Considerable knowledge has accumulated over the years on the structure and function of the dental pulp and dentin. Some of this knowledge has important clinical implications. This review, which is the first of seven articles, will be limited to those parts of the normal structure and physiology of the pulp and dentin that have been shown to result in, or are likely to lead to, tissue reactions associated with the clinical treatment of these tissues. Although certain normal structures will be highlighted in some detail, a basic knowledge of pulpal and dentinal development and structure is a prerequisite for an understanding of this text.

**Key words:** dentin, dentinal tubule, odontoblast, pulp, tooth structure

In countries where endodontics has been identified as a specialty, and especially where it has been administratively separated from teaching programs in restorative and conservative dentistry, there has been a tendency to classify studies of dentin and pulp as “endodontics.” In diagnosing pain and attempting to clinically predict the physiologic or pathologic state of the dentin and pulp, endodontists depend on a thorough knowledge of the tissues. However, this diagnostic responsibility also extends to restorative dentistry, including operative and conservative dentistry. The treatment phase of restorative dentistry is, or should be, more involved than endodontics with the structure, function, tissue reactions, and potential healing capacities of dentin and pulp. All caries prophylactic measures and treatment phases of restorative dentistry should be considered “preventive endodontics.” To optimally achieve this goal, clinicians working with dentin and pulp must have detailed knowledge of normal tooth structure; age-related changes; tissue responses to caries, trauma, and restorative procedures; and the effect of the application of different agents and materials on the tissues. Knowledge of the biology of the pulp and dentin, coupled with an understanding of the materials and techniques applied to tissues, will provide a sound basis for restorative dentistry. Such knowledge will make it possible for the dentist to select materials and methods that will produce no or favorable reactions in the tissues to optimally conserve damaged teeth. It should also provide opportunities for new biologic approaches to restorative dentistry.

**STRUCTURE OF THE PULP-DENTIN ORGAN**

Despite the differences in structure and composition, pulp and dentin are integrally connected in the sense that physiologic and pathologic reactions in one of the tissues will also affect the other. This close association includes reactions to caries and common clinical procedures such as cavity or crown preparations and restorative procedures. Not only do the two tissues have a common embryonic origin, but they also remain in an intimate relationship throughout the life of the vital tooth. Anything that affects dentin will affect the pulp and vice versa. The concept of a pulp-dentin organ or a pulp-dentin complex is, therefore, well-founded and generally recognized. However, the concept has been challenged by reference to the marked differences in chemistry between dentin and pulp.

Because this review will focus on restorative dentistry, it will be limited to the coronal and cervical part of the pulp-dentin organ, recognizing that differences in structure and physiology exist between pulp and dentin in the coronal and root parts of teeth. The peripheral coronal dentin is covered by enamel, which acts as a semipermeable membrane. It allows the permeation of fluids, atoms, and small molecules. Vital or cellular reactions do not occur in enamel, but physicochemical reactions, such as ion exchange, take place. The interactions between the minute liquid phase in enamel and that in
dentin, which has a 12% water content by weight, have not been established in detail, but they may be particularly important in the development of caries lesions.

All components of the dental pulp, including the cells, blood and lymph vessels, nerves, and the interstitial fluid, are important in the response to restorative procedures. Fibers are scarce in the pulp of the newly erupted tooth. Most cells are considered to be of an undifferentiated or immature type. They are abundant in newly erupted teeth and have the potential to develop into specialized cells, eg, odontoblast-like cells. An interstitial fluid surrounds the morphologic elements (Fig 1). It is similar in composition to plasma, but it contains less protein than plasma. The interstitial fluid is an important intermediary link between cells, the blood and lymphatic vessels of the pulp, the interstitial fluid, and nerves. These processes may be regulated by various factors, including the release of neuropeptides from pulpal nerves.

**CELLS OF THE DENTAL PULP**

The most prominent cells of the pulp-dentin organ are the odontoblasts (Fig 2). A single layer of these cells lines the peripheral part of the pulp, separating the loose connective tissue of the pulp from the predentin. Each odontoblast has an extension into a dentinal tubule, the odontoblastic process. Because of crowding of the odontoblasts in the coronal portion of the teeth, especially in pulp horns, they appear pseudostratified. Odontoblasts are attached to each other by junctional complexes.

After odontoblasts have formed the primary dentin and the teeth have erupted, odontoblasts continue to form dentin at a slow rate. This dentin is called physiologic secondary dentin, and often it cannot be distinguished from primary coronal dentin. It should be differentiated from localized masses of reparative, irregular, irritation, reactionary, or tertiary dentin formed in response to localized stimuli of any sort, eg, a caries lesion or a restorative procedure (Fig 3). All these terms denote basically the same type of local additional dentin formed posteruptively.

