Enamel

Enamel formation, amelogenesis, is accomplished by cells called ameloblasts. These cells originate from the embryonic germ layer known as ectoderm. Enamel covers the anatomic crown of the tooth and varies in thickness in different areas (see Fig. 1-3). It is thicker at the incisal and occlusal areas of a tooth and becomes progressively thinner until it terminates at the cementoenamel junction (CEJ). The thickness also varies from one class of tooth to another, averaging 2 mm at the incisal ridges of incisors, 2.3 to 2.5 mm at the cusps of premolars, and 2.5 to 3 mm at the cusps of molars. The cusps of posterior teeth begin as separate ossification centers, which form lobes that coalesce. Enamel usually decreases in thickness toward the junction of these developmental features and can approach zero where the junction is fissured (noncoalesced). Chemically, enamel is a highly mineralized crystalline structure. Hydroxyapatite, in the form of a crystalline lattice, is the largest mineral constituent (90%–92% by volume). Other minerals and trace elements are present in smaller amounts. The remaining constituents of tooth enamel include organic matrix proteins (1%–2%) and water (4%–12%) volume

Structurally, enamel is composed of millions of enamel rods or prisms, which are the largest structural components, rod sheaths, and a cementing inter-rod substance in some areas. The inter-rod substance, or sheath, may be the increased spacing between crystallites oriented differently to where the “tail” portion of one rod meets the “head” portion of another. This spacing apparently is partially organic material. The rods vary in number from approximately 5 million for a mandibular incisor to about 12 million for a maxillary molar. The rods are densely packed and intertwined in a wavy course, and each extends from the DEJ to the external surface of the tooth. In general, the rods are aligned perpendicularly to the DEJ and the tooth surface in the primary and permanent dentitions except in the cervical region of permanent teeth, where they are oriented outward in a slightly apical direction. In the primary dentition, the enamel rods in the cervical and central parts of the crown are nearly perpendicular to the long axis of the tooth and are similar in their direction to permanent teeth in the occlusal two thirds of the crown. Enamel rod diameter near the dentinal borders is about 4 μm and about 8 μm near the surface. This difference accommodates the larger outer surface of the enamel crown compared with the dentinal surface at the DEJ.

Enamel is the hardest substance of the human body. Hardness can vary over the external tooth surface according to the location; also, it decreases inwardly, with hardness lowest at the DEJ. The density of enamel also decreases from the surface to the DEJ. Enamel is a rigid structure that is both strong and brittle (high elastic modulus, high compressive strength, and low tensile strength) and requires a dentin support to withstand masticatory forces. Dentin is a more flexible substance that is strong and resilient (low elastic modulus, high compressive strength, and high tensile strength), which essentially increases the fracture toughness of the more superficial enamel. Enamel rods that lack dentin support because of caries or improper preparation design are easily fractured away from neighboring rods. For optimal strength in tooth preparation, all enamel rods should be supported by dentin (Fig. 1-4).

Human enamel is composed of rods that, in transverse section, have a rounded head or body section and a tail section, forming a repetitive series of interlocking prisms. The rounded head portion of each prism (5 μm wide) lies between the narrow tail portions (5 μm long) of two adjacent prisms (Fig. 1-5). Generally, the rounded head portion is oriented in the incisal or occlusal direction; the tail section is oriented cervically.

The structural components of the enamel prism are millions of small, elongated apatite crystallites that vary in size and shape. The crystallites are tightly packed in a distinct pattern of orientation that gives strength and structural identity to the enamel prisms. The long axis of the apatite crystallites within the central region of the head (body) is aligned almost parallel to the rod long axis, and the crystallites incline with increasing angles (65 degrees) to the prism axis in the tail region. The susceptibility of these crystallites to acid, from either an etching procedure or caries, may be correlated with their orientation. Although the dissolution process occurs more in the head regions of the rod, the tail regions and the periphery of the head regions are relatively resistant to acid attack. The crystallites are irregular in shape, with an average length of 160 nm and an average width of 20 to 40 nm. Each apatite crystallite is composed of thousands of unit cells that have a highly ordered arrangement of atoms. A crystallite may be 300 unit cells long, 40 cells wide, and 20 cells thick in a hexagonal configuration (Fig. 1-6). An organic matrix or prism sheath also surrounds individual crystals and appears to be an organically rich interspace rather than a structural entity.

