where the pulp terminates and the PDL begins, and it would be the ideal point for a procedure aimed at removing the pulp. However, clinically, it is not always possible to locate that point. Cleaning, shaping, and obturation of the root canal should terminate short of the apical foramen and remain confined to the canal to avoid unnecessary injury to the periapical tissues. *The determination of root length and the establishment of a working length are essential steps in root canal preparation. Radiographs and electronic apex locators are helpful in establishing the root length.*

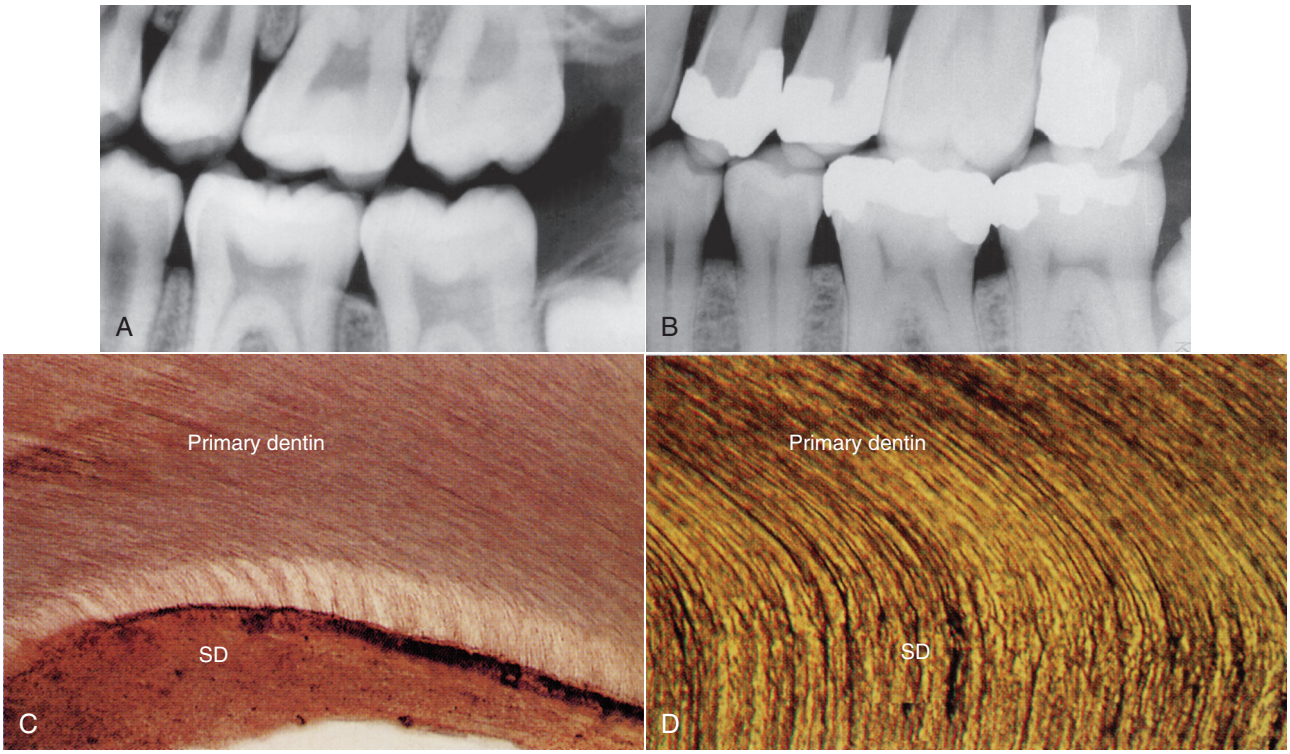

Fig. 1.6 **A** and **B,** Radiographic changes noted in the shape of the pulp chamber over time. The posterior bitewing radiographs were taken 15 years apart. The shapes of the root canal systems have been altered as a result of secondary dentinogenesis and by the deposition of tertiary dentin when deep restorations are present. **C,** Secondary dentin *(SD).* Ground section at low power. **D,** Secondary dentin *(SD)* at high power.

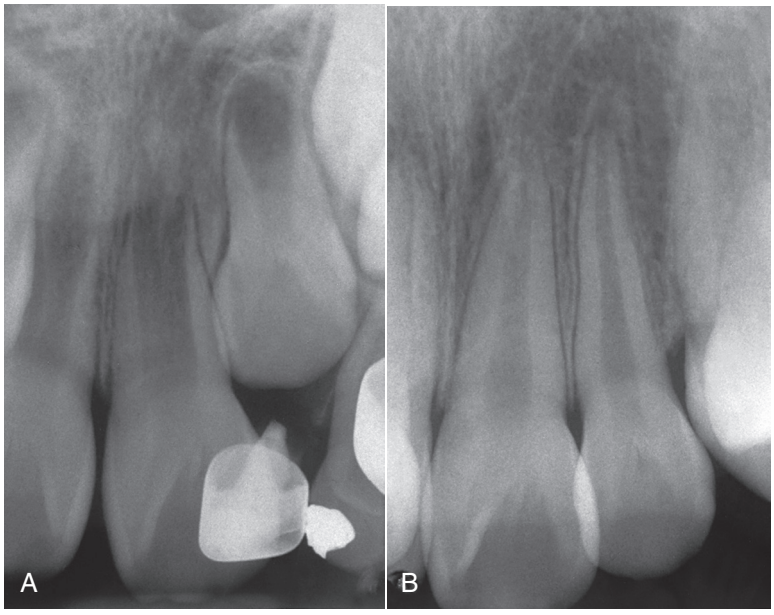

Fig. 1.7 Changes in the anatomy of the tooth root and pulp space. **A,** A small crown-to-root ratio, thin dentin walls, and divergent shape in the apical third of the canal are seen. **B,** Four years later, a longer root, greater crown-to-root ratio, smaller pulp space, and thicker dentin walls with a convergent shape are seen.

PULP FUNCTION

The pulp performs five functions, some formative and others supportive.

Induction

Pulp participates in the initiation and development of dentin.[9] When dentin is formed, it leads to the formation of enamel. These events are interdependent, in that enamel epithelium induces the differentiation of odontoblasts, and odontoblasts and dentin induce the formation of enamel. Such epithelial-mesenchymal interactions are the core processes of tooth formation.

Formation

Odontoblasts form dentin.[10] These highly specialized cells participate in dentin formation in three ways: (1) by synthesizing and secreting inorganic matrix, (2) by initially

transporting inorganic components to newly formed matrix, and (3) by creating an environment that permits mineralization of the matrix. During early tooth development, primary dentinogenesis is a rapid process. After tooth maturation, when elongation of the root is complete, dentin formation continues at a much slower rate and in a less symmetric pattern *(secondary dentinogenesis)*. Odontoblasts can also form dentin in response to injury, which may occur in association with caries, trauma, or restorative procedures. In general, this dentin is less organized than primary and secondary dentin and mostly localized to the site of injury. This dentin is referred to as *tertiary dentin*. Tertiary dentin has two forms. *Reactionary* tertiary dentin is tubular, with the tubules continuous with those of the original dentin. It is formed by the original odontoblasts. *Reparative* dentin is formed by new odontoblasts differentiated from stem cells after the original odontoblasts have been killed. It is largely atubular (Fig. 1.8).

Nutrition

The pulp supplies nutrients that are essential for dentin formation and for maintaining the integrity of the pulp itself.

Defense

In the mature tooth, the odontoblasts form dentin in response to injury, particularly when the original dentin thickness has been reduced by caries, attrition, trauma, or restorative procedures. Dentin can also be formed at sites where its continuity has been lost, such as a site of pulp exposure. Dentin formation occurs in this situation by the induction, differentiation, and migration of new odontoblasts to the exposure site (Fig. 1.9).

Pulp also has the ability to process and identify foreign substances, such as the toxins produced by bacteria of dental caries, and to elicit an immune response to their presence.

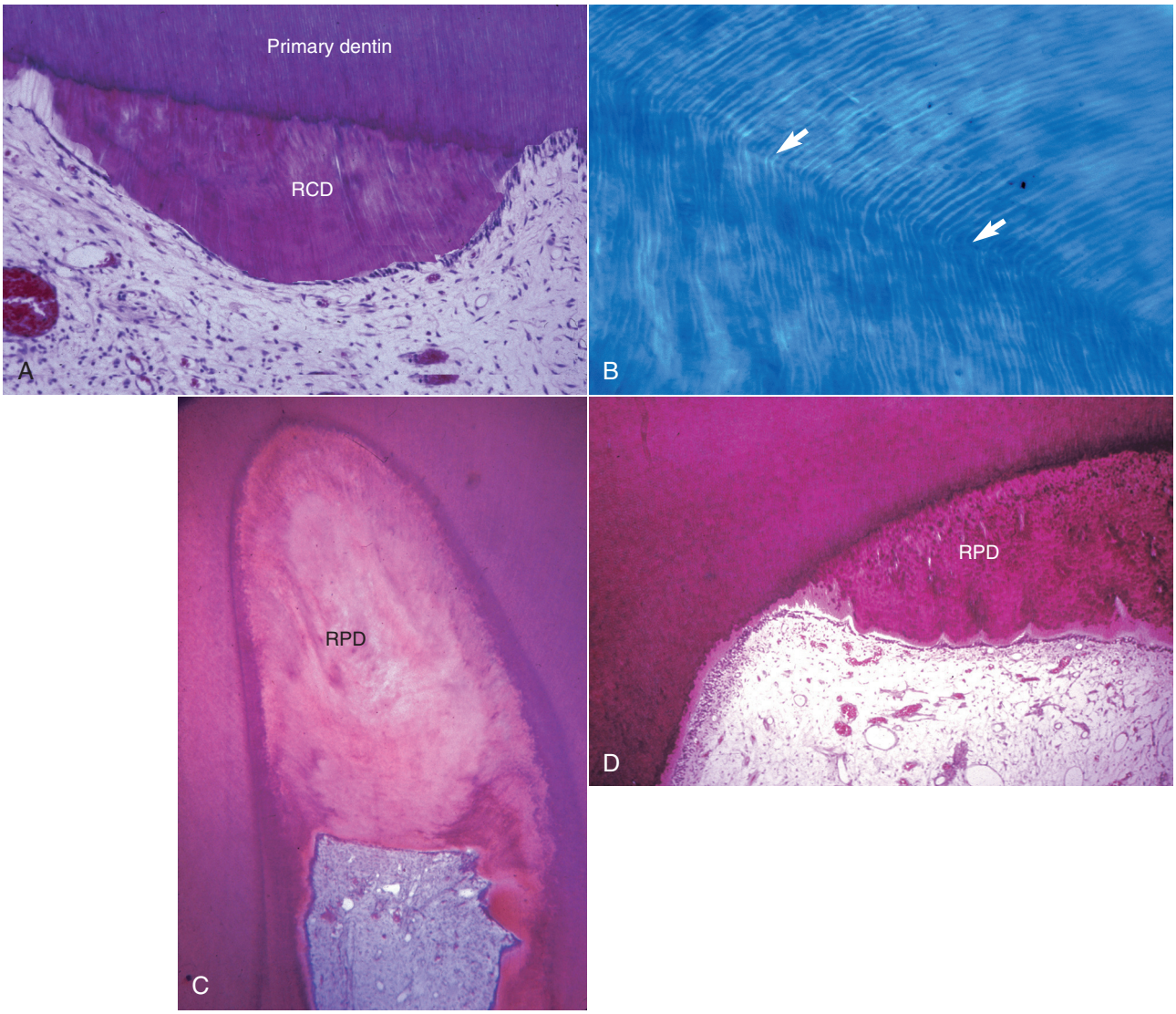

Fig. 1.8 **A,** Reactionary dentin *(RCD)* at low power. **B,** RCD at high power showing change in direction of tubules *(arrows)*. **C,** Reparative dentin *(RPD)* at low power. **D,** RPD at high power. (Courtesy Dr. H. Trowbridge.)

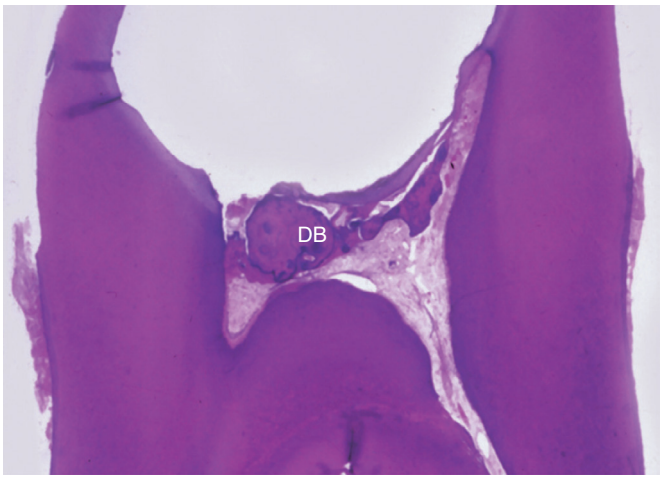

Fig. 1.9 Reparative dentin bridge *(DB)* formed over a cariously exposed pulp. (Courtesy Dr. H. Trowbridge.)

Sensation

Nerves in the pulp can respond to stimuli applied directly to the tissue or through enamel and dentin. Physiologic stimuli can only result in the sensation of pain. The stimulation of myelinated sensory nerves in the pulp results in fast, sharp pain. Activation of the unmyelinated pain fibers results in a slower, duller pain. Pulp sensation through dentin and enamel is usually fast and sharp and is transmitted by Aδ fibers *(narrow myelinated fibers).*

MORPHOLOGY

Dentin and pulp are actually a single-tissue complex with a histologic appearance that varies with age and exposure to external stimuli.