A distinction between the dentin that is formed by the primary odontoblasts and that formed by new, posteruptive, odontoblast-like cells or secondary odontoblasts may be clinically important. The localized tertiary dentin formed by surviving primary odontoblasts following a mild stimulus, such as attrition, has been referred to as reactionary dentin, while that formed by a new generation of odontoblasts has been termed reparative dentin. The dentin formed by odontoblast-like cells is often irregular in structure, at least the first formed tissue at the interface with the existing dentin (Fig 3). A combination of reactionary and reparative secondary dentin may be found in the same specimen (Fig 4).

The important point in this context is that the primary odontoblasts retain their ability to form dentin in vital teeth throughout the life of the tooth, and, if they are destroyed, mesenchymal precursor cells in the pulp are able to differentiate into new, odontoblast-like cells. These progenitor cells are recruited from subodontoblastic cells and periocytes. In fact, an early histopathologic reaction to procedures affecting the dentin involves an influx of cells into the subodontoblastic cell-free zone.
Fig 2. Electron micrograph of odontoblasts with two insets showing light microscopy of the odontoblastic area of a pulp removed from a tooth that was opened immediately after the tooth was extracted. The electron micrograph shows cytoplasmic organelles, including rough surface endoplasmic reticulum (RER), Golgi complex (G), mitochondria (M), vacuoles (Va), vesicles (Ve), and nuclei (N). Note the cell-free zone adjacent to odontoblasts in the left inset and remnants of torn odontoblastic processes in the right inset. (Electron micrograph: original magnification x 14,200; left inset: hematoxylin-eosin stain, original magnification x 220; right inset: toluidine blue stain, original magnification x 350.)

Fig 3. (left) Tertiary dentin (TD) in a pulp horn as a response to attrition, mainly of the reactive type. (Hematoxylin-eosin stain; original magnification x 90.)

Fig 4. (right) Tertiary dentin (TD) in a pulp horn showing continuity among the tubules in the primary dentin (P), physiologic secondary dentin (SD), and tertiary dentin in some areas (arrows). However, there is also an area with cellular inclusion (C), which indicates that the primary odontoblasts were destroyed. (Hematoxylin-eosin stain; original magnification x 220.)

Tertiary dentin formation, irrespective of type, represents an important defense mechanism and a regenerative property of the pulp-dentin organ. If the primary odontoblasts are destroyed, the new odontoblasts differentiate from undifferentiated cells that predominate in pulps from young individuals. The dentin formed locally may vary in structure and composition (Figs 3 to 7). The tubules are often more irregular, the dentin is less mineralized, and it may have a higher content of organic material than does primary dentin (Fig 8). The interface between the dentin formed by primary odontoblasts and that formed by odontoblast-like cells may be particularly important because the tubules in the two dentins do not directly communicate and therefore act as a barrier to ingress of agents from the dentin to the pulp. This "barrier effect" is a very important defense mechanism in restorative dentistry.

The odontoblasts, being matrix-producing cells, present all the characteristic organelles associated with protein (primarily collagen) and proteoglycan (ground substance) production (Fig 2). The activity of the odontoblasts is reflected in the number and types of organelles present in the cytoplasm. An abundance of rough endoplasmic reticulum, a well-developed
Golgi apparatus, scattered ribosomes, microtubules, vesicles, and vacuoles are all characteristic structures associated with protein synthesis. Microtubules and filaments are also seen. Evidence of collagen synthesis by odontoblasts is seen as discharging cisternae at the cell membrane (Fig 9).

The odontoblastic process lacks the major organelles found in the cell body. Its ultrastructure is characterized by microtubules and filaments (Fig 10). Occasional mitochondria and ribosome-like structures may be present under normal conditions. When enhanced peritubular matrix formation takes place, eg,
following certain operative procedures, organelles such as endoplasmic reticulum and mitochondria may be found in the odontoblastic process. The odontoblastic process in the predentin region exhibits characteristics that reflect the transition from the cell body to the process, and the number of types of organelles vary depending on the activity in the area.

The extent of the odontoblastic process has long been a controversial topic. Because the processes are lodged within the often more than 3-mm-long coronal dentinal tubules, it is hard to understand how the odontoblasts can sustain the vitality of the process. Many investigations and much discussion have been devoted to the extent of the cytoplasmic processes in the dentinal tubules in fully formed teeth. Most investigations suggest that the cytoplasmic process only extends about a third of the distance from predentin to the enamel in normal teeth from young adults. This finding indicates that vital tissue changes in coronal dentin only occur in the pulpal third of the tissue. Changes occurring in the outer two thirds of the dentin are likely either to be (1) of a physiochemical nature by precipitation of mineral salts within the tubules or (2) a growth of the peritubular dentin via components secreted into the periodontoblastic space at the vital, cytoplasmic part of the process. These components may diffuse peripherally to form a matrix that will mineralize.