Enamel rods follow a wavy, spiraling course, producing an alternating arrangement for each group or layer of rods as they change direction in progressing from the dentin toward the enamel surface, where they end a few micrometers short of the tooth surface. Enamel rods rarely run a straight radial course, as there is an alternating clockwise and counterclockwise deviation of the rods from the radial course at all levels of the crown. They initially follow a curving path through one third of the enamel next to the DEJ. After that, the rods usually follow a more direct path through the remaining two thirds of the enamel to the enamel surface. Groups of enamel rods may entwine with adjacent groups of rods, and they follow a curving irregular path toward the tooth surface. These constitute gnarled enamel, which occurs near the cervical regions and the incisal and occlusal areas (Fig. 1-7). Gnarled enamel is not subject to fracture as much as is regular enamel. This type of enamel formation does not yield readily to the pressure of bladed, hand-cutting instruments in tooth preparation.

The changes in direction of enamel prisms that minimize fracture in the axial direction produce an optical appearance called Hunter-Schreger bands (Fig. 1-8). These bands appear to be composed of alternate light and dark zones of varying widths that have slightly different permeability and organic content. These bands are found in different areas of each class of teeth. Because the enamel rod orientation varies in each tooth, Hunter-Schreger bands also have a variation in the number present in each tooth. In anterior teeth, they are located near the incisal surfaces. They increase in numbers and areas of teeth, from canines to premolars. In molars, the bands occur from near the cervical region to the cusp tips. The orientation of the enamel rod heads and tails and the gnarling of enamel rods provide strength by resisting, distributing, and dissipating impact forces.

Enamel tufts are hypomineralized structures of the enamel rods and the inter-rod substance that project between adjacent groups of enamel rods from the DEJ (Fig. 1-9). These projections arise in dentin, extend into enamel in the direction of the long axis of the crown, and may play a role in the spread of dental caries. Enamel lamellae are thin, leaf-like faults between enamel rod groups that extend from the enamel surface toward the DEJ, sometimes extending into dentin (see Fig. 1-9). They contain mostly organic material, which is a weak area predisposing a tooth to the entry of bacteria and dental caries. Enamel rods are formed linearly by successive apposition of enamel in discrete increments. The resulting variations in structure and mineralization are called incremental striae of Retzius and can be considered growth rings (see Fig. 1-3). In horizontal sections of a tooth, the striae of Retzius appear as concentric circles. In vertical sections, the lines traverse the cuspal and incisal areas in a symmetric arc pattern, descending obliquely to the cervical region and terminating at the DEJ. When these circles are incomplete at the enamel surface, a series of alternating grooves, called imbrication lines of Pickerill, are formed. The elevations between the grooves are called perikymata; these are continuous around a tooth and usually lie parallel to the CEJ and each other.

A structureless outer layer of enamel about 30 μm thick is found most commonly toward the cervical area and less often on cusp tips. No prism outlines are visible, and all of the apatite crystals are parallel to one another and perpendicular to the striae of Retzius. This layer, referred to as prismless enamel, may be more heavily mineralized. Microscopically, the enamel surface initially has circular depressions indicating where the enamel rods end. These concavities vary in depth and shape, and they may contribute to the adherence of plaque material, with a resultant caries attack, especially in young individuals. The dimpled surface anatomy of the enamel, however, gradually wears smooth with age.

The interface of enamel and dentin (dentinoenamel junction, or DEJ) is scalloped or wavy in outline, with the crest of the waves penetrating toward enamel (Fig. 1-10). The rounded projections of enamel fit into the shallow depressions of dentin. This interdigitation may contribute to the firm attachment between dentin and enamel. The DEJ is also a hypermineralized zone approximately 30 μm thick.

The occlusal surfaces of premolars and molars have grooves and fossae that form at the junction of the developmental lobes of enamel. These allow movement of food to the facial and lingual surfaces during mastication. A functional cusp that opposes a groove (fossa) occludes on enamel and inclines on each side of the groove and not in the depth of the groove. This arrangement leaves a V-shaped escape path between the cusp and its opposing groove for the movement of food during chewing. Failure of the enamel of the developmental lobes to coalesce results in a deep invagination of the enamel surface and is termed fissure. Non-coalesced enamel at the deepest point of a fossa is termed pit. These fissures and pits act as food and bacterial traps that predispose the tooth to dental caries (Fig. 1-11).

Once damaged, enamel is incapable of repairing itself because the ameloblast cell degenerates after the formation of the enamel rod. The final act of the ameloblast is secretion of a membrane covering the end of the enamel rod. This layer is referred to as Nasmyth's membrane, or primary enamel cuticle. This membrane covers the newly erupted tooth and is worn away by mastication and cleaning. The membrane is replaced by an organic deposit called the pellicle, which is a precipitate of salivary proteins. Microorganisms may attach to the pellicle to form bacterial plaque, which, if acidogenic in nature, can be a potential precursor to dental disease.