Under light microscopy, a young, fully developed permanent tooth shows certain recognizable aspects of pulpal architecture. In its outer (peripheral) regions subjacent to predentin is the odontoblast layer. Internal to this layer is a relatively cell-free area *(zone of Weil).* Internal to the zone of Weil is a higher concentration of cells (cell-rich zone). (These features are limited to the coronal pulp and are sometimes difficult to discern.) In the center is an area containing mostly fibroblasts and major branches of nerves and blood vessels referred to as the *pulp core* (Fig. 1.10).

CELLS OF THE DENTAL PULP

Odontoblasts

Odontoblasts are the characteristic cells of pulp. They form a single layer at its periphery, synthesize the matrix, and control the mineralization of dentin.[11] They produce collagen that becomes fibrous and three noncollagenous proteins in which the collagen fibers are embedded. In the coronal part of the pulp space, the odontoblasts are numerous (between 45,000 and 65,000/mm^2), relatively large, and columnar in shape. In the cervical and midportion of the root, their numbers are lower and they appear flattened. The morphology of the cell reflects its level of activity; larger cells have a well-developed synthetic apparatus and the capacity to synthesize more matrix. During their life cycle, they go through functional, transitional, and resting phases, all marked by differences in cell size and organelle expression.[12] Odontoblasts can continue at varying levels of activity for a lifetime. Some die by planned cell death (apoptosis), using an autophagic-lysosomal system as the volume of the pulp decreases.[12,13] Disease processes, principally dental caries, can kill odontoblasts, but if conditions are favorable, these cells can be replaced by new odontoblasts that have differentiated from stem cells. (Odontoblasts are end cells and as such do not undergo further cell division.)

The odontoblast consists of two major components, the cell body and the cell processes. The *cell body* lies subjacent to the unmineralized dentin matrix (predentin). One large *cell process* extends outward for a variable distance through a tubule in the predentin and dentin. Other, much smaller processes extend from the cell body and link odontoblasts to each other and possibly to fibroblasts. The cell body is the synthesizing portion of the cell and contains a basally located nucleus and a variety of organelles in the cytoplasm that are typical of a secreting cell. During active dentinogenesis, the endoplasmic reticulum and the Golgi apparatus are prominent, and there are numerous mitochondria and vesicles (Fig. 1.11).

Cell bodies are joined by a variety of membrane junctions, including gap junctions, tight junctions, and desmosomes. Each junction type has specific functions. Desmosomal junctions mechanically link the cells into a coherent layer. Gap junctions allow communication between cells in the layer. Tight junctions control the permeability of the layer. The secretory products of the odontoblasts are released through the cell membrane at the peripheral end of the cell body and through the cell process. The cell-to-cell junctions are specialized areas of the cell membrane. Other parts of the cell membrane are specialized to be *membrane receptors* to which signaling molecules can attach (as *ligands*) and thereby modify the behavior of the cell.

There are many types of membrane receptors. The type and number of receptors vary greatly between cell types and at different times of the cell's life. The odontoblast has several types of receptors on or within its cell membrane. Toll-like receptors (TLR2 and TLR4), when activated by components of gram-positive bacteria (lipoteichoic acid), cause the odontoblasts to release proinflammatory cytokines (Fig. 1.12). This indicates that the odontoblasts can act as antigen-recognition cells when bacterial products penetrate the dentin.[14] Other known receptors (e.g., TRPV1, capsaicin receptor, and TRK-1, vanilloid receptor) are thermosensitive and can sense heat- or cold-induced fluid movement in the tubules (Fig. 1.13).[15,16] Thus, the odontoblast has a role in the immune response and may act as a nociceptor.

Stem Cells (Preodontoblasts)

Newly differentiated odontoblasts develop after an injury that results in the death of existing odontoblasts. They develop from stem cells (also known as *undifferentiated mesenchymal cells*), which are present throughout the pulp, although densest in its core.[17] Under the influence of signaling molecules released in response to injury and cell death, these precursor cells migrate to the site of injury and differentiate into odontoblasts.[18] The key signaling molecules in this process are

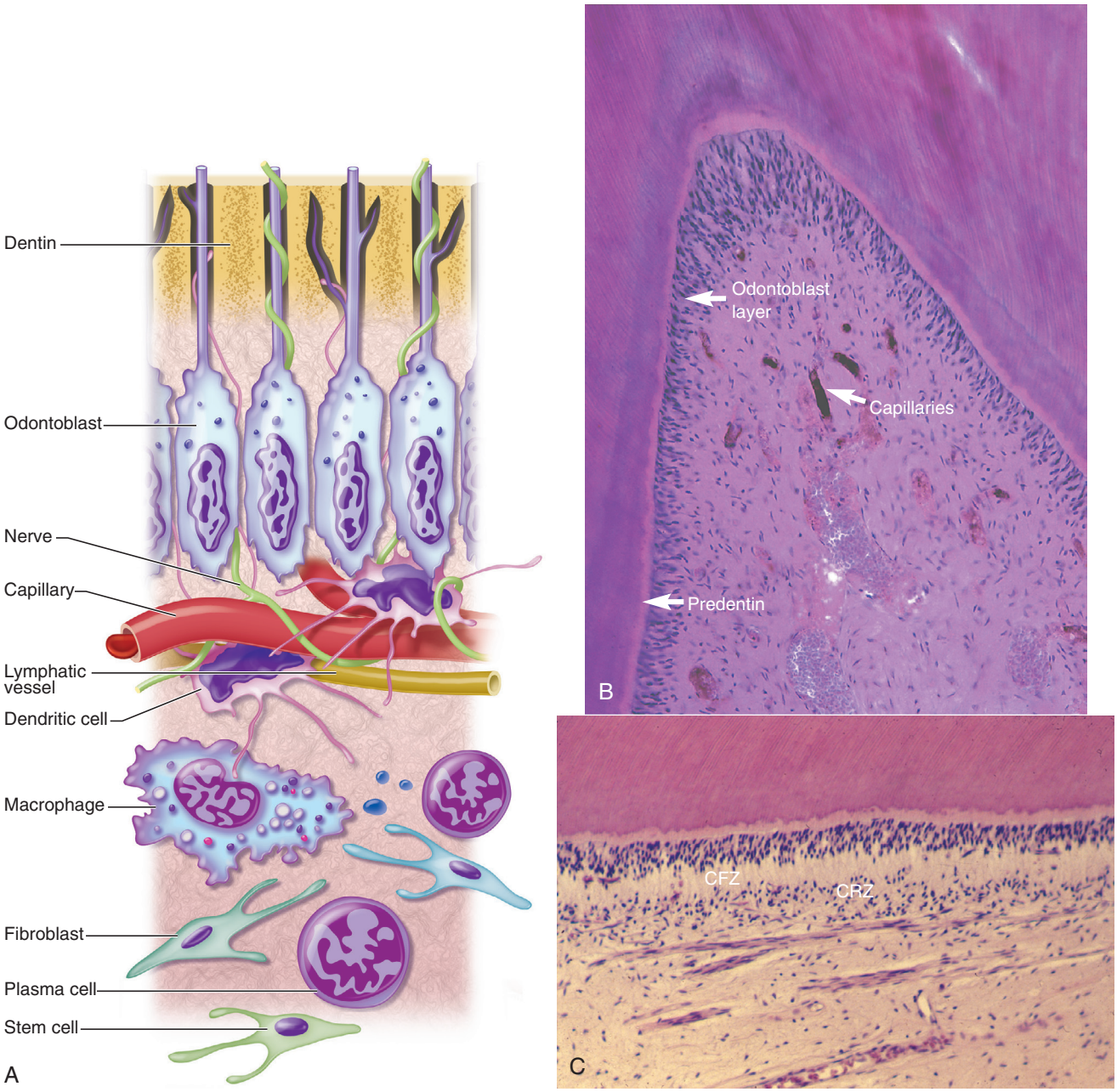

Fig. 1.10 **A,** Diagram of the organization of the peripheral pulp. **B,** Peripheral pulp at low power. **C,** Peripheral pulp showing cell-free zone *(CFZ)* and cell-rich zone *(CRZ)*.

members of the bone morphogenetic protein (BMP) family and transforming growth factor β. These (and other) growth factors are embedded in dentin matrix, although their origin is unknown.

Dental pulpal stem cells (DSPC) can differentiate not only into odontoblasts, but also into other cell types, such as osteoblasts, adipocytes, cardiac muscle cells, and even neurons. These cells promise to be useful therapeutically in the regeneration of pulp and other tissues (Fig. 1.14).

Fibroblasts

Fibroblasts are the most common cell type in the pulp and are seen in greatest numbers in the coronal pulp. They produce and maintain the collagen and ground substance of the pulp and alter the structure of the pulp in disease. As with odontoblasts, the prominence of their cytoplasmic organelles changes according to their activity. The more active the cell, the more prominent the organelles and other components necessary for synthesis and secretion. As do odontoblasts, these cells undergo apoptotic cell death and are replaced when necessary by the maturation of less differentiated cells.

Before immunocytochemistry and DNA/RNA analysis became available, simple techniques, such as hematoxylin-eosin staining, were used to identify cell types. However, they could not detect subtle differences between cell types. Using those methods, the majority of cells in loose connective tissues such as the pulp were designated as "fibroblasts." Certainly there are some main fibroblasts that synthesize and

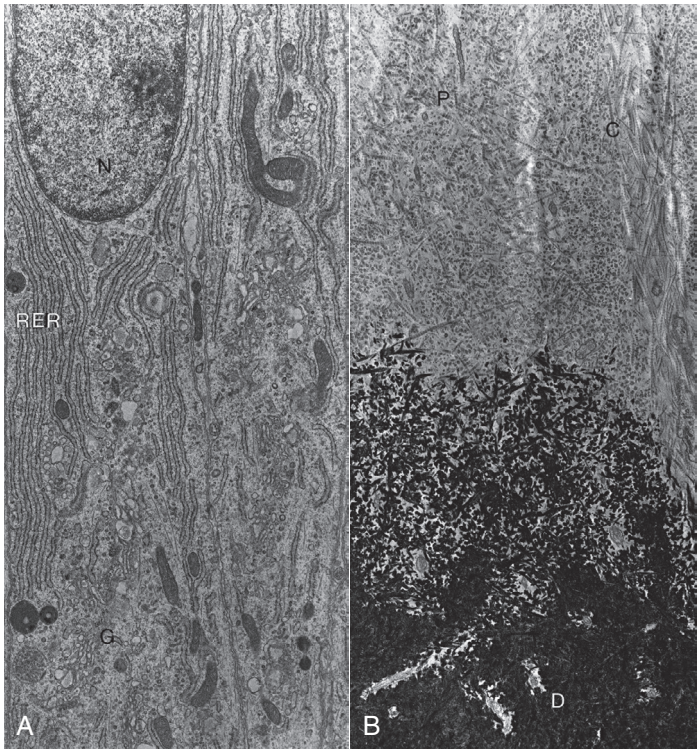

Fig. 1.11 **A,** Odontoblast cell body. The nucleus *(N)* is proximal, and the numerous organelles, such as rough endoplasmic reticulum *(RER)* and Golgi apparatus *(G),* which are responsible for synthesis of matrix components, occupy the central-distal regions. **B,** Predentin *(P)* shows the orientation of collagen *(C)* to the odontoblastic process, which is the secretory organ that extends through the predentin into the dentin *(D).* (Courtesy Dr. P. Glick and Dr. D. Rowe.)

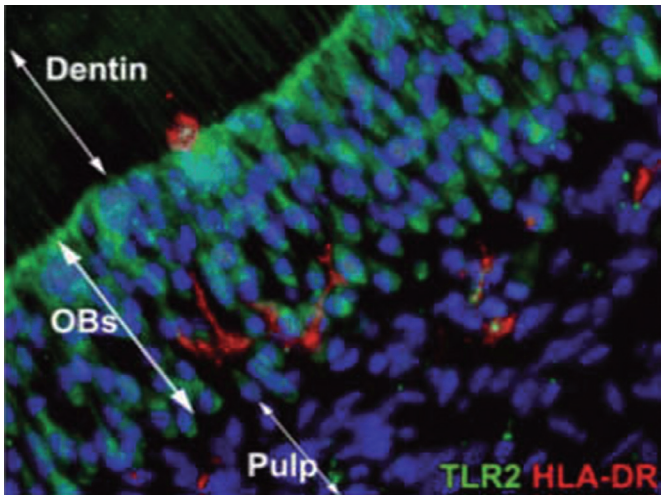

Fig. 1.12 The odontoblast layer, dentin, and subodontoblastic zone immunostained to label Toll-like receptors (TLR2) *(green)* and dendritic cells *(red)*. (Veerayutthwilai O, Byers MR, Darveau RP, Dale BA: Differential regulation of immune responses by odontoblasts, *Oral Microbiol Immunol* 2007: 22: 5-13, 2007.)

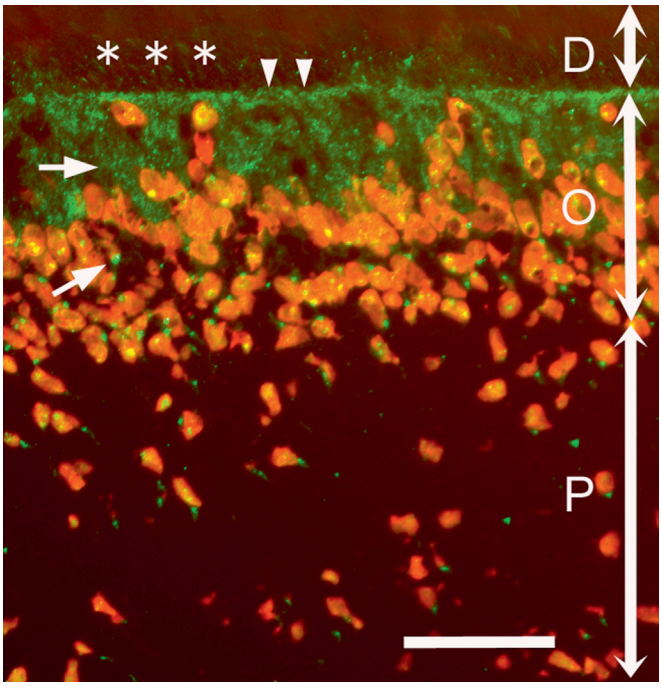

Fig. 1.13 Immunohistochemical staining of transient receptor potential vanilloid 1 (TRPV1) channels in rat odontoblasts that could induce electrical activity in the odontoblasts when stretched or compressed by fluid movement. Asterisks and arrowheads show TRPV1-positive staining (green) on odontoblast processes in the tubules and on the distal end of the odontoblastic cell membrane. The red stain indicates nuclei in all the cells present. TRPV1 staining is largely limited to the odontoblasts. D, Dentin; O, odontoblast layer; P, pulp. (Courtesy Dr. Y. Shibukawa.) (From Okumura R, Shima K, Muramatsu T, et al: The odontoblast as a sensory receptor cell? The expression of TRPV1 (VR-1) channels, Archives of Histology and cytology, 2005.)

secrete matrix components, but there is now a recognition of the heterogeneity of cells in the pulp.