The lack of cytoplasmic processes in the outer part of the tubules suggests that transduction mechanisms for dentin sensitivity do not directly involve the odontoblasts. However, the limited extent of the odontoblastic process does not exclude the most widely accepted theory, which proposes hydrodynamic movement of fluid as a basis for dentin sensitivity, because that part of the tubule that does not contain a cytoplasmic process will still be filled with tissue fluid.

The possibility of differences in regulation of growth of the peritubular dentin in the crown and the root must be taken into consideration. In the root, and especially in the apical region of teeth where the dentin is narrow, dentin sclerosis is typically found as transparent apical dentin in teeth from old individuals. No such complete sclerosis has been shown to occur in coronal dentin, but localized areas of sclerosis frequently occur, eg, subjacent to caries lesions. This sclerosis reduces the permeability of the dentin and represents an important defense mechanism in restorative dentistry.

The periodontoblastic space is a fluid-filled space located between the dentinal tubule and the cell wall of the cytoplasmic part of the odontoblastic process (see Fig 10). This interstitial fluid continues beyond the cytoplasmic part of the process and extends the full length of the tubule, surrounding remnants of the odontoblastic processes found in peripheral circumpulpal dentin. It plays an important role when tissue changes...
occur within the primary dentin. It is within the periodontoblastic space that the scanty matrix for the highly mineralized peritubular dentin is discharged from the odontoblast or its process.

The odontoblast and its process have an intimate relationship with pulpal nerves (Fig 11). Nerve endings, such as gap junctions, have been shown to terminate on the odontoblastic cell body15 (Figs 12 and 13). The sensitivity of the dentin may be closely associated with these nerve endings and their presence in the periodontoblastic space. The hydrodynamic theory helps to explain pain transduction in dentin.11,12 It postulates that minute movements of the fluid in the tubules initiate impulses in the nerve fibers.

The predominant cells in the central part of the pulp in newly erupted teeth are undifferentiated mesenchymal cells and fibroblasts (Figs 14 to 16). Judging by the scanty amount of organelles in the cytoplasm in many of the cells (Figs 15 and 16), they have a low metabolic activity. They are irregularly shaped with long cytoplasmic processes in the interstitial fluid of the pulp. Collagen fibers are sparse, but they are found mainly associated with nerves and blood vessels. This fiber-poor and cell-rich state is a characteristic feature of the young pulp (Fig 17), but it changes with age. In teeth of older individuals, a large fibrous component is present and the number of cells is low (Fig 18). Clinically, this change is important because progenitor cells are available to differentiate into other cell types or to take part in reparative processes in the pulps of young patients and are less effective in the pulps of the elderly. Age-related changes in the pulp nerves and blood vessels accompany the cellular changes.16

Other cells of clinical importance in the dental pulp are macrophages (Fig 19). They are seen in the normal pulp, and their numbers increase in association with pulpal injury. An occasional polymorphonuclear leukocyte (Fig 20) may also be found in the normal pulpal tissue.15,16 Mast cells are not typically found in
Fig 14 Fibroblasts (FB) and undifferentiated cells (UC) in the central part of the pulp. (Toluidine blue stain; 1-μm-thick section, original magnification x 1,400.)

Fig 15 Electron micrograph of an undifferentiated mesenchymal cell in the pulp. The nucleus (N) occupies the main part of the cell, and few organelles may be discerned in the cytoplasm. Note the large number of cytoplasmic processes (CP) and the lack of collagen fibers. (Original magnification x13,000. From Dahl and Mjör. Reprinted with permission from Taylor & Francis AS.)

Fig 16 Electron micrograph of a fibroblast from the central part of the pulp with relatively large nuclei (N) in relation to the cytoplasm, which contains few organelles. Note the large number of cytoplasmic processes (CP) and the scarcity of collagen fibers (CF). (RER) Rough surface endoplasmic reticulum; (G) Golgi complex; (Va) vacuole; (Nu) nucleolus. (Original magnification x13,500.)

Fig 17 (left) Tissue in the central part of the pulp in a newly erupted tooth. Note the large number of cells. (BV) Blood vessel. (Hematoxylin-eosin stain; original magnification x350.)

Fig 18 (right) Tissue in the central part of a pulp from a 67-year-old individual. Few cells are found. (BV) Blood vessel. (Hematoxylin-eosin stain; original magnification x350.)
Fig 19  Electron micrograph of a macrophage with dark intracytoplasmic granules in a normal pulp. (N) Nucleus. (Original magnification x13,000.)

Fig 20  (right) Electron micrograph of a neutrophilic leukocyte with multilobulated nucleus (N) in a normal pulp. Note the numerous dark intracytoplasmic granules. (Original magnification x11,000.)