Although enamel is a hard, dense structure, it is permeable to certain ions and molecules. The route of passage may be through structural units that are hypomineralized and rich in organic content, such as rod sheaths, enamel cracks, and other defects. Water plays an important role as a transporting medium through small intercrystalline spaces. Enamel permeability decreases with age because of changes in the enamel matrix, a decrease referred to as enamel maturation.

Enamel is soluble when exposed to an acid medium, but the dissolution is not uniform. Solubility of enamel increases from the enamel surface to the DEJ. When fluoride ions are present during enamel formation or are topically applied to the enamel surface, the solubility of surface enamel is decreased. Fluoride concentration decreases toward the DEJ. Fluoride can affect the chemical and physical properties of the apatite mineral and influence the hardness, chemical reactivity, and stability of enamel, while preserving the apatite structures. Trace amounts of fluoride stabilize enamel by lowering acid solubility, decreasing the rate of demineralization, and enhancing the rate of remineralization.

Pulp–Dentin Complex

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

The dental pulp occupies the pulp cavity in the tooth and is a unique, specialized organ of the human body that serves four functions: (1) formative or developmental, (2) nutritive, (3) sensory or protective, and (4) defensive or reparative. The formative function is the production of primary and secondary dentin by odontoblasts. The nutritive function supplies nutrients and moisture to dentin through the blood vascular supply to the odontoblasts and their processes. The sensory function provides nerve fibers within the pulp to mediate the sensation of pain. Dentin receptors are unique because various stimuli elicit only pain as a response. The pulp usually does not differentiate between heat, touch, pressure, or chemicals. Motor fibers initiate reflexes in the muscles of the blood vessel walls for the control of circulation in the pulp.

Finally, the defensive function of the pulp is related primarily to its response to irritation by mechanical, thermal, chemical, or bacterial stimuli. The deposition of reparative dentin acts as a protective barrier against caries and various other irritating factors. In cases of severe irritation, the pulp responds by an inflammatory reaction similar to that for any other soft tissue injury. The inflammation may become irreversible, however, and can result in the death of the pulp because the confined, rigid structure of the dentin limits the inflammatory response and the ability of the pulp to recover.

The pulp is circumscribed by the dentin and is lined peripherally by a cellular layer of odontoblasts adjacent to dentin. Anatomically, the pulp is divided into (1) coronal pulp located in the pulp chamber in the crown portion of the tooth, including the pulp horns that are directed toward the incisal ridges and cusp tips, and (2) radicular pulp located in the pulp canals in the root portion of the tooth. The radicular pulp is continuous with the periapical tissues by connecting through the apical foramen or foramina of the root. Accessory canals may extend from the pulp canals laterally through the root dentin to the periodontal tissues. The shape of each pulp conforms generally to the shape of each tooth (see Fig. 1-3).

The pulp contains nerves, arterioles, venules, capillaries, lymph channels, connective tissue cells, intercellular substance, odontoblasts, fibroblasts, macrophages, collagen, and fine fibers.[1] The pulp is circumscribed peripherally by a specialized odontogenic area composed of the odontoblasts, the cell-free zone, and the cell-rich zone.

Knowledge of the contour and size of the pulp cavity is essential during tooth preparation. In general, the pulp cavity is a miniature contour of the external surface of the tooth. Pulp cavity size varies with tooth size among individuals and even within a single person. With advancing age, the pulp cavity usually decreases in size. Radiographs are an invaluable aid in determining the size of the pulp cavity and any existing pathologic condition (Fig. 1-12). A primary objective during operative procedures must be the preservation of the health of the pulp.

Dentin formation, dentinogenesis, is accomplished by cells called odontoblasts. Odontoblasts are considered part of pulp and dentin tissues because their cell bodies are in the pulp cavity, but their long, slender cytoplasmic cell processes (Tomes fibers) extend well (100–200 μm) into the tubules in the mineralized dentin (Fig. 1-13).

Because of these odontoblastic cell processes, dentin is considered a living tissue, with the capability of reacting to physiologic and pathologic stimuli. Odontoblastic processes occasionally cross the DEJ into enamel; these are termed enamel spindles when their ends are thickened (Fig. 1-14). They may serve as pain receptors, explaining the enamel sensitivity experienced by some patients during tooth preparation.