Cells of the Immune System

The most prominent immune cells in the dental pulp are the dendritic cells.[19] These are antigen-presenting cells present most densely in the odontoblast layer and around blood vessels. They recognize a wide range of foreign antigens and, along with odontoblasts, initiate the immune response. Many other cells (e.g., macrophages and neutrophils) have antigen-presenting properties, but dendritic cells in the pulp, in terms

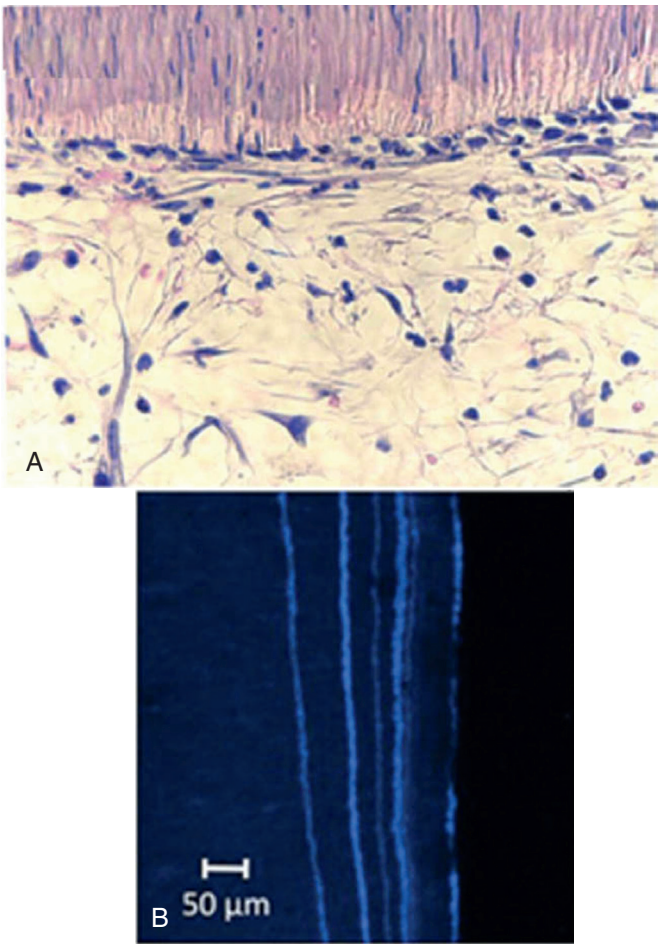

Fig. 1.14 Stem cells from exfoliated deciduous teeth (SHED) were placed on a scaffold in a tooth slice from which the pulp had been removed. The slice was then placed subcutaneously in a mouse and left for 32 days. **A,** The pulp and dentin were examined a month after placement. The stem cells differentiate into functional odontoblasts and endothelial cells (hematoxylin-eosin.) **B,** Once the stem cells differentiated into functional odontoblasts, they generated tubular dentin. This is demonstrated by injecting tetracycline intraperitoneally every 5 days and observing a section of the slice in a confocal microscope. The bright lines indicate areas where the tetracycline has been incorporated into the dentin. (From Sakai VT, Cordeiro MM, Dong Z, et al: *Advances in dental research: tooth slice/scaffold model of dental pulp tissue engineering*, Thousand Oaks, Calif., Jun 15, 2011, Sage Publishing.)

of numbers (estimated at 8% of the pulp) and position, are the most prominent in the pulp. Special stains are needed to recognize them histologically.

Macrophages in a resting form (histiocytes) and some T lymphocytes are also found in the normal pulp.[20]

EXTRACELLULAR COMPONENTS[21]

Fibers

The predominant collagen in dentin is type I; both type I and type III collagens are found within pulp in a ratio of approximately 55:45. Odontoblasts produce only type I collagen for incorporation into the dentin matrix, whereas fibroblasts produce both type I and type III. Pulpal collagen is present as fibrils that are 50 nm wide and several micrometers long. They form bundles that are irregularly arranged except in the periphery, where they lie approximately parallel to the predentin surface. The only noncollagenous fibers present in the pulp are tiny, 10 to 15 nm wide beaded fibrils of fibrillin, a large glycoprotein. Elastic fibers are absent from the pulp.

The proportion of collagen types is constant in the pulp, but with age there is an increase in the overall collagen content and an increase in the organization of collagen fibers into collagen bundles. Normally, the apical portion of pulp contains more collagen than the coronal pulp, facilitating pulpectomy with a barbed broach or endodontic file during root canal treatment.

Noncollagenous Matrix[22]

The collagenous fibers of the pulp are embedded in a histologically clear gel made up of glycosaminoglycans and other adhesion molecules. The glycosaminoglycans link to protein and other saccharides to form proteoglycans, a very diverse group of molecules. They are bulky hydrophilic molecules that, with water, make up the gel. At least six types of adhesion molecules have been detected in the pulp matrix. One of these, fibronectin is responsible for cell adhesion to the matrix.

Calcifications

Pulp stones or denticles (Fig. 1.15) were once classified as true or false, depending on the presence or absence of a tubular structure. This classification has been challenged, and a new nomenclature based on the genesis of the calcification has been suggested. Pulp stones have also been classified according to location. Three types of pulp stones have been described: *free stones,* which are surrounded by pulp tissue; *attached stones,* which are continuous with the dentin; and *embedded stones,* which are surrounded entirely by tertiary dentin.

Pulp stones occur in both young and old patients and may occur in one or several teeth. A recent radiographic (bitewing) survey of undergraduate dental students found that 46% of them had one or more pulp stones and that 10% of all the teeth contained a pulp stone. Pulp stones occur in normal pulps and in chronically inflamed pulps. They are not responsible for painful symptoms, regardless of size.

Calcifications may also occur in the form of diffuse or linear deposits associated with neurovascular bundles in the pulp core. This type of calcification is seen most often in aged, chronically inflamed, or traumatized pulp. Depending on shape, size, and location, pulp calcifications may or may not be detected on a dental radiograph (Fig. 1.16). *Large pulp stones are clinically significant, because they may block access to canals or the root apex during root canal treatment.*

BLOOD VESSELS

Mature pulp has an extensive and specialized vascular pattern that reflects its unique environment.[23] The vessel network has been examined using a variety of techniques, including India ink perfusion, transmission electron microscopy, scanning electron microscopy, and microradiography.

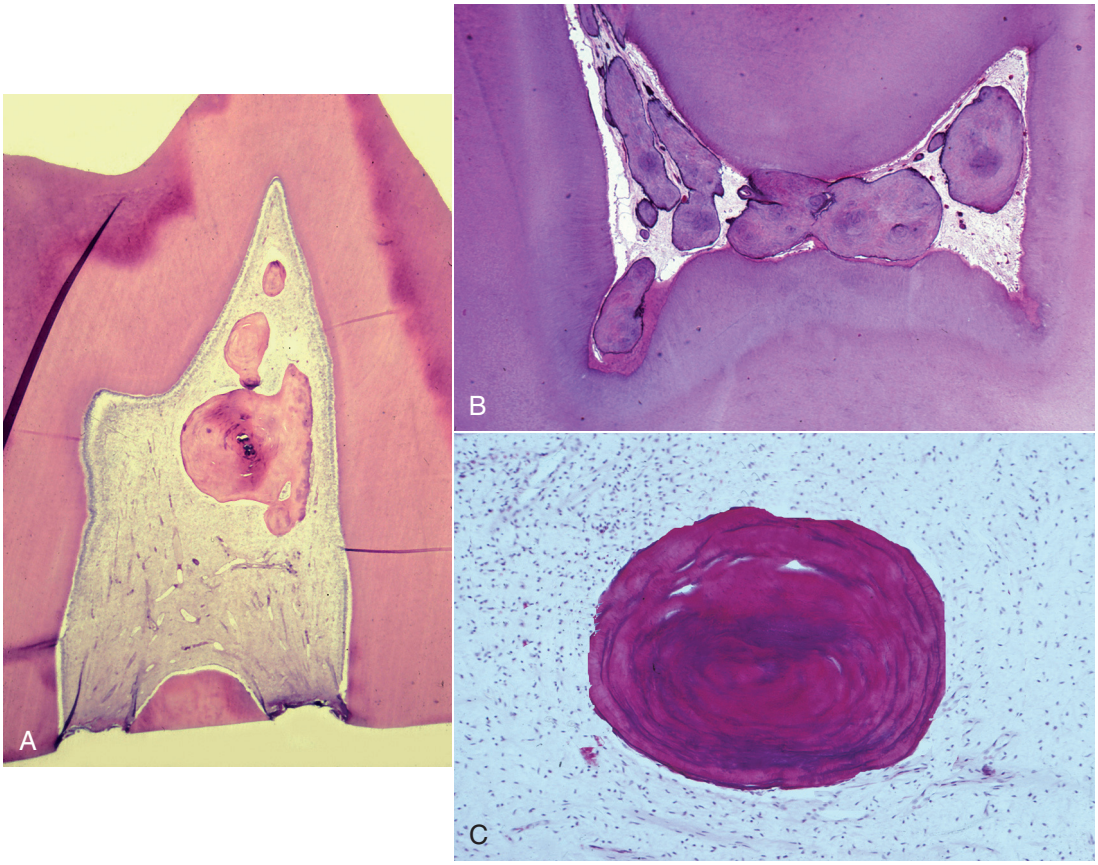

Fig. 1.15 **A,** Multiple stones in coronal pulp. **B,** Stones occluding a pulp chamber. **C,** Lamellated pulp stone. (Courtesy Dr. H. Trowbridge.)

Afferent Blood Vessels (Arterioles)

The largest vessels to enter the apical foramen are arterioles that are branches of the inferior alveolar artery, the superior posterior alveolar artery, or the infraorbital artery.

Once inside the radicular pulp, the arterioles travel toward the crown. They narrow, then branch extensively and lose their muscle sheath before forming a capillary bed (Fig. 1.17). The muscle fibers before the capillary bed form the "precapillary sphincters," which control blood flow and pressure. The most extensive capillary branching occurs in the subodontoblastic layer of the coronal pulp, where the vessels form a dense plexus (Fig. 1.18).[24] The loops of some of these capillaries extend between odontoblasts.[22] The exchange of nutrients and waste products takes place in the capillaries (Fig. 1.19).[25] There is an extensive shunting system composed of arteriovenous and venovenous anastomoses; these shunts become active after pulp injury and during repair.

Efferent Blood Vessels

Venules constitute the efferent (exit) side of the pulpal circulation and are slightly larger than the corresponding arterioles. Venules are formed from the junction of venous capillaries and enlarge as more capillary branches unite with them. They run with the arterioles and exit at the apical foramen to drain posteriorly into the maxillary vein through the pterygoid plexus or anteriorly into the facial vein.

Lymphatics[26,27]

Lymphatic vessels arise as small, blind, thin-walled vessels in the periphery of the pulp. They pass through the pulp to exit as one or two larger vessels through the apical foramen (Figs. 1.20 and 1.21). The lymphatic vessel walls are composed of an endothelium rich in organelles and granules. There are discontinuities in the walls of these vessels and in their basement membranes. This porosity permits the passage of interstitial tissue fluid and, when necessary, lymphocytes into the negative-pressure lymph vessel. The lymphatics assist in the removal of inflammatory exudates and transudates and cellular debris. After exiting from the pulp, some vessels join similar vessels from the PDL and drain into regional lymph glands (submental, submandibular, or cervical) before emptying into the subclavian and internal jugular veins. *An understanding of lymphatic drainage assists in the diagnosis of infection of endodontic origin.*

Vascular Physiology

The dental pulp, at least when young, is a highly vascular tissue. Capillary blood flow in the coronal region is almost twice that of the radicular region. Blood supply is regulated largely by the precapillary sphincters and their sympathetic innervation.[28] Other local factors and peptides released from sensory nerves also affect the vessels most prominently during inflammation.

As in other tissues, the volume of the vascular bed is much greater than the volume of blood that is normally passing through it. Only part of the vascular bed is perfused at any one time. This capacity allows for sizable local increases in blood flow in response to injury.