Fig 21  Dendritic cells in the odontoblastic region. The dendritic cells are visualized by immunohistochemistry using human leukocyte antigen (HLA)-DR. (O) Odontoblasts; (D) dentin. (Original magnification x70. From Jontell M, et al. Reprinted with permission from Crit Rev Oral Biol Med.)


Fig 23  Perivascular dendritic cells surrounding a blood vessel in the central part of the pulp. The cells are visualized by immunohistochemistry using anti-HLA-DR antibodies. (Original magnification x62. Courtesy of Dr. T. Oki.)
the normal pulp, but they become abundant during pulp inflammation. A number of immunocompetent, dendritic cells in the dental pulp expressing macrophage-related phenotypes have been demonstrated by immunohistochemical methods; some are located near the odontoblasts (Figs 21 and 22) and others more centrally located in the pulp (Fig 23). These cells can induce lymphocyte T-cell proliferation. They increase in number during inflammation and may play roles in repair processes in the pulp and immunologic defense reactions.

**PHYSIOLOGY OF THE PULP-DENTIN ORGAN**

From a functional point of view and especially in relation to restorative dentistry, dentin and pulp are integrated to an extent that they should be regarded as one tissue or organ. The interstitial fluid of the pulp and the dentinal tubules form a continuum that extends from the dentinoenamel and cementodentinal junctions to the central parts of the soft connective tissue in the pulp. Hydrodynamic effects and fluid shifts are, therefore, important under normal and pathologic conditions and they will affect the pulp-dentin organ. The mere cutting of dentin, as it occurs during cavity and crown preparations, will result in a number of reactions in the pulp and the dentin.

**Vascularity of the normal pulp**

Arterioles enter and venules and lymphatics leave the dental pulp through the apical foramen or foramina. Vessels also enter and leave the pulp via accessory lateral canals, which may be located anywhere on the root but are most commonly found in the apical region. Relatively large arterioles pass through the root pulp to supply the coronal pulp (Fig 24). They branch and terminate as capillaries (Figs 25 and 26), which are particularly abundant in the coronal subodontoblastic region (Fig 24). It is clinically important to recognize that many of the capillaries in the pulp are largely nonfunctional in the normal pulp (Fig 26). Because the capillaries are already present, the blood flow to specific areas can be increased quickly; i.e., local and general hyperemia in the pulp can occur almost instantaneously without requiring the ingrowth of new capillaries.

The structure of blood vessels in the pulp is basically similar to that in other organs, but the blood vessels are thin-walled both in absolute dimension and in comparison to the size of the lumen. Clinically important structural characteristics include discontinuities in the endothelial walls (Fig 25) and fenestra-

**Interstitial fluid pressure**

The interstitial fluid pressure in the pulp is relatively high and it plays a role in the sudden pain experienced when a cavity preparation reaches unaffected dentin. The exposure of dentin causes sudden movement of the contents of the tubules, leading to activation of nerves adjacent to the odontoblasts and resulting in pain. The fluid flow from the pulp to exposed dentin is dependent on the hydraulic conductivity of the dentin fluid. A certain threshold has to be reached to activate the nerve terminals at the pulpal ends of the dentinal tubules and close to the odontoblast layer. Any reduction in conductance will reduce the dentin sensitivity, e.g., by growth of peritubular dentin, occlusion of the tubules by mineral precipitation, adsorption of organic materials in the tubules, or by hypermineralization of the surface dentin. The formation of atubular dentin at the interface between primary or secondary dentin and tertiary dentin will also reduce the conductivity of dentin fluid.

**Nerve impulses in pulp and dentin**

Myelinated and unmyelinated nerves (Fig 27) enter the pulp through the apical foramen or foramina and through accessory canals. They mainly follow the blood vessels as they branch and form a network of terminal endings in the odontoblastic-subodontoblastic region (Fig 28) and in the periodontoblastic spaces of dentinal tubules (see Fig 11).

Myelinated A fibers and nonmyelinated C fibers are somatic afferent nerves that carry pain impulses. Unmyelinated efferent nerves from the sympathetic nervous system are more sparse. Both the sensory and the sympathetic nerve endings may terminate in the walls of blood vessels in the main pulp, and they are associated with vasomotor control (Fig 29). They are activated at an early stage in the inflammatory process and are, in fact, the initiators of vasodilation, which starts the protective response to injury by increasing blood volume and vascular permeability in the affected area. A number of neuroreactive peptides have been demonstrated in pulpal nerve endings, including neurokinins, substance P, and calcitonin gene-related peptide (CGRP).
Both the sympathetic nerve fibers and the sensory fibers have effects on the pulpal circulation. The number of nerve fibers and the associated neuropeptides decrease with age, which explains the reduced sensitivity of teeth in adults and older individuals. Ultrastructural changes as well as changes in the expression of some neuropeptides have been demonstrated in the cat. Degeneration of axons and demyelination occur, and immunohistochemical studies have shown a decrease in CGRP and substance P. These age-related changes result in both reduced pulpal sensitivity and probably altered hemoregulation of the pulp.