Dentin forms the largest portion of the tooth structure, extending almost the full length of the tooth. Externally, dentin is covered by enamel on the anatomic crown and cementum on the anatomic root. Internally, dentin forms the walls of the pulp cavity (pulp chamber and pulp canals) (Fig. 1-15). Dentin formation begins immediately before enamel formation. Odontoblasts generate an extracellular collagen matrix as they begin to move away from the adjacent ameloblasts. Mineralization of the collagen matrix, facilitated by modification of the collagen matrix by various noncollagenous proteins, gradually follows its secretion. The most recently formed layer of dentin is always on the pulpal surface. This unmineralized zone of dentin is immediately next to the cell bodies of odontoblasts and is called predentin. Dentin formation begins at areas subjacent to the cusp tip or incisal ridge and gradually spreads to the apex of the root (see Fig. 1-15). In contrast to enamel formation, dentin formation continues after tooth eruption and throughout the life of the pulp. The dentin forming the initial shape of the tooth is called primary dentin and is usually completed 3 years after tooth eruption (in the case of permanent teeth).

The dentinal tubules are small canals that extend through the entire width of dentin, from the pulp to the DEJ (Figs. 1-16 and 1-17). Each tubule contains the cytoplasmic cell process (Tomes fiber) of an odontoblast and is lined with a layer of peri-tubular dentin, which is much more mineralized than the surrounding intertubular dentin (see Fig. 1-17).

The surface area of dentin is much larger at the DEJ or dentinocemental junction than it is on the pulp cavity side. Because odontoblasts form dentin while progressing inward toward the pulp, the tubules are forced closer together. The number of tubules increases from 15,000 to 20,000/mm2 at the DEJ to 45,000 to 65,000/mm2 at the pulp.2 The lumen of the tubules also varies from the DEJ to the pulp surface. In coronal dentin, the average diameter of tubules at the DEJ is 0.5 to 0.9 μm, but this increases to 2 to 3 μm near the pulp (Fig. 1-18).

The course of the dentinal tubules is a slight S-curve in the tooth crown, but the tubules are straighter in the incisal ridges, cusps, and root areas (Fig. 1-19). The ends of the tubules are perpendicular to the DEJ. Along the tubule walls are small lateral openings called canaliculi. As the odontoblastic process proceeds from the cell in the pulp to the DEJ, lateral secondary branches extend into the canaliculi and can communicate with the lateral extensions of adjacent odontoblastic processes. Near the DEJ, the tubules divide into several terminal branches, forming an intercommunicating and anastomosing network (Fig. 1-20).

After the primary dentin is formed, dentin deposition continues at a reduced rate even without obvious external stimuli, although the rate and amount of this physiologic secondary dentin vary considerably among individuals. In secondary dentin, the tubules take a slightly different directional pattern in contrast to primary dentin (Fig. 1-21). Secondary dentin forms on all internal aspects of the pulp cavity, but in the pulp chamber, in multi-rooted teeth, it tends to be thicker on the roof and floor than on the side walls When moderate stimuli are applied to dentin, such as caries, attrition, and some operative procedures, the affected odontoblasts may die. Replacement odontoblasts (termed secondary odontoblasts) of pulpal origin then begin to form reparative dentin (tertiary dentin). The reparative dentin usually appears as a localized dentin deposit on the wall of the pulp cavity immediately subjacent to the area on the tooth that has received the injury (a dentin deposit underneath the affected tubules) (Fig. 1-22). Being highly atubular, the reparative dentin is structurally different from the primary and secondary dentin.

Sclerotic dentin results from aging or mild irritation (e.g., slowly advancing caries) and causes a change in the composition of the primary dentin. The peritubular dentin becomes wider, gradually filling the tubules with calcified material, progressing pulpally from the DEJ (Fig. 1-23). These areas are harder, denser, less sensitive, and more protective of the pulp against subsequent irritations. Sclerosis resulting from aging is called physiologic dentin sclerosis; sclerosis resulting from a mild irritation is called reactive dentin sclerosis. Reactive dentin sclerosis often can be seen radiographically in the form of a more radiopaque (lighter) area in the S-shape of the tubules.

Human dentin is composed of approximately 50% inorganic material and 30% organic material by volume. The organic phase is approximately 90% type I collagen and 10% noncollagenous proteins. Dentin is less mineralized than enamel but more mineralized than cementum or bone. The mineral content of dentin increases with age. This mineral phase is composed primarily of hydroxyapatite crystallites, which are arranged in a less systematic manner than are enamel crystallites. Dentinal crystallites are smaller than enamel crystallites, having a length of 20 to 100 nm and a width of about 3 nm, which is similar to the size seen in bone and cementum.[3] Dentin is significantly softer than enamel but harder than bone or cementum. The hardness of dentin averages one-fifth that of enamel, and its hardness near the DEJ is about three times greater than near the pulp. Dentin becomes harder with age, primarily as a result of increases in mineral content. Although dentin is a hard, mineralized tissue, it is flexible, with a modulus of elasticity of approximately 18 gigapascals (GPa).[4] This flexibility helps support the more brittle, nonresilient enamel. Often small “craze lines” are seen in enamel, indicating minute fractures of that structure.