The factors that determine what passes in and out between the blood and the tissue include concentration gradients,

osmosis, and hydraulic pressure. Concentration gradients vary along the capillary bed as oxygen, for example, diffuses out into the depleted tissue and carbon dioxide (CO_2) enters from high to low concentration. The hydraulic pressure in the pulpal capillaries falls from 35 mm Hg at the arteriolar end to 19 mm Hg at the venular end. Outside the vessel, the interstitial fluid pressure varies, but a normal figure would be 6 mm Hg.[29]

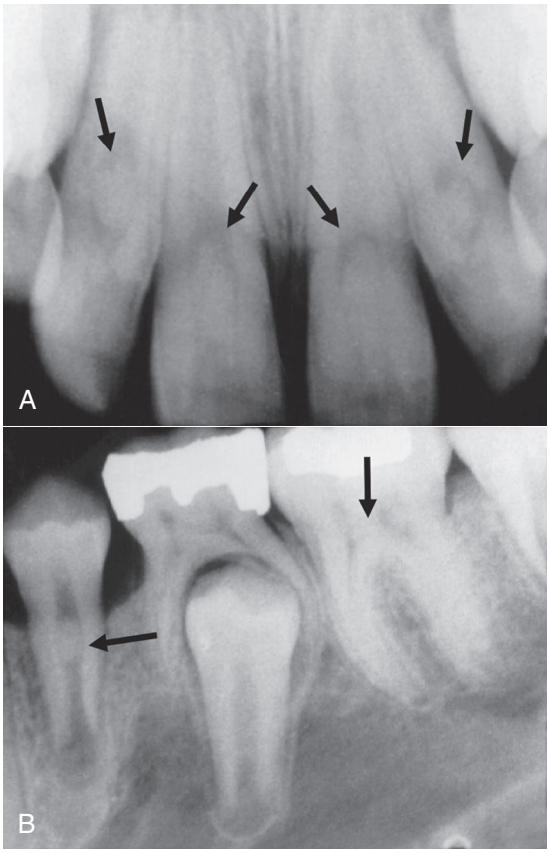

Fig. 1.16 Multiple pulp stones *(arrows)* in the pulp chamber and root canals of the anterior **(A)** and posterior **(B)** teeth of a young patient.

Vascular Changes During Inflammation[30]

When the dental pulp is injured, it responds in the same way as other connective tissues with a two-phase immune response. The initial immune response is nonspecific but rapid, occurring in minutes or hours. The second response is specific and includes the production of specific antibodies. Before the detailed nature of the immune response was known, the phenomenon associated with the response to tissue injury, including redness, pain, heat, and swelling, was known as *inflammation.* Although much more is now known about the response to injury at the cellular level, these "cardinal signs" remain important. Except for pain, they are all vascular in origin. Heat and redness are results of increased blood flow, and swelling results from increased formation of interstitial tissue fluid because of increased permeability of the capillaries. In other tissues, such as skin (in which inflammation was first described), the increased production of tissue fluid results in swelling. Because the dental pulp is within a rigid, noncompliant chamber, it cannot swell, and the increased interstitial fluid formation results in an increase in tissue fluid pressure.

At one time, it was thought that this rise in interstitial fluid pressure would spread rapidly and strangle vessels entering the root canal at the apical foramen. Closer study has revealed that this is not the case. Elevations in tissue fluid pressure remain localized to the injured area. A short distance from the injury, tissue fluid pressure is maintained within normal limits. As interstitial fluid pressure rises, the intraluminal (inside) pressure of the local capillaries increases to balance this so that the vessels remain patent. During the response to injury, the gradients by which nutrients and wastes leave and enter the capillaries change to allow greater exchange. At the same time these changes occur in the capillaries, lymphatic vessels become more heavily employed, removing excess tissue fluid and debris. In addition, anastomoses in the microvascular bed allow blood to be shunted around an area of injury, so that the oxygenation and nutrition of nearby uninjured tissue are not compromised. If the cause of the injury is removed, these processes gradually return the vasculature to normal and repair or regeneration can take place. If the injury persists and increases in size, this tissue necroses. This necrosis can remain localized as a pulpal abscess, although it more often spreads throughout the pulp. The necrosis extends as the toxins from the carious lesion diffuse through the tissue.

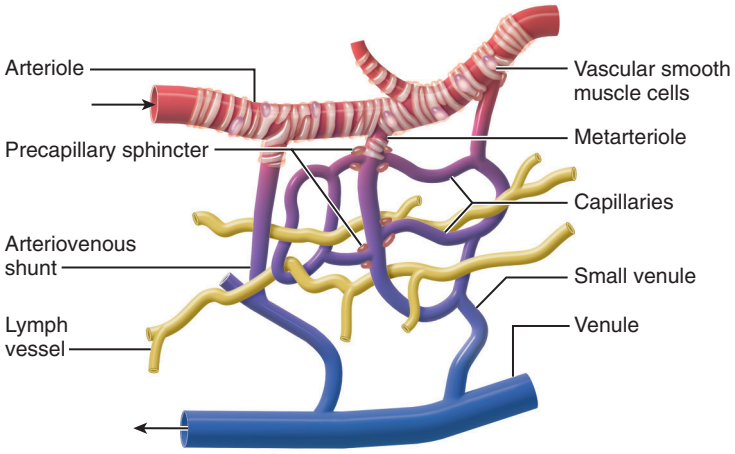

Fig. 1.17 Schematic of the pulpal vasculature. Smooth muscle cells that surround vessels and precapillary sphincters selectively control blood flow. Arteriovenous shunts bypass capillary beds.

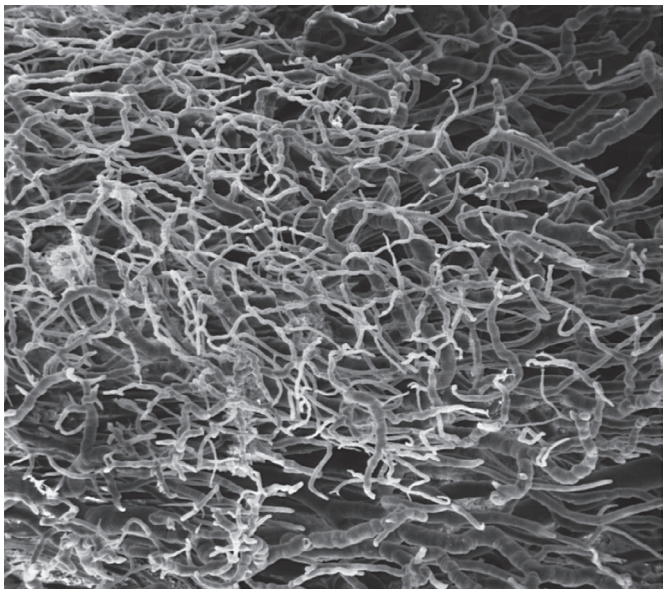

Fig. 1.18 The dense capillary bed in the subodontoblastic region is shown by resin cast preparation and scanning electron microscopy. (Courtesy Dr. C. Kockapan.)

The vascular changes seen in inflammation are largely mediated by local nerves. The sympathetic fibers through the precapillary sphincters can alter the pressure, flow, and distribution of blood. Sensory nerve fibers release a number of neuropeptides, most prominently calcitonin gene–related peptide (CGRP) and substance P. (These names are of historic origin and unrelated to the function of these molecules in this setting.) The release of these neuropeptides comes about through axon reflexes, whereby one branch of a sensory nerve stimulated by the injury causes the release of the peptides by another branch. This mechanism, in which excitation of sensory elements results in increased blood flow and increased capillary permeability, is known as *neurogenic inflammation.*

INNERVATION

The second and third divisions of the trigeminal nerve (V_2 and V_3) provide the principal sensory innervation to the pulp of maxillary and mandibular teeth, respectively. Mandibular premolars can also receive sensory branches from the mylohyoid nerve of V_3, which is principally a motor nerve. Branches from this nerve reach the teeth via small foramina on the lingual aspect of the mandible. Mandibular molars occasionally receive sensory innervation from the second and third cervical spinal nerves (C2 and C3). This can create difficulties in anesthetizing these teeth with an inferior dental block injection only.

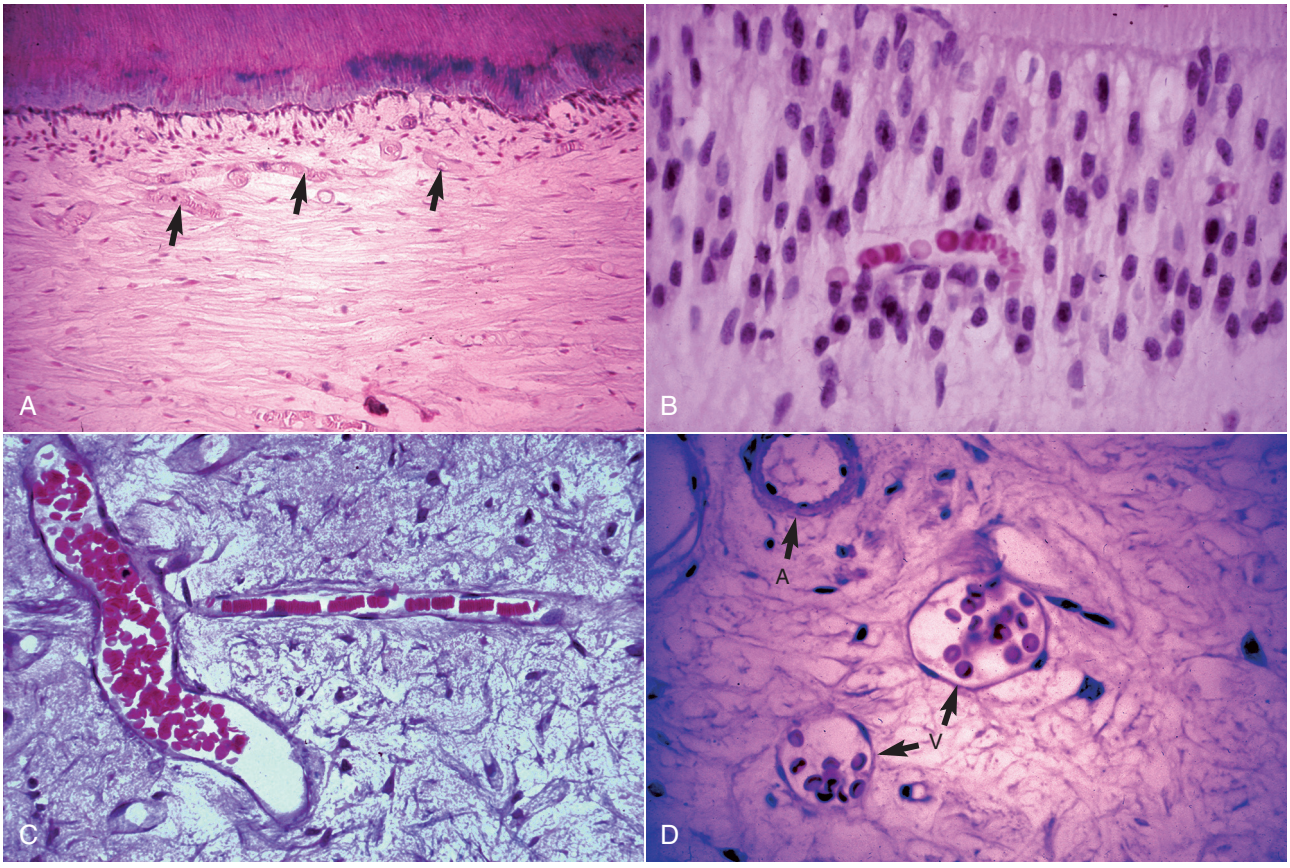

Fig. 1.19 **A,** Subodontoblastic capillary plexus. **B,** Capillary within the odontoblast layer. **C,** Branching capillaries in subodontoblastic plexus. **D,** Arteriole *(A)* and venules *(V)* in the peripheral pulp. (Courtesy Dr. H. Trowbridge.)

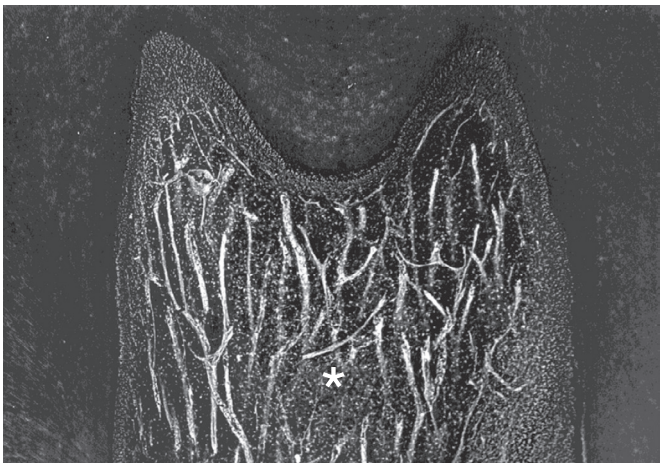

Fig. 1.20 Distribution of lymphatics. Scanning electron micrograph of secondary and back-scattered electrons after specific immune staining. (From Matsumoto Y, Zhang B, Kato S: *Microsc Res Tech* 56:50, 2002.)

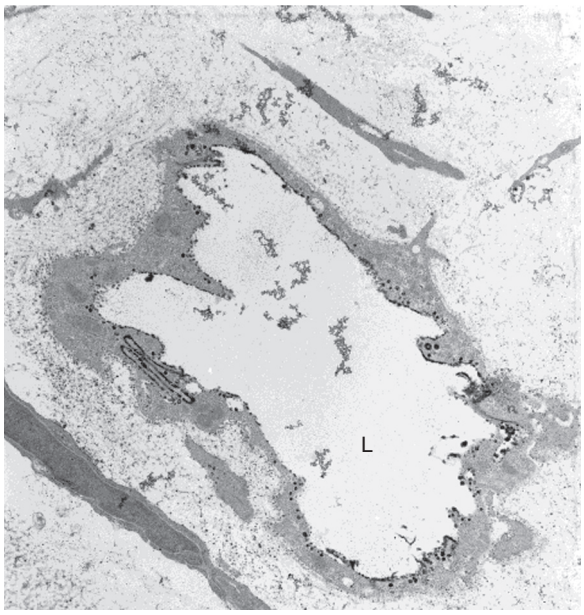

Fig. 1.21 Transmission electron micrograph of a lymphatic vessel *(L)* in the peripheral pulp. (From Matsumoto Y, Zhang B, Kato S: Lymphatic networks in the periodontal tissue and dental pulp as revealed by histochemical study, *Microsc Res Tech* 56:50, 2002.)

Cell bodies of trigeminal nerves are located in the trigeminal ganglion. Dendrites from these nerves synapse with neurons in the trigeminal sensory nucleus in the brainstem. Second-order neurons here travel to specific nuclei in the thalamus. Third-order neurons and their branches reach the sensory cortex and a number of other higher centers.