Because nerves play a central role in tissue responses in the pulp, teeth from older individuals are less likely to show reparative processes than are teeth from young individuals. Nerves may also have an effect on odontoblasts and on dentinogenesis. It has been suggested that some nerve fibers that terminate in the dentinal tubules may be branches of the same nerves that terminate in the wall of blood vessels. Such a dual effect would be an excellent preparatory defense mechanism, ie, an axon reflex. It may also explain the difficulties in localizing pulpal pain.
Nerve activity in the pulp can be modified by anesthetic solutions and epinephrine, which may decrease the release of neuropeptides. Even epinephrine in gingival retraction cord may diffuse across the full thickness of root dentin, at least in vitro. Eugenol, known for its sedative effect on pulpal pain, has been shown to have an inhibitory effect on sensory nerve action. It also depresses the vasoconstrictor responses to epinephrine and other vascular stimulants.

Pain of short duration is commonly noted when a clinician first drills through the enamel and into dentin, especially in young patients. Attempts to demonstrate nerve fibers in the peripheral dentin have not been successful, and for a long time it was believed that this observation was due to inadequate methods for demonstration of nerves in dentin. It was also believed that the odontoblast, via the odontoblastic process, may have the ability to act as a sensory receptor. However, it is considered unlikely that the same cell could have such diverse, specialized functions as dentinogenesis and sensory reception. Furthermore, it is now generally accepted that the odontoblastic process does not extend for more than about a third of the distance toward the enamel and that sensations in dentin are based on hydrodynamic concepts of fluid movement.

It has been repeatedly pointed out over the last 150 years that fluid movements in the dentin may transmit impulses that stimulate nerve endings on odontoblasts. The experimental evidence for the prevailing hydrodynamic theory of dentin pain has come from a series of in vivo and in vitro experiments by Brännström and coworkers. Cold stimuli were found to be more painful than hot stimuli, probably because of the outward fluid flow that results from shrinkage of the contents of the tubules when cold is applied. When heat is applied, the contents of the tubules expand and an inward flow occurs. Agents that prevent the serum albumin flux across exposed dentin may eliminate or reduce dentin pain.

Pulpal pain is characteristically pulsating, long-lasting, and of variable severity, sometimes excruciating. It is also affected by changes in blood pressure to the head. Typical dentin pain is short-lasting, sharp, and may be described as lancinating.

**STRUCTURE AND PHYSIOLOGY OF DENTIN**

The mineralized component of the pulp-dentin organ is a unique tissue traversed by tubules 1 to 2 μm in diameter. The dentinal tubules in the coronal part of the tooth extend from the enamel to the pulp and are 2.5 to 3.5...
mm long. They harbor the odontoblastic process or they contain the remnants of the processes and tissue fluid. The tubules have a highly mineralized lining, the peritubular dentin, along most of their length (Fig 30). The peritubular dentin is formed as a primary structure in the main part of the coronal circumpulpal dentin; ie, it is formed as a highly mineralized structure during dentinogenesis. Highly mineralized peritubular dentin is not found in the most pulpal part of the dentin in newly erupted teeth (Fig 31). This feature is important in restorative dentistry, because the main part of a deeply prepared tooth in a young individual will comprise cytoplasmic material rather than mineralized dentin matrix.

In fact, as much as 80% of the pulpal floor of a preparation may be made up of tubular openings.

The highly mineralized peritubular dentin can easily be distinguished from the other mineralized component of dentin, the intertubular dentin (Figs 30 and 31). It contains little collagen, while the intertubular matrix has a dense collagen matrix. The intertubular matrix is crisscrossed by numerous branches of variable sizes from the tubules (Figs 32 and 33). Anastomoses also occur between the branches (Fig 34). The number of tubules per square millimeter and type of branching vary depending on the location in coronal dentin (Table 1). The further apart the tubules are, the more branching is found.

A gradual development of peritubular dentin occurs in locations where it is not developed as a primary structure, ie, in the most pulpal part of coronal dentin in newly erupted teeth. The continuous growth of the peritubular dentin in the main bulk of the dentin as an age-related change or for other reasons, eg, due to restorative procedures, leads to obturation of the tubules. Furthermore, nerve fibers extend a short distance into the periodontoblastic space (see Fig 11) of many tubules in the crown. They play a significant role in dentin hypersensitivity reactions and could also have a regulatory function on the growth of peritubular dentin. In addition, the periodontoblastic space is also the likely location for any physiologic changes in the primary dentin associated with restorative procedures. The tissue fluid in the tubules in peripheral dentin will play a role in any physicochemical reactions that may take place.