The craze lines usually are not clinically significant unless associated with cracks in the underlying dentin. Dentin is not as prone to fracture as is the enamel rod structure. The ultimate tensile strength of dentin is approximately 98 megapascals (MPa), whereas the ultimate tensile strength of enamel is approximately 10 MPa. The compressive strength of dentin and enamel are approximately 297 and 384 MPa, respectively.[4]

During tooth preparation, dentin usually is distinguished from enamel by (1) color and opacity, (2) reflectance, (3) hardness, and (4) sound. Dentin is normally yellow-white and slightly darker than enamel. In older patients, dentin is darker, and it can become brown or black when it has been exposed to oral fluids, old restorative materials, or slowly advancing caries. Dentin surfaces are more opaque and dull, being less reflective to light than similar enamel surfaces, which appear shiny. Dentin is softer than enamel and provides greater yield to the pressure of a sharp explorer tine, which tends to catch and hold in dentin.

Sensitivity is encountered whenever odontoblasts and their processes are stimulated during operative procedures, even though the pain receptor mechanism appears to be within the dentinal tubules near the pulp. Physical, thermal, chemical, bacterial, and traumatic stimuli are transmitted through the dentinal tubules, although the precise mechanism of the transmissive elements of sensation has not been conclusively established. The most accepted theory of pain transmission is the hydrodynamic theory, which accounts for pain transmission through rapid movements of fluid within the dentinal tubules.[5] Because many tubules contain mechanoreceptor nerve endings near the pulp, small fluid movements in the tubules arising from cutting, drying, pressure changes, osmotic shifts, or changes in temperature account for most pain transmission (Fig. 1-24).

Dentinal tubules are filled with dentinal fluid, a transudate of plasma. When enamel or cementum is removed during tooth preparation, the external seal of dentin is lost, allowing tubular fluid to move toward the cut surface. Pulpal fluid has a slight positive pressure that forces fluid outward toward any breach in the external seal. Permeability studies of dentin indicate that tubules are functionally much smaller than would be indicated by their measured microscopic dimensions as a result of numerous constrictions along their paths (see Fig. 1-17).[6] Dentin permeability is not uniform throughout the tooth. Coronal dentin is much more permeable than root dentin. There also are differences within coronal dentin (Fig. 1-25).[7] Dentin permeability primarily depends on the remaining dentin thickness (i.e., length of the tubules) and the diameter of the tubules. Because the tubules are shorter, more numerous, and larger in diameter closer to the pulp, deep dentin is a less effective pulpal barrier compared with superficial dentin.

Cementum

Cementum is a thin layer of hard dental tissue covering the anatomic roots of teeth and is formed by cells known as cementoblasts, which develop from undifferentiated mesenchymal cells in the connective tissue of the dental follicle. Cementum is slightly softer than dentin and consists of about 45% to 50% inorganic material (hydroxyapatite) by weight and 50% to 55% organic matter and water by weight. The organic portion is composed primarily of collagen and protein polysaccharides. Sharpey's fibers are portions of the principal collagenous fibers of the periodontal ligament embedded in cementum and alveolar bone to attach the tooth to the alveolus (Fig. 1-27). Cementum is avascular.

Cementum is light yellow and slightly lighter in color than dentin. It is formed continuously throughout life because as the superficial layer of cementum ages, a new layer of cementum is deposited to keep the attachment intact. Two kinds of cementum are formed: acellular and cellular. The acellular layer of cementum is living tissue that does not incorporate cells into its structure and usually predominates on the coronal half of the root; cellular cementum occurs more frequently on the apical half. Cementum on the root end surrounds the apical foramen and may extend slightly onto the inner wall of the pulp canal. Cementum thickness can increase on the root end to compensate for attritional wear of the occlusal or incisal surface and passive eruption of the tooth.

The cementodentinal junction is a relatively smooth area in the permanent tooth, and attachment of cementum to dentin is firm, but this is not understood completely yet. Cementum joins enamel to form the CEJ. In about 10% of teeth, enamel and cementum do not meet, and this can result in a sensitive area. Abrasion, erosion, caries, scaling, and restoration finishing and polishing procedures can denude dentin of its cementum covering, which can cause the dentin to be sensitive to various stimuli (e.g., heat, cold, sweet substances, sour substances). Cementum is capable of repairing itself to a limited degree and is not resorbed under normal conditions. Some resorption of the apical portion of the root can occur, however, if orthodontic pressures are excessive and movement is too fast