Pulp also receives sympathetic (motor) innervation from T1 and, to some extent, C8 and T2 via the superior cervical ganglion. These nerves enter the pulp space alongside the main pulp blood vessels and are distributed with them. They maintain the vasomotor tone in the precapillary sphincters, which control the pressure and distribution of blood. The presence of parasympathetic nerve fibers in the pulp has been controversial. The current consensus is that there is no

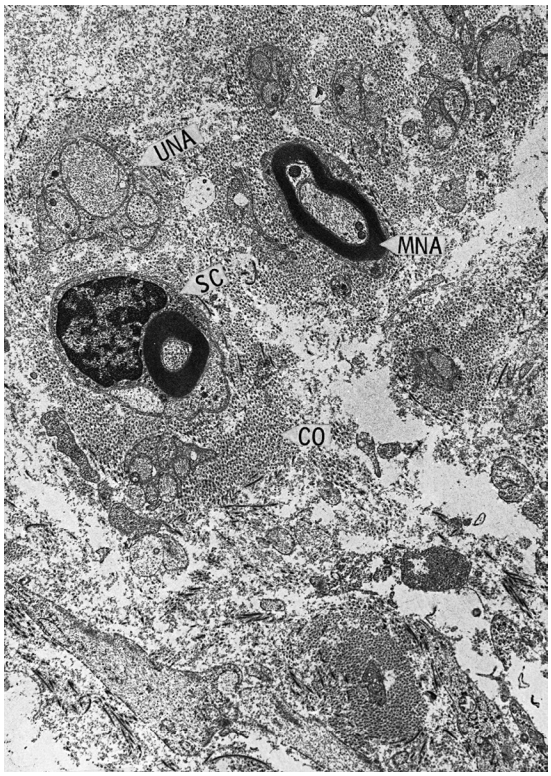

Fig. 1.22 Pulp nerves in region of the pulp core. A group of unmyelinated *(UNA)* and myelinated *(MNA)* nerve axons are shown in cross section. A Schwann cell *(SC)* associated with one of the myelinated axons is evident. Nerves are surrounded by collagen fibers *(CO)*.

parasympathetic innervation of the pulp. This is not unusual. All tissues have an autonomic innervation, but not always from both divisions.

Neuroanatomy

Pulpal and Dentinal Nerves

Sensory nerves supplying the dental pulp contain both myelinated and unmyelinated axons (Fig. 1.22). The myelinated axons are almost all narrow, slow-conducting Aδ axons (1 to 6 μm in diameter) associated with nociception. A small percentage of the myelinated axons (1% to 5%) are faster-conducting Aβ axons (6 to 12 μm in diameter). In other tissues, these larger fibers can be proprioceptive or mechanoreceptive. Their role in the pulp is uncertain, but it is now known from other tissues that, in inflammation, these Aβ axons can be recruited to the pain system. Before they terminate, all the myelinated axons lose their myelin sheath and terminate as small, unmyelinated branches either below the odontoblasts, around the odontoblasts, or alongside the odontoblast process in the dentinal tubule (Fig. 1.23).[31] Beneath the odontoblast layer, these terminating fibers form the subodontoblastic plexus of Raschkow (Fig. 1.24).

The nerves that enter the dentinal tubules do not synapse with the process but remain in close proximity with it for part of its length. Approximately 27% of the tubules in the area of the pulp horn of a young, mature tooth contain an intratubular nerve. These nerves occur less often in the middle (11%) and cervical portions (8%) of the crown and not at all in the root.[32]

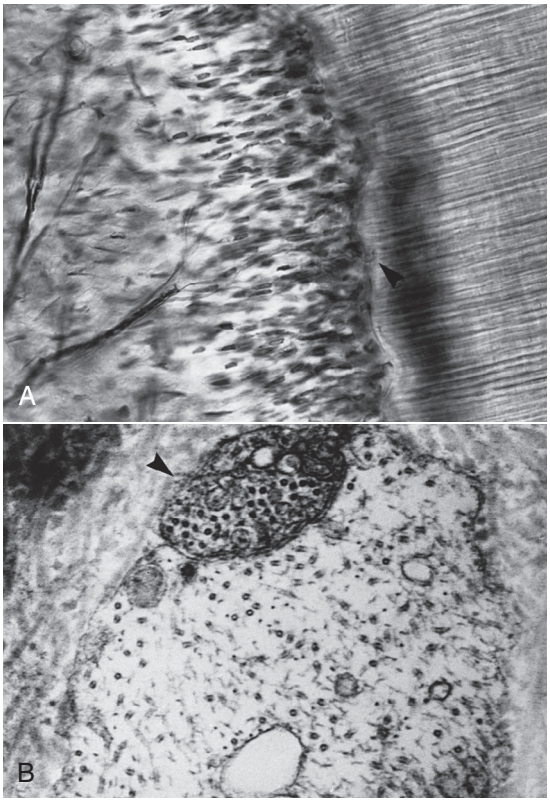

Fig. 1.23 **A,** Silver-stained section of pulp in a young human molar demonstrates arborization of nerves in the subodontoblastic region and a nerve *(arrow)* passing between odontoblasts into the predentin area. **B,** Transmission electron micrograph demonstrates an unmyelinated nerve axon *(arrow)* alongside the odontoblast process in the dentin tubule at the level of the predentin. (**A,** Courtesy Dr. S. Bernick.)

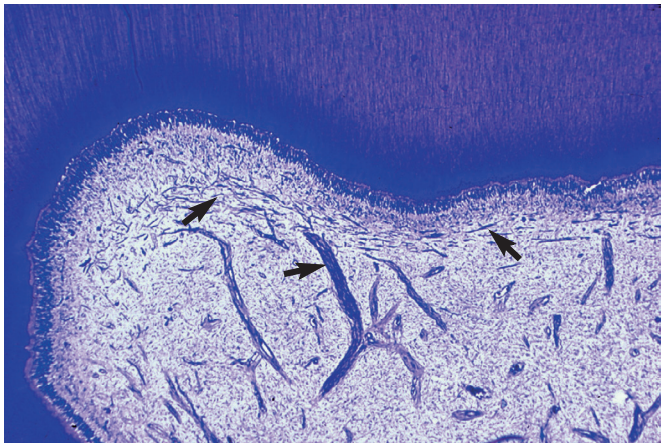

Fig. 1.24 Raschkow's subodontoblastic plexus *(arrows)* stained with silver.

Their incidence is higher in predentin than in mineralized dentin.

Developmental Aspects of Pulp Innervation

The types and relative number of nerves depend on the state of tooth maturity. Myelinated nerves enter the pulp at about the same time as unmyelinated nerves but in most instances do not form the subodontoblastic plexus of Raschkow until some time after tooth eruption. As a result, there are significant variations in the responses of partially developed teeth to pulp vitality tests. *This undermines the value of stimulatory tests for determining pulp status in young patients, particularly after trauma.*

The number of pulpal nerves diminishes with age. The significance of this reduction in terms of responses to vitality testing is undetermined.

Pathways of Transmission from Pulp to Central Nervous System

Mechanical, thermal, and chemical stimuli initiate an impulse that travels along the pulpal axons in the maxillary (V_2) or mandibular (V_3) branches of the trigeminal nerve to the trigeminal (gasserian) ganglion, which contains the cell body of the neuron. Dendrites from the ganglion then pass centrally and synapse with second-order neurons in the trigeminal nuclear complex located at the base of the medulla and the upper end of the spinal cord. Most of the activity that originates in the dental pulp is conducted along axons that synapse with neurons in the spinal portion of the complex, most notably the subnucleus caudalis.

Many peripheral axons from different sites synapse on a single secondary neuron, a phenomenon known as *convergence.* Activity in a single synapse does not result in excitation of the second-order neuron. Activity in many synapses must summate to reach the threshold of the second-order neuron. The activation of the second-order neuron is also affected by fibers from the midbrain that belong to the endogenous opioid system. These, when active, reduce the activity of the second-order neurons. Thus, noxious input is modulated, explaining why the pain experience is not always closely related to the degree of peripheral noxious stimulation. Axons from the second-order neurons cross the midline and synapse in thalamic nuclei. From here, third-order neurons pass information to a variety of higher centers, the sensory cortex being only one of them. The distribution of noxious input centrally and the presence of a pain-modulating system descending from higher centers provide the broad framework for understanding and controlling pain. As a result of persistent noxious input, the properties of second-order neurons can change. These changes can be used to explain some of the complexities of diagnosing and treating pain as described in other sections of this text.

Theories of Dentin Hypersensitivity

Pain elicited by scraping or cutting of dentin or by the application of cold or hypertonic solutions to exposed dentin gives the impression that there may be a nerve pathway from the central nervous system to the dentinoenamel junction (DEJ). However, no direct pathway is present. The application of pain-producing substances, such as histamine, acetylcholine, or potassium chloride, to exposed dentin surface fails to produce pain. Eliciting pain from exposed dentin by heat or cold is not blocked by local anesthetics. At one time it was thought that dentin sensitivity was due to sensory nerves within the dentinal tubules.

Currently, two explanations for peripheral dentin sensitivity have broad acceptance (Fig. 1.25). One is that stimuli that are effective in eliciting pain from dentin cause fluid flow through the dentinal tubules.[33] This disturbance results in the activation of nociceptors in the inner dentin and peripheral pulp.

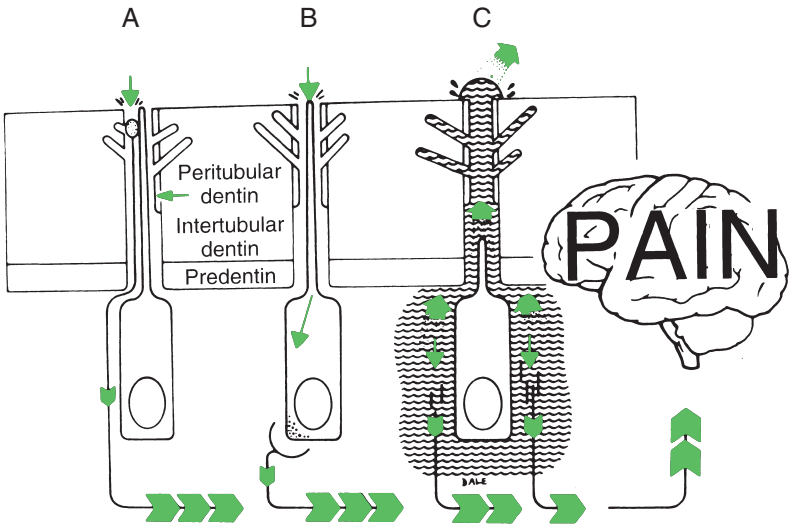

Fig. 1.25 Schematic drawing of theoretic mechanisms of dentin sensitivity. **A,** Classic theory (direct stimulation of nerve fibers in the dentin). **B,** Odontoblasts as a mediator between the stimuli and the nerve fibers. **C,** Fluid movement as proposed in hydrodynamic theory. (Modified from Torneck CD: Dentin-pulp complex. In Ten Cate AR, editor, *Oral histology,* ed 4, St Louis, 1994, Mosby.)

Several observations support this "hydrodynamic hypothesis." In experiments on extracted teeth, it has been shown that hot, cold, and osmotic stimuli cause fluid flow through dentin. In human subjects, the success of solutions in inducing pain is related to the osmotic pressure of the solution. Exposed dentin that is sensitive in patients has patent dentinal tubules.[34]

In exposed dentin that is not sensitive, the dentinal tubules are occluded. Substances and techniques that occlude dentinal tubules in sensitive dentin eliminate or reduce the sensitivity. A second explanation is that some substances can diffuse through the dentin and act directly on pulpal nerves. Evidence for this largely comes from animal experiments, which show that the activation of pulpal nerves is sometimes related to the chemical composition of a stimulating solution rather than its osmotic pressure. These are not mutually exclusive hypotheses; both may apply, and both should be addressed in treating sensitive dentin.

AGE CHANGES IN THE DENTAL PULP AND DENTIN

Secondary dentin is laid down throughout life. As a result, both the pulp chamber and root canals become smaller, sometimes to the point where they are no longer visible on radiographs. As age increases, more peritubular dentin is laid down, often completely occluding the dentinal tubules in the periphery (sclerotic dentin). As a result of these processes, the permeability of the dentin is reduced. The pulp tissue itself becomes less cellular and less vascular and contains fewer nerve fibers. Between the ages of 20 and 70, cell density decreases by approximately 50%. This reduction affects all cells, from the highly differentiated odontoblast to the undifferentiated stem cell.

REPAIR AND REGENERATION

The dental pulp can respond positively to external irritants, including the toxins released during dental caries. Inflammation is part of the response that leads to the formation of new dentin. This occurs in two forms: (1) tertiary response dentin, which is formed by the original odontoblasts and is tubular in structure, and (2) tertiary reparative dentin, which is formed after the original odontoblasts have been killed and is created by odontoblasts differentiated from stem cells. The type of dentin laid down is determined by the intensity of the stimulus.

Stem cells can be isolated from exfoliated deciduous teeth (known as "SHED" cells) and have been shown in an animal model to form new dentin and pulp in slices of tooth from which the pulp has been removed (Fig. 1.14).[35] This leads to the happy prospect that the pulp may be regenerated in pulpless teeth.

PERIRADICULAR TISSUES

The periodontium, the tissue surrounding and investing the root of the tooth, consists of the cementum, PDL, and alveolar bone (Fig. 1.26). These tissues originate from the dental follicle that surrounds the enamel organ; their formation is initiated when root development begins.[36] After the tooth has erupted, the cervical portion of the tooth is in contact with the epithelium of the gingiva, which, in combination with reduced dental epithelium on the enamel, forms the dentogingival junction. When intact, this junction protects the underlying periodontium from potential irritants in the oral cavity. The pulp and the periodontium form a continuum at sites along the root where blood vessels enter and exit the pulp at the apical foramen and lateral and accessory canals (Fig. 1.27).