Occluded dentinal tubules, referred to as dentin sclerosis, will react differently to acid etching than will unaffected dentin. This condition causes differences in the collagen mesh when exposed to acid etching. The etching time may have to be modified to provide an adequate hybrid layer of collagen and resin. The degree of wetness of the hybrid layer is important for the resin penetration into the collagen mesh. Differences in wetness because of differences in the tubule-intertubule ratio and different degrees of obturation of
the tubules on the same prepared surface\(^5\) cannot be controlled clinically.

The permeability of dentin is an important property that will influence the extent of pulpal reactions in many clinical situations.\(^4\) Dentin permeability varies with the age of the tooth, the degree of mineralization of the tubules, tissue changes in the dentin, the location within the dentin, the tubule-intertubule ratio, and anything that reduces the conductance of fluids within the tubules. The great variation in the number of tubules and the type of branching in different locations of coronal dentin is also likely to result in marked differences in permeability.

Interface dentin\(^6\) with irregular, often atubular dentin forms a barrier between the physiologic secondary dentin and the tertiary dentin (Fig 35). This barrier, which corresponds to the “hyalin zone” of the “dead tract,”\(^5\) reduces the permeability of the affected dentin and may make it impermeable because the tubules from primary dentin do not cross the interface dentin. This type of reaction is important for protection of the pulp.

The number of tubules in a given area is dependent on the location within the dentin. In coronal dentin it varies from about 8,000 to 58,000/mm\(^2\) (see Table 1). These differences are important in the evaluation of biologic reactions to restorative procedures. The lowest

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**TABLE 1** Approximate number of dentinal tubules per square millimeter in coronal human teeth in four locations at three different levels\(^a\)

<table>
<thead>
<tr>
<th>Location</th>
<th>Outer</th>
<th>Middle</th>
<th>Inner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occlusal</td>
<td>8,000</td>
<td>32,000</td>
<td>58,000</td>
</tr>
<tr>
<td>Cuspal</td>
<td>20,000</td>
<td>36,000</td>
<td>58,000</td>
</tr>
<tr>
<td>Middle crown</td>
<td>10,000</td>
<td>32,000</td>
<td>48,000</td>
</tr>
<tr>
<td>CEJ</td>
<td>10,000</td>
<td>29,000</td>
<td>48,000</td>
</tr>
</tbody>
</table>

\(^a\)Data from Mjör and Nordin.\(^4\)

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\(^5\) Outer dentin (250 \(\mu\)m from the enamel), middle dentin, and inner dentin (50 \(\mu\)m from the predentin).

\(^6\) CEJ = cementoenamel junction.
The marked variations in the number of tubules per square millimeter have several clinical implications. The ratio of tubules to intertubular dentin on the pulpal wall of a preparation, for example, will be notably different in deep and shallow cavities; consequently, the vulnerability of the pulp will differ. This ratio will also be affected by the age of the tooth, because occlusion of tubules by peritubular dentin growth will reduce or even eliminate the lumen of the tubules.

Branching of dentinal tubules differs, depending on the location within the tooth, and it is likely to have a profound effect on certain clinical procedures, notably those associated with adhesive dentistry. In coronal dentin, the most characteristic branching is found in the peripheral 250 μm, where the typical Y-shaped terminal branches are found (Fig 36). These branches are relatively large, approaching 0.5 to 1.0 μm in diameter. The other type of branches that predominate in coronal dentin are microbranches (Fig 37). They are only 50 to 100 nm in diameter and may be more important for physiologic changes in dentin than for adhesion arising from penetration of resin materials. Fine branches, 300 to 700 nm in diameter, are predominantly found in the root dentin, but they may be found anywhere the density of tubules is low, eg, subjacent to fissures in molar and premolar teeth and in cervical dentin at or below the neck of the tooth.

Dentin in the cervical area of the tooth at the cementoenamel junction is usually covered by cementum, but cementum may be missing in this location in some teeth. If Hertwig’s epithelial root sheath does not disintegrate to allow contact between root dentin and the dental follicle, cementum will not form. If the tooth later supererupts, or if the 50- to 100-μm-thin cervical cementum is worn off, the cervical part of the root dentin will be exposed to the oral environment. In both instances, this exposure of dentin may lead to hypersensitivity.

The cervical area is also particularly important clinically because the cavosurface margins of restorations are often located below the cementoenamel junction. The difference between root and crown dentin is fairly sharply delineated (Figs 38 to 40). The structure of the cementum and the dentin below the cementoenamel junction may form an inferior type of hybrid layer after acid etching because of the lack of or low number of tubules and tubule branches (Figs 38 and 40). This situation may predispose the restoration to leakage, washout of cement, accumulation of plaque, and possibly development of secondary caries. The lack of terminal branches and tubules in the most peripheral dentin in the cervical area and the presence of acellular cementum will result in a relatively thin hybrid layer, which may not provide good micromechanical attachment of resin-based restorative materials or luting cements.