Cementum

Cementum is a bonelike tissue that covers the root and provides attachment for the principal periodontal fibers. The several types of cementum that have been identified are as follows:

1. *Primary acellular intrinsic fiber cementum.* This is the first cementum formed, and it is present before principal periodontal fibers are fully formed. It extends from the cervical margin to the cervical third of the tooth in some

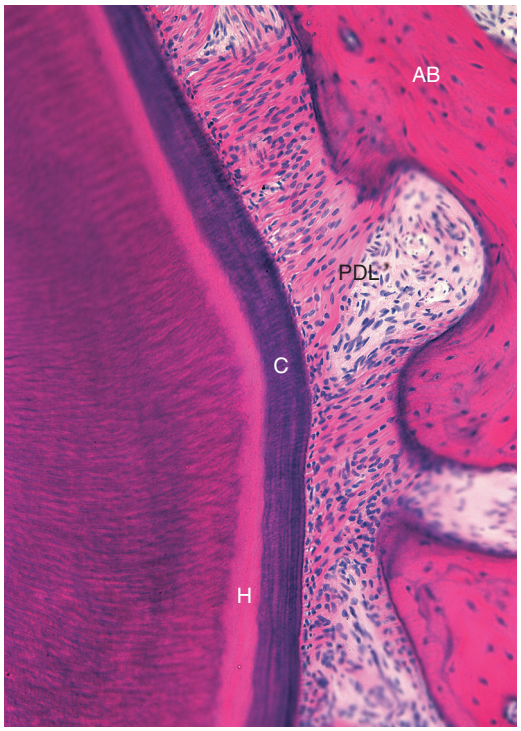

Fig. 1.26 Peripheral radicular dentin (*H,* hyaline layer), cementum *(C),* periodontal ligament *(PDL),* and alveolar bone *(AB).*

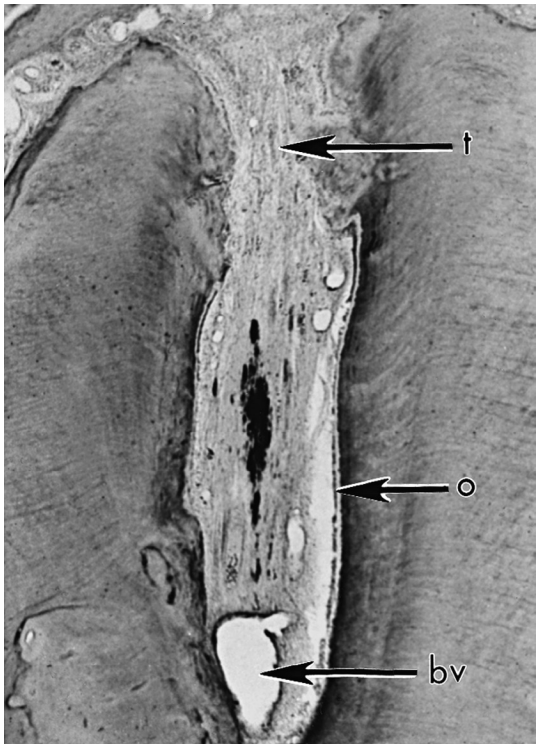

Fig. 1.27 Apical region of maxillary incisor showing apical foramen. *t,* Transitional tissue between periodontal ligament and pulp; *o,* odontoblasts; *bv,* blood vessel.

teeth and around the entire root in others (incisors and cuspids). It is more mineralized on the surface than near the dentin and contains collagen produced initially by cementoblasts and later by fibroblasts.

2. *Primary acellular extrinsic fiber cementum.* This is cementum that continues to be formed about the primary periodontal fibers after they have been incorporated into primary acellular intrinsic fiber cementum.
3. *Secondary cellular intrinsic fiber cementum.* This cementum is bonelike in appearance and only plays a minor role in fiber attachment. It occurs most often in the apical part of the root of premolars and molars.
4. *Secondary cellular mixed fiber cementum.* This is an adaptive type of cellular cementum that incorporates periodontal fibers as they continue to develop. It is variable in its distribution and extent and can be recognized by the inclusion of cementocytes, its laminated appearance, and the presence of cementoid on its surface.
5. *Acellular afibrillar cementum.* This is the cementum sometimes seen overlapping enamel, which plays no role in fiber attachment.

Cementum is similar to bone but harder and thus resists resorption during tooth movement. The junction between the cementum and the dentin (CDJ) that forms the apical constriction is ill defined and not uniform throughout its circumference. Biologic principles suggest that the most appropriate point to end a root canal preparation is at the junction of the pulp and periodontium, which occurs at the apical constriction. *Although many practitioners debate the probabilities and practicalities of achieving this goal, most agree that it is essential to measure canal length accurately and to restrict all procedures to a canal length that estimates this point as closely as possible.*

Although dentin is harder than bone and resorbs more slowly, it does resorb in periapical inflammatory lesions, often resulting in loss of the apical constriction. Occasionally, more rapid resorption of unknown cause is seen (idiopathic resorption), but this is often self-limiting.

Cementoenamel Junction

The junction of cementum and enamel at the cervix of the tooth varies in its arrangement even around a single tooth. Sometimes cementum overlies enamel and vice versa. When there is a gap between the cementum and the enamel, the exposed dentin may be sensitive.

Periodontal Ligament

As is dental pulp, the periodontal ligament is a specialized connective tissue.[36] Its function relates in part to the presence of specially arranged bundles of collagen fibers that support the tooth in the socket and absorb the forces of occlusion, preventing them from being transmitted to the surrounding bone. The PDL space is small, varying from an average of 0.21 mm in young teeth to 0.15 mm in older teeth. The uniformity of its width (as seen in a radiograph) is one of the criteria used to determine its health.

Lining the periodontal space are cementoblasts and osteoblasts. Interwoven between the principal periodontal fibers is a loose connective tissue that contains fibroblasts, stem cells, macrophages, osteoclasts, blood vessels, nerves, and lymphatics. Epithelial cell rests of Malassez are also present (Fig. 1.28). As already noted, these cells are of no known

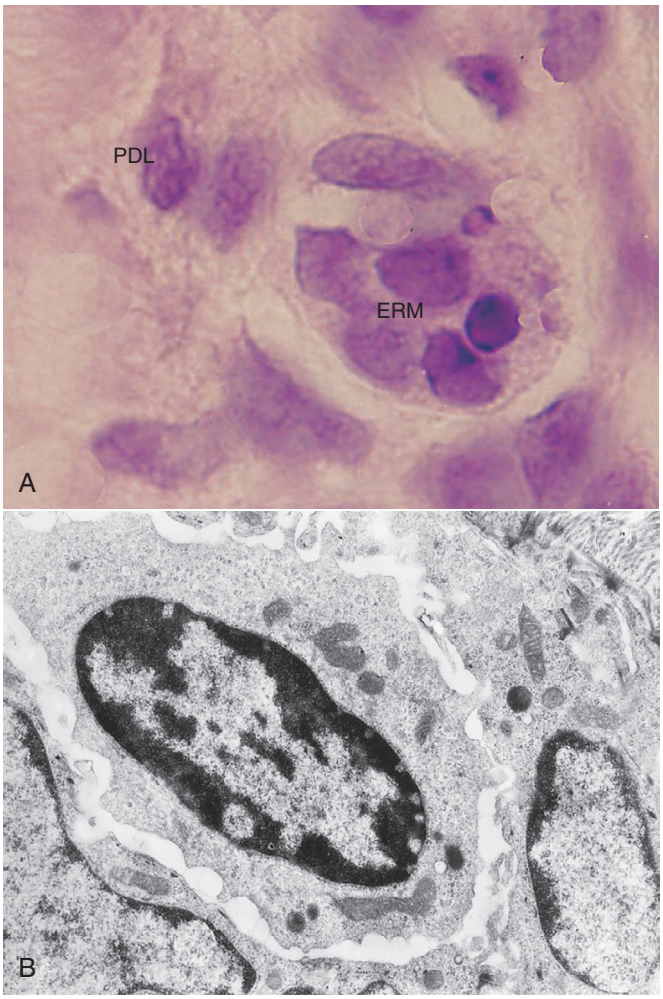

Fig. 1.28 **A,** Epithelial rest of Malassez *(ERM)* in periodontal ligament *(PDL).* **B,** Transmission electron micrograph of epithelial rests. (From Cerri PS, Katchburian E: *J Periodont Res* 40:365, 2005.)

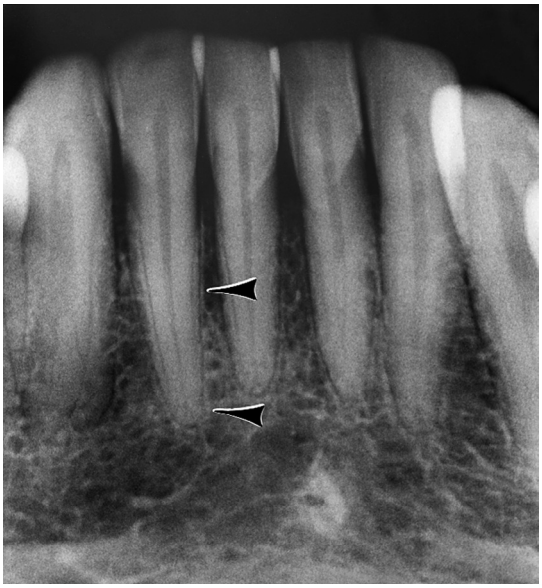

Fig. 1.29 Mandibular anterior teeth with normal, uniform periodontal ligament (PDL) space and identifiable lamina dura *(arrows).* This usually, but not always, indicates the absence of periradicular inflammation.

significance in the healthy periodontium, but during inflammatory states they can proliferate and give rise to cyst formation.

The vasculature of the periodontium is extensive and complex. Arterioles that supply the PDL arise from the superior and inferior alveolar branches of the maxillary artery in the cancellous bone. These arterioles pass through small openings in the alveolar bone of the socket, at times accompanied by nerves, and extend upward and downward throughout the periodontal space. They are more prevalent in posterior than anterior teeth. Other vessels arise from the gingiva or from dental vessels that supply the pulp. These latter vessels branch and extend upward into the periodontal space before the pulpal vessels pass through the apical foramen. The degree of collateral blood supply to the PDL and the depth of its cell resources impart an excellent potential for its repair subsequent to injury, a potential that is retained for life in the absence of systemic or prolonged local disease.

The periodontium receives both autonomic and sensory innervation. Autonomic nerves are sympathetics arising from the superior cervical ganglion and terminating in the smooth muscle of the periodontal arterioles. Activation of the sympathetic fibers induces constriction of the vessels. As in the pulp, there is no convincing evidence that a parasympathetic nerve supply exists.

Sensory nerves that supply the periodontium arise from the second and third divisions of the trigeminal nerve (V_2 and V_3). They are mixed nerves of large and small diameter. Unmyelinated sensory fibers terminate as nociceptive free endings. Large fibers are mechanoreceptors that terminate in special endings throughout the ligament but are in greatest concentration in the apical third of the periodontal space. These are highly sensitive, recording pressures in the ligament associated with tooth movement. They allow patients to identify teeth with acute periodontitis with some precision.

Alveolar Bone

The bone of the jaws that supports the teeth is referred to as the *alveolar process.* Bone that lines the socket and into which the principal periodontal fibers are anchored is referred to as the *alveolar bone proper* (bundle bone, cribriform plate). Alveolar bone is perforated to accommodate vessels, nerves, and investing connective tissues that pass from the cancellous portion of the alveolar process to the periodontal space. Despite these perforations, alveolar bone proper is denser than the surrounding cancellous bone and has a distinct opaque appearance when seen in periapical radiographs. On the radiograph, alveolar bone proper is referred to as *lamina dura* (Fig. 1.29). Its continuity is equated with periodontal health and its perforation with disease. Radiographic changes associated with periradicular inflammatory disease usually follow rather than accompany the disease. Significant bone loss is necessary before a radiographic image is seen.

Alveolar bone proper is principally lamellar and continually adapts to the stress of tooth movements. Because pressures are not constant, bone is constantly remodeling (by resorption and apposition).

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CHAPTER 2

Protecting the pulp and promoting tooth maturation

Ashraf F. Fouad, Anthony J. Smith

CHAPTER OUTLINE

LEARNING OBJECTIVES

After reading this chapter, the student should be able to:

1. Describe pulp protection and pulp therapy.
2. Understand the special physiologic and structural characteristics of the pulp-dentin complex and how they affect the pulpal response to injury.
3. Describe the reparative mechanisms of the pulp, including immune responses and tertiary dentin formation.
4. Describe the effects of dental procedures and materials on the pulp.
5. Appreciate the significance of microleakage and smear layer on pulp response.
6. Describe the indications and procedures for vital pulp therapy.
7. Discuss the effects of pulpal injury in teeth with developing roots.
8. Describe diagnosis and case assessment of immature teeth with pulp injury.
9. Describe the techniques for vital pulp therapy (apexogenesis) and root-end closure (apexification).
10. Describe the prognosis for vital pulp therapy and root-end closure.
11. Describe the technique for pulp revascularization and the goals of regenerative endodontic therapy.
12. Recognize the potential of tissue engineering techniques in regenerating pulpal tissue.
13. Consider restoration of the treated immature tooth.

DEFINITIONS

Pulp Protection

Dental caries represents one of the principal challenges to the health of the dental pulp, although its treatment may well exacerbate the challenge. Cavity preparation and associated procedures, the toxicity of restorative materials and, significantly, the continuing challenge from leakage of bacteria and their products at the margins of restorations can contribute further damage to that caused by the original caries. This may tip the balance from a reversible to an irreversible pulpitis; it also highlights the importance of a holistic approach to management of dental caries, which aims to restore the functional integrity of the tooth while preserving its vitality and protect the pulp from further damage.

A fundamental consideration in pulp protection is the recognition that infection is a key driver of inflammation, which often determines the outcomes for pulp survival. Thus, the pulp always is likely to be inflamed when bacteria from dental caries are present, and their control should be a significant feature of any treatment planning. Even in teeth with white spot lesions and for which restorative procedures are not indicated, pulpal inflammation is frequently present (Fig. 2.1).[1]

When treatment plans are designed for patients who have several teeth with carious lesions, especially when lesions are extensive, a "triage" approach is preferable. In this approach, active caries is removed and good temporary restorations are placed at an early stage, allowing the pulp the maximum opportunity for recovery.

Vital Pulp Therapy

Maintenance of pulp vitality should always be the goal in treatment planning, and considerable interest is developing in the concept of regenerative endodontics for complete or partial pulp tissue regeneration. With mechanical exposure of the dental pulp by trauma or during cavity preparation, the pulp may be protected and its vitality maintained by immediately covering it (pulp capping) and placing a restoration, thereby avoiding root canal treatment. If the exposure is large or seriously contaminated, it may be possible to remove the more superficial diseased part of the pulp (pulpotomy), cap the remaining pulp, and place a restoration. This approach probably has the best prognosis in incompletely formed teeth (especially primary teeth) when the root has not yet reached its full length (apexogenesis); however, it can also be considered for fully formed and permanent teeth with reversible

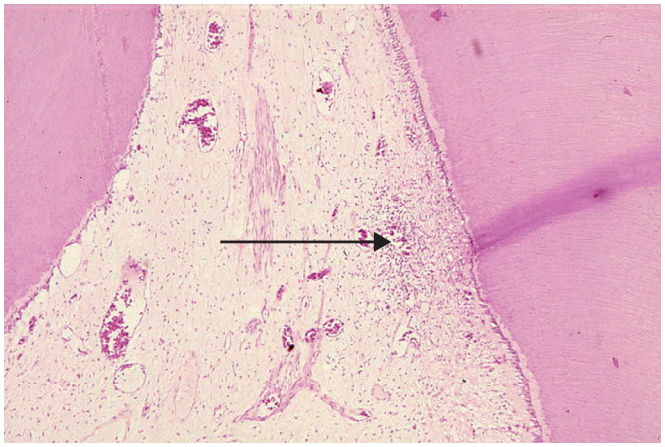

Fig. 2.1 Pulpal inflammation *(arrow)* at the base of the tubules beneath a white spot lesion in enamel.

pulpitis. In teeth with necrotic pulps and incomplete root formation, apical closure (but not root elongation) can be obtained by apexification. It is important to recognize, however, that pulp inflammation is a progressive disease, and the use of regenerative approaches to maintain pulp vitality requires a good understanding of the interplay of biologic factors influencing regenerative events, in addition to appropriate case selection. Such approaches may not be suitable for all cases, especially those showing deep pulp inflammation involving the radicular tissue, and the correlation of clinical symptoms with the pathophysiologic status of the dental pulp remains a significant challenge. In the future, tissue engineering may allow replacement of part or all of the pulp with new tissue[2,3] in the clinical setting.

Regeneration, Revascularization, and Revitalization

Pulp necrosis is clearly a terminal, irreversible pathosis of this tissue. In cases of pulp necrosis after complete tooth maturation, the tooth may survive in a state of normal health after root canal therapy. However, for the immature tooth, this treatment may be difficult to perform, and the tooth may be too weak to withstand normal function because of the thin dentinal wall and short root length. Therefore, techniques to control intracanal infection and induce regrowth of connective tissue that would then promote normal root maturation have been introduced in the past few years.[4] The use of the terms *revascularization, revitalization,* and *regeneration* to describe the result of these procedures has been open to some debate in the field. Most authors would use the term *revascularization* or *revitalization,* because animal studies have not shown that a functional dental pulp actually regenerates after these techniques.[5]

Table 2.1 presents the principal terms currently used in pulpal protection and vital pulp therapy.[6]

Table 2.1 Definitions of the principal terms used in pulpal protection and vital pulp therapy

Term	Definition
Pulp cap	Treatment of an exposed vital pulp in which the pulpal wound is sealed with a dental material, such as calcium hydroxide or mineral trioxide aggregate (MTA), to facilitate the formation of reparative dentin and maintenance of a vital pulp.
Direct pulp cap	A dental material placed directly on a mechanical or traumatic vital pulp exposure.
Step-wise caries excavation	Incremental removal of caries over a period of time to allow pulpal healing and to minimize exposure[7]
Pulpectomy (pulp extirpation)	The complete surgical removal of the vital pulp.
Pulpotomy (pulp amputation)	Surgical removal of the coronal portion of a vital pulp as a means of preserving vitality of the remaining radicular portion; pulpotomy usually is performed as an emergency procedure for temporary relief of symptoms or as a therapeutic measure.
Partial pulpotomy (shallow pulpotomy; Cvek pulpotomy)	Surgical removal of a small diseased portion of vital pulp as a means of preserving the remaining coronal and radicular pulp tissues.
Apexification	Induction of a calcified or an artificial barrier in a root with an open apex or the continued apical development of an incompletely formed root in teeth with a necrotic pulp.
Apexogenesis	A vital pulp therapy procedure performed to enable continued physiologic development and formation of the root end; the term frequently used to describe vital pulp therapy that encourages the continuation of this process.
Pulp regeneration	The ability to recreate lost or damaged pulp tissue
Pulp revascularization	The restoration of blood supply in the pulp space
Pulp revitalization[8]	Recreation of vital connective tissue in the pulp space

From the American Association of Endodontists: *Glossary of endodontic terms,* Chicago, 2012, The Association.

IATROGENIC EFFECTS ON THE DENTAL PULP

Local Anesthesia

When most local anesthetics containing vasoconstrictors are used in restorative dentistry, the blood flow to the pulp is reduced to less than half of its normal rate.[9] In the case of lidocaine with epinephrine, this effect is entirely a result of the vasoconstrictor.[10] In procedures on teeth with pulps that are already compromised, this may be an additional stressor. A healthy pulp may survive episodes of ischemia lasting for 1 hour or longer. An already ischemic pulp subjected to severe injury may hemorrhage (blush) when subjected to trauma such as that associated with full crown preparation without the use of an adequate coolant.

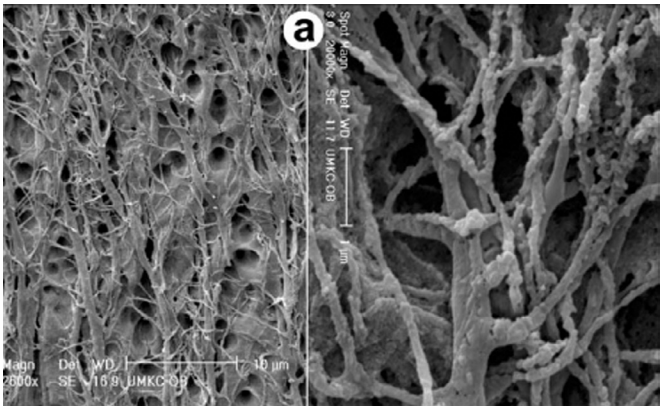

Fig. 2.2 Low- and high-power scanning electron microscopy (SEM) images of dentin after surface etching to reveal the intricate network of odontoblast processes and lateral branches permeating dentin matrix and facilitating communication by odontoblasts. (Lu Y, Xie Y, Zhang S, et al: DMP1-targeted Cre expression in odontoblasts and osteocytes, *J Dent Res* 86(4):320-325, 2007.)

Cavity/Crown Preparation

An appreciation of the cellular structure of the dentin-pulp complex is critical for cavity/crown preparation if further tissue injury is to be minimized and pulp vitality maintained. This is elegantly illustrated in Fig. 2.2, which demonstrates the intimate contact between odontoblasts, through their processes, and the dentin matrix, highlighting the communication between these cells and their environment.

Any surgical intervention to the dentin during cavity preparation may result in some degree of injury to the odontoblasts and their processes. Although this cannot be avoided during cavity preparation, it is important to recognize the consequences of such treatment and to minimize the extent of injury. It is also important to recognize that dentin matrix is not comprised simply of structural components (e.g., collagen and mineral); rather, it also contains a diverse mixture of biologically active molecules, including growth factors, cytokines, and other constituents. Both matrix dissolution during the carious process and the cutting and etching of the dentin during cavity preparation can lead to release of these molecules, with the consequent potential for stimulation of cellular responses in the pulp.[11]

Heat

Frictional heat is produced whenever a revolving bur or stone contacts tooth structure. Until the advent of the high-speed handpiece, enamel and dentin preparation involved heavy torque, low rotational speeds, and steel burs that were not cooled with water. Consequently, vital dentin was often scorched, and pulps were injured as a result of extreme heat (Fig. 2.3).[12]

Dentin is an effective insulator; for this reason, careful cutting with adequate cooling is less likely to damage the pulp unless the thickness of the dentin between preparation and pulp is less than 1 mm.[13] Even then, the inflammatory response may be mild (Fig. 2.4). The greatest amount of frictional heat is generated with a large diamond stone when teeth are prepared for a full crown, and the pulp is particularly at risk of injury. The heat generated may also have a desiccating effect by "boiling" away dentinal tubule fluid at the dentin surface.

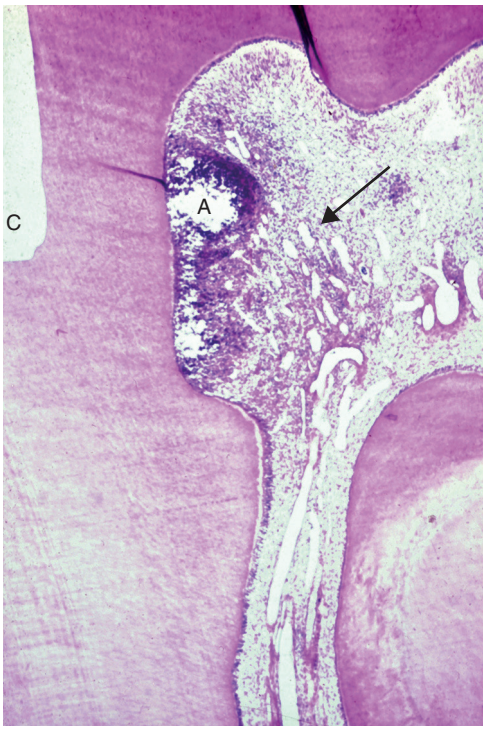

Fig. 2.3 Localized inflammation *(arrow)* and abscess *(A)* formation beneath a deep cavity preparation *(C)* without adequate coolant. (Courtesy Dr. H. Trowbridge.)

Fig. 2.4 Mild inflammation beneath a deep cavity preparation with adequate coolant. (Courtesy Dr. H. Trowbridge.)

The "blushing" of dentin during cavity or crown preparation is thought to be due to frictional heat resulting in vascular injury (hemorrhage) in the pulp.[14] The dentin takes on an underlying pinkish hue soon after the operative procedure, reflecting significant vascular injury. Crown preparation

performed without the use of a coolant leads to a marked reduction in pulpal blood flow, presumably because of vascular stasis and thrombosis. The amount of heat produced during cutting is determined by the sharpness of the bur, the amount of pressure exerted on the bur or stone, and the length of time the cutting instrument contacts the tooth structure. The safest way to prepare tooth structure is to make sure the bur-dentin interface is constantly wet.

The use of laser beams to fuse enamel and reduce the likelihood of carious invasion has been suggested.[15] Different lasers with different energy levels may also be used to remove caries. Lasers generate heat and increase the intrapulpal temperature. The heat generated varies with a number of parameters, but can be reduced by water cooling to a level similar to that for a water-cooled high-speed drill.[16]

Cavity Depth/Remaining Dentin Thickness

Dentin permeability increases exponentially with increasing cavity depth, because both the diameter and density of dentinal tubules increase with cavity depth (Fig. 2.5).[17] Thus the deeper the cavity, the greater the tubular surface area into which potentially toxic substances can penetrate and diffuse to the pulp. The length of the dentinal tubules beneath the cavity is also important. The farther substances diffuse, the more they are diluted and buffered by the dentinal fluid.