**Variation in mineralization**

The bulk of the circumpulpal coronal dentin is fairly evenly mineralized (Fig 41). Two locations are less mineralized than the rest: (1) the mantle dentin adjacent...
Scanning electron micrograph of fractured dentin showing a microbranch (MB) running from a tubule in coronal dentin. This type of branch can be found anywhere in dentin but is frequently present in areas where the tubules are wide apart. (PT) peritubular dentin. (Original magnification x17,000.)

Cervical area of a tooth showing the cemento-enamel junction (CEJ) and adjacent structures. (D) Dentin; (AC) acellular cementum; (PL) periodontal ligament. (Hematoxylin-eosin stain; original magnification x350.)

Higher magnification of the peripheral dentin just coronal to the cemento-enamel junction. Note the presence of major branches, similar to those shown in Fig 36. (Hematoxylin-eosin stain; original magnification x1,000.)

Higher magnification of the peripheral dentin just below the cemento-enamel junction. Note the lack of tubules and major branches in the peripheral dentin compared to the structure of coronal peripheral dentin in Figs 36 and 39. (D) Dentin; (C) cementum. (Hematoxylin-eosin stain; original magnification x1,000.)

A differential staining pattern corresponding to the less mineralized zone near the predentin is found if demineralized sections of teeth from young individuals are stained for glycosaminoglycans. The dentin stains more intensely than the main part of the dentin in two areas (Figs 42 and 43). The stained area at the predentin border is due to intense staining of the intertubular matrix (Fig 44), and it may reflect the mineralization of the intertubular area during physiologic
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Fig 41 Microradiograph of a ground section of a newly erupted tooth. The main part of the circumpulpal dentin is evenly mineralized, but the mantle dentin (MD) close to the enamel (E) and a dark, broad zone (Z) of coronal dentin close to the pulp are less mineralized than the bulk of the dentin. These areas of less mineralized dentin are limited to coronal dentin. (dotted line) Border between the root and the crown of the tooth. (CEJ) Cementoenamel junction. (Original magnification x12.)

The nature and significance of the less mineralized band of dentin located a short distance from the coronal pulp is not clear. It may represent the dentin formed during the 3 to 4 years after the crown is fully formed while it remains in the jaw prior to tooth eruption. This band of less mineralized intertubular dentin also lacks highly mineralized peritubular dentin lining the tubules as primary structures (see Fig 31). It may be an especially vulnerable part of the dentin in teeth of young individuals during restorative procedures because the tubule-intertubule ratio is high. It is also a particularly reactive area with a high water content that is difficult to control during the formation of the hybrid layer with adhesive restorative techniques. The peripheral part of this less mineralized zone represents a mineralization front in primary dentin that may be of clinical significance in the use of restorative materials.

After the tooth has erupted, physiologic secondary dentin with a normal degree of mineralization forms slowly but without highly mineralized peritubular dentin as primary structures. Peritubular dentin may form later as an age-related change or as a result of caries and restorative procedures.

Growth factors are present in the dentin matrix. Release of these growth factors as a result of clinical procedures or in association with the development of caries lesions may have important biologic effects on the healing processes by acting as signaling molecules. Growth factors may also be liberated during the demineralization associated with caries lesions in dentin. Identification of these bioactive molecules highlights the intimate relationship between cellular behavior and the matrix secreted by these cells. It is possible that these bioactive molecules will play an important role in mediating the pulpal responses to injury, cavity and crown preparation, and restorative procedures, and they may provide the basis for new biologic approaches to dental tissue repair.

Interglobular areas are poorly mineralized or unmineralized islands in the primary dentin, and they may be found anywhere in coronal dentin. They are frequently found subjacent to pits and fissures and at a short distance from the mantle dentin. Their significance in restorative dentistry has not been established, but they may influence the transport of nutrients within the dentin or have an effect on the reactivity or progression of caries lesions in the tissue.

The cuspal and incisal areas of dentin have some characteristic structural features that may be important in restorative dentistry, especially in relation to Class IV lesions. Central areas of unmineralized dentin (Fig 49) may give the cuspal-incisal area a unique microradiographic appearance. Depending on the position of the section through the cusp, this dentin may appear hypermineralized and bordered by

secondary dentin formation. The stained predentin area is variable, possibly reflecting an incremental pattern of mineralization. The broader stained zone further peripherally corresponds to the outer part of the less mineralized, dark zone seen microradiographically (Fig 41). The contents of the dentinal tubules are heavily stained in this zone (Figs 45 and 46), probably reflecting activity within the tubules at the location where highly mineralized peritubular dentin will form as secondary structures.