A remaining dentin thickness of 1 mm is often regarded as sufficient to shield the pulp from most forms of irritation. In noncarious teeth, tertiary reactionary dentin is formed most rapidly when the remaining dentin thickness is between 0.5 and 0.25 mm.[18] With a narrower remaining dentin thickness, odontoblast survival is compromised, and any regenerative response would likely involve reparative dentin formation by newly differentiated cells.[19]

The effects of remaining dentin thickness on cellular responses, however, are not only a function of the diffusion of noxious stimuli to the pulp. The morphology of the odontoblast processes is of a more tapered shape, with greater thickness near the cell body of the odontoblast.[20] Deeper cavity preparations sever the odontoblast processes in their regions of greater thickness; this affects the cell's attempts to restore its membrane integrity and increases the risk of a cell leaking its contents. Cells have well-developed mechanisms for responding to mechanical stress and repairing minor breaks in the integrity of their plasma membranes; however, failure of these mechanisms can lead to disease and loss of cell viability.[21]

Cavity Drying and Cleansing[12]

A prolonged blast of compressed air aimed onto freshly exposed vital dentin causes a rapid outward movement of fluid in patent dentinal tubules through strong capillary forces. Rapid outward flow of fluid in the dentinal tubules stimulates nociceptors in the dentin pulp, thus producing pain. Rapid outward fluid movement may also result in *odontoblast displacement* (Fig. 2.6).[22] Odontoblasts are dislodged from the odontoblast layer and drawn outward into the tubules, where they undergo autolysis and disappear. Providing the pulp has not been severely injured, displaced odontoblasts may be replaced by new cells derived from stem/progenitor cells deeper in the pulp. In this way, the odontoblast layer is reconstituted by "replacement" odontoblast-like cells capable of producing tertiary reparative dentin.[23] Although drying agents

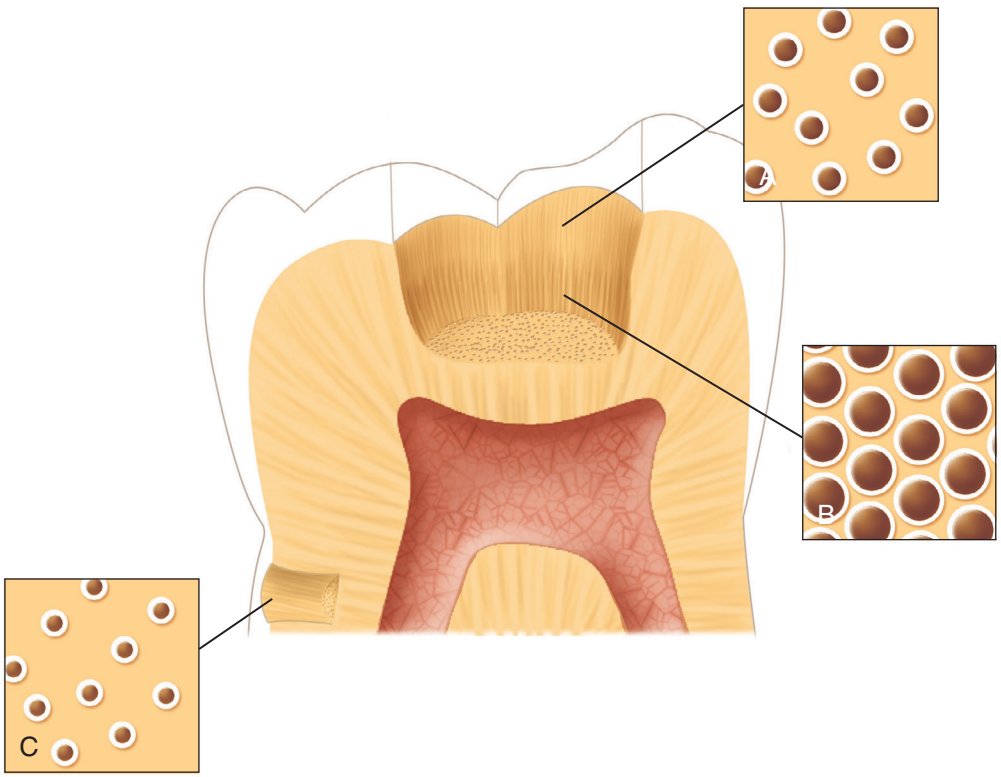

Fig. 2.5 Difference in size and number of tubules in the dentinal floor of a shallow **(A),** deep **(B),** and radicular dentin **(C)** cavity preparation. (From Trowbridge HO: *Dentistry* 82:22, 1982.)

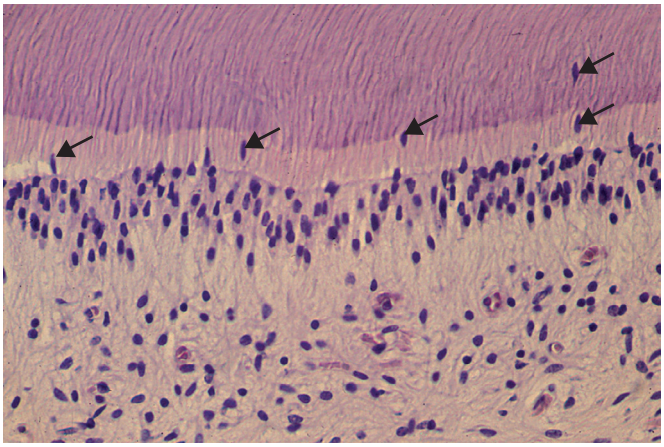

Fig. 2.6 Aspiration of odontoblasts *(arrows)* into dentinal tubules after desiccation of a cavity. (Courtesy Dr. H. Trowbridge.)

containing lipid solvents, such as acetone and ether, have been used to clean cavity floors, their rapid rate of evaporation can produce strong hydrodynamic forces in the tubules, causing odontoblast displacement. *Cavities should be dried with cotton pellets, and only short blasts of air should be carefully applied, rather than harsh chemicals.* Toxic antibacterial agents are not advisable for use on the cavity floor due to the risk of injury to the pulp or their limited broad-spectrum specificity to the microflora present. A new generation of antibacterial bonding agents for use with resin-bonded composites is emerging,[24-26] and such approaches may have merit in the control of residual bacteria. In contrast, use of antibacterial agents is of paramount importance to successful outcomes for root canal therapy, although even in the absence of vital pulp tissue within the root canal, care is required to avoid leakage of potent antibacterial agents into the periapical tissues, where they may compromise tissue vitality.

Etching Dentin/Smear Layer Removal[27-29]

Cutting dentin produces a smear layer on the cut surface consisting of fragments of microscopic mineral crystals and organic matrix debris, which may interfere with the adherence of adhesive restorative materials. Acidic cavity-cleansing products and chelating agents are often used to remove the smear layer, but their use is mainly justified only with the placement of an adhesive restoration. The smear layer does have one desirable property; by blocking the orifices of dentinal tubules, the smear plugs greatly decrease the permeability of dentin. Although the smear layer is largely impervious to bacteria, it is not a barrier to bacterial products. Complete dissolution of the smear layer opens the dentinal tubules, significantly increasing the permeability of dentin. If the dentin is left unsealed, the diffusion of irritants to the pulp may intensify and prolong the severity of pulpal reactions.

Traditionally, cavity etchants have been used based on their physicochemical properties of smear layer removal and cavity cleansing. It is now apparent, however, that they may also locally release some of the biologically active molecules contained within the dentin matrix.[30-32] Release of these molecules can signal the cellular responses, leading to stimulation of regenerative events[33]; therefore, it is important to consider the use of cavity etchants within this broader context. This has implications for the application time of these etchants,[33] which reflects a compromise between achieving optimal smear layer removal and maximizing stimulation of regenerative cellular responses.

Other Restorative Procedures

Pulp damage may result from pinhole preparation or pin placement. Coolants do not reach the depth of the pin preparation. During pinhole preparation, there is always the risk of pulp exposure. Furthermore, friction-locked pins often produce microfractures that may extend to the pulp, subjecting the pulp to irritation and the effects of microleakage.[34,35]

Rubber-base and hydrocolloid materials do not injure the pulp. However, temperatures of up to 52°C have been recorded in the pulp during impression taking with modeling compound, and such temperatures may damage the pulp, especially if it is already inflamed.

Cooling is strongly recommended when provisional crowns are fabricated directly because of the exothermic reaction of autopolymerizing resins. *The temporary crown/cement should be left in place for a short period;* temporary cements are not stable and eventually wash out. Microleakage around temporary crowns is a common cause of postoperative sensitivity. During the cementation of crowns, inlays, and bridges, strong hydraulic forces may be exerted on the pulp as cement compresses the fluid in the dentinal tubules.

Continuous polishing of amalgam or other metallic restorations with rubber cups at high speeds causes a damaging temperature increase of up to 20°C. *Therefore, polishing with rubber wheels, points, or cups should be performed at low speeds using intermittent pressure and a coolant.*

The use of burs to remove metallic restorations can produce very high levels of frictional heat. A coolant, such as water spray or a combination of water and air, avoids a burn lesion in the pulp.

Postrestorative Hypersensitivity[36,37]

Many patients complain of hypersensitivity after a restorative procedure as a result of cumulative effects that irritate the pulp. Discomfort is usually of short duration. If the pain is prolonged, a preexisting pulpitis may have been exacerbated. If it is delayed in onset by days, the cause may be microleakage of bacterial irritants under a poorly sealed restoration. The absence of postoperative sensitivity after restoration with modern composites of both Class I and Class II preparations has been demonstrated in clinical studies, suggesting that variations in technique may be responsible for the anecdotal reports.[38,39] The use of hydroxymethacrylate/glutaraldehyde "desensitizer" does not reduce the incidence of sensitivity.[40] Self-etching, self-priming dentin bonding systems reduce the incidence of sensitivity after the restoration of deep carious cavities.[41,42]

One important clinical factor in the placement of resin restorations is the control of moisture. Applying a dental dam during the procedure is thought to help in moisture control. However, there are situations in which the restoration extends subgingivally. Proper moisture control for bonding of the restoration is difficult to achieve in these situations.

If pain is evoked by biting on a recently restored tooth, an intracoronal restoration may be exerting a strong shearing force on the dentin walls of the preparation. It is more likely to be caused by an injury to the periodontal ligament as a result of hyperocclusion. Hyperocclusion from an

extracoronal restoration does not injure the pulp but may cause a transient hypersensitivity.

Dental Materials

Microleakage[42-44]

The most important characteristic of any restorative material in determining its effect on the pulp is its ability to form a seal that prevents the leakage of bacteria and their products onto dentin and then into the pulp.

Cytotoxicity

Certain restorative materials are composed of chemicals that have the potential to irritate the pulp. However, when these materials are placed in a cavity, the intervening dentin usually neutralizes or prevents leachable ingredients from reaching the pulp in a high enough concentration to cause injury. For example, eugenol in zinc oxide–eugenol (ZnOE) is potentially irritating but very little can reach the pulp. Phosphoric acid is a component of silicate and zinc phosphate cements and was thought to be highly injurious to the pulp. However, the buffering capacity of dentin greatly limits the ability of hydrogen ions to reach the pulp. It is now clear that the problems that occurred after use of these materials were a result of their high degree of shrinkage and subsequent microleakage.[45]

Clearly, the thickness and permeability of dentin between a material and the pulp affect the response to the material. In addition, the penetration of some materials through dentin may be limited by the outward flow of fluid through the tubules, which is increased if the pulp is inflamed.[46] This factor has been overlooked in many in vitro studies investigating the passage of materials through dentin.

Many cytotoxicity studies examine isolated cell types in culture and do not take into account the immunocompetent cells present in the intact pulp. Materials may have a differential effect on these cells by either stimulating or inhibiting their activity.[47]

Materials are more toxic when they are placed directly on an exposed pulp. Cytotoxicity tests carried out on materials in vitro or in soft tissues may not predict the effect of these materials on the dental pulp. The toxicity of the individual components of a material may vary.[48,49] A set material may differ in toxicity from an unset material. The immediate pulpal response to a material is much less significant than the long-term response. A few days after placement, the pulp may show a strong inflammatory response. A few months later, the inflammatory response may subside and repair occurs. A good measure of long-term response is the thickness of tertiary dentin laid down by the affected pulp (Fig. 2.7).

Depth of Preparation

Deep cavity preparations are likely to destroy odontoblasts. These are replaced by new odontoblasts that often form an irregular, reparative dentin that has few tubules (see Figure 1-8, *A*). Deep preparations also limit the amount of dentin that separates the cavity from the pulp, thus increasing the deleterious effects of biologic and chemical irritants.[33]

Desiccation by Hygroscopy[50]

Some hygroscopic materials may cause injury by withdrawing fluid from dentin. However, the relationship between the hydrophilic properties of materials and their effect on the pulp is minimal. Moisture absorbed by materials is probably much less than that removed from dentin during cavity drying, which is a procedure that produces a small amount of pulpal inflammation.

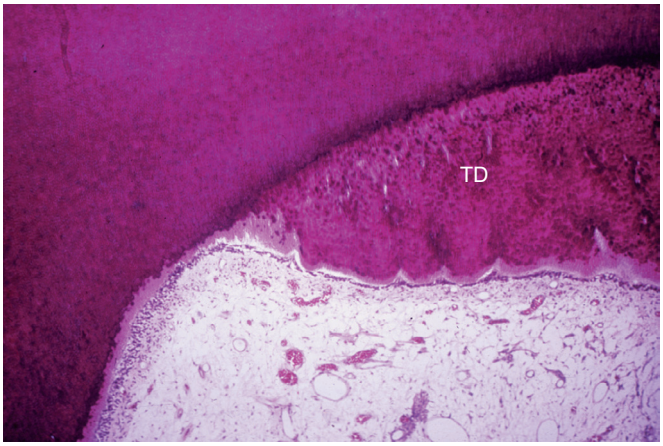

Fig. 2.7 Tertiary dentin *(TD)* formed under a deep preparation and irritating material. (Courtesy Dr. H. Trowbridge.)

Specific Materials

Zinc Oxide–Eugenol[18,51-53]

ZnOE has many uses in dentistry. It has a long history as a temporary filling material, cavity liner, cement base, and luting agent for provisional cementation of castings. Before the introduction of calcium hydroxide, ZnOE was the material of choice for direct pulp capping.

Eugenol, biologically the most active ingredient in ZnOE, is a phenol derivative and is toxic when placed in direct contact with tissue.[54] It also has antibacterial properties.[55] Eugenol's usefulness in pain control is attributed to its ability to block the transmission of nerve impulses.[56] Researchers have found that a thin mix of ZnOE significantly reduces intradental nerve activity when placed in a deep cavity preparation in cats' teeth; however, a dry mix of ZnOE has no effect.[57]

When included in cements to temporize crown preparation, some eugenol does reach the pulp, but the amounts are small and unrelated to remaining dentin thickness. "Desensitizing" agents do not seem to reduce the penetration.[42] The release of eugenol is by a hydrolytic mechanism, which depends on the presence of water. With little water available, release is low.[52,53]

The most important property of ZnOE is that it prevents microleakage of bacterial cells, thereby reducing hypersensitivity and providing antimicrobial properties.

Restorative Resins[58-60]

Early adhesive bonding and resin composite systems contract during polymerization, resulting in gross microleakage and bacterial contamination of the cavity. Bacteria on cavity walls and within axial dentin are associated with moderate pulpal inflammation. Over a period of time, some composites absorb water and expand; this tends to compensate for initial contraction. To limit microleakage and improve retention, enamel margins are beveled and acid etched to facilitate mechanical bonding. Compared with unfilled resins, the newer resin