Thus, two mineralization fronts are found in coronal dentin of newly erupted teeth, one at the predentin-dentin interface dealing with secondary and possibly also tertiary dentin formation (Fig 47). The more peripherally located mineralization front is not as well defined as that at the predentin-dentin border, but it is considered to reflect peritubular dentin formation as secondary structures in newly erupted teeth. Both are important for tissue changes in dentin associated with restorative dentistry. In teeth from adults, the two intensely stained zones are close together (Fig 48), indicating that in physiologic secondary dentin formation, the mineralization of the peritubular dentin does not lag far behind that of the intertubular matrix at the predentin border.
Fig 42  Section of a demineralized, intact premolar from a 13-year-old individual. The two intensely stained bands (Z1 and Z3) in the coronal dentin correspond to the microradiographic appearance (Fig 47). Band Z1 is at the dentin-predentin border. Band Z3 corresponds to the peripheral aspect of Z in Fig 41. (Toluidine blue stain; original magnification ×10.)

Fig 43  Section of a demineralized, intact premolar from a 13-year-old individual. This section shows a zoned staining pattern in coronal dentin. Two bands (Z1 and Z3) are stained more intensely than is the rest of the coronal dentin, like those seen in Fig 42, and they correspond to the zones with different degrees of mineralization, seen in the pulpal part of the dentin in Fig 41. (Alcian blue stain; original magnification ×10.)

Fig 44  Higher magnification of the dentin-predentin area, corresponding to Z1 in Fig 43, showing cross-sectioned dentinal tubules. The intubular matrix stains intensely in Z1, while further peripherally it is unstained. (Alcian blue stain; original magnification ×100.)

Fig 45  Higher magnification of the area corresponding to Z3 in Fig 43, showing cross-sectioned dentinal tubules. The contents of the tubules stain intensely, but the intubular matrix is virtually unstained. (Alcian blue stain; original magnification ×260.) (From Mjör. Reprinted with permission from Elsevier Science.)

Fig 46  Toluidine blue-stained (left) and alcian blue-stained (right) sections showing longitudinally sectioned dentinal tubules corresponding to Z3 in Figs 42 and 43. Note the granular appearance of the contents of the tubules in this location. (Original magnification ×260.) (From Mjör. Reprinted with permission from Elsevier Science.)
Fig 47  (left) Diagram showing relationship between a stained, demineralized section (top) and the microradiographic appearance of a ground section (bottom). The encircled detail from each zone shows details of the dental tubules and the intertubular matrix in the respective areas. The stainable components of the dentin denote the stainability of the corresponding areas in alcian blue- and toluidine blue-stained sections. The variation in grayness in the microradiographic appearance reflects differences in the degree of mineralization.

Fig 48  (below) Demineralized section of a tooth from a 71-year-old individual. It appears as if the two zones, Z1 and Z3, seen in newly erupted teeth (Fig 43) have merged into one stainable area from the predentin (PD) and peripherally for a short distance. (Original magnification ×10.)

Fig 49  Dentin in the cuspal area of a pre-molar. Predentin-like tissue (PD) extends occlusally. (PH) Pulp horn. (Original magnification ×90.)

Fig 50  Microradiograph of an intact incisor showing a narrow band of hypermineralized dentin (D1) bordered by two narrow hypomineralized bands (D2) in the incisal region. (E) Enamel; (MD) mantle dentin. (Original magnification ×12. Courtesy of Dr. L. Tronstad.)

Fig 51  Microradiograph of a worn incisor showing a streak of hypermineralized dentin (D1) in the incisal area lined by hypomineralized bands of dentin (D2). The area of attrition is larger than that corresponding to the hypermineralized dentin. (E) Enamel; (MD) mantle dentin. (Original magnification ×12. Courtesy of Dr. L. Tronstad.)
hypomineralized dentin even in intact teeth from young individuals (Fig 50). These particular structural characteristics may represent a vestigial extension of pulp horns into the cuspal and incisal region. They are normal variations in structure, and they are not associated with changes caused by attrition (Fig 51). They may represent vulnerable areas during treatment of fractured incisors and in the development and treatment of Class IV lesions because of the apparently easy access to the pulp.

CONCLUDING REMARKS

A biologic approach to restorative dentistry requires knowledge of the normal structure and physiology of dentin and pulp, including age-related changes. Some of this knowledge that is known to have, or may have, clinical implications has been outlined in this review. Tissue changes associated with injury, age, wear, and pathologic processes affecting dentin and pulp, and those occurring as a result of common clinical procedures, have been briefly discussed. They will be outlined in some detail, in a series of articles.

Further details related to the structure and physiology of the dentin and pulp may be obtained from the proceedings of two international conferences held in 1991 and in 1995.83,84 Another Dentin/Pulp Complex Symposium will be held in Japan in 2001 (Shimono M, personal communication, July 4, 2000).

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