Enamel, the hard protective substance that covers the crown of the tooth, is the hardest biologic tissue in the body. It consequently is able to resist fractures during the stress of mastication. Enamel provides shape and contour to the crowns of teeth and covers the part of the tooth that is exposed to the oral environment.

Enamel is composed of interlocking rods that resist masticatory forces. Enamel rods are deposited in a keyhole shape by the formative ameloblastic cells. Groups of ameloblasts migrate peripherally from the dentinoenamel junction as they form these rods. Ameloblasts take variable paths, which produces a bending of the rods. These cells maintain a relationship as they travel in different directions and produce adjacent rods. The enamel rod configuration viewed in incidental light appears as light and dark bands of rod groups termed Hunter-Schreger bands. Because these rods bend in an exaggerated, twisted manner at the cusp tips, they are called gnarled enamel.

All enamel rods are deposited at a daily appositional rate or increment of 4 μm. Such increments are noticeable, like rings in a cross section of a tree, and appear as dark lines known as striae of Retzius or lines of Retzius. The growth lines become apparent on the surface of enamel as ridges, known as perikymata. Two structures are noticeable at the dentinoenamel junction: spindles, the termination of the dentinal tubules in enamel, and tufts, hypocalcified zones caused by the bending of adjacent groups of rods.

Because enamel is composed of bending rods, which in turn are composed of crystals, minute spaces or gaps exist where crystals did not form between rods. This feature causes enamel to be variable in its density and hardness. Therefore some areas of enamel may be more prone to penetration by small particles. This characteristic leads to tooth destruction by dental caries. After enamel is completely formed, no more enamel can be deposited.

**CLINICAL COMMENT**

Perikymata are surface manifestations of the incremental lines usually found at the cervix of the crown. Some perikymata are more prominent and present difficulties to the novice clinician, who may confuse them with calculus.
Because enamel is very hard, it is also brittle and subject to fracture. Fracture is especially likely to occur if the underlying dentin is carious and has weakened the enamel’s foundation.

Enamel is about 96% inorganic mineral in the form of hydroxyapatite and 4% water and organic matter. Hydroxyapatite is a crystalline calcium phosphate that is also found in bone, dentin, and cementum. The organic component of enamel is the protein enamelin, which is similar to the protein keratin that is found in the skin. The distribution of enamelin between and on the crystals aids enamel permeability. Enamel is grayish white but appears slightly yellow because it is translucent, and the underlying dentin is yellowish. Enamel ranges in thickness from a knife-like edge at its cervical margin to about 2.5 mm maximum thickness over the occlusal incisal surface.

**ROD STRUCTURE**

Enamel is composed of rods that extend from their site of origin, at the dentinoenamel junction, to the enamel outer surface (Fig. 7-1). Each rod is formed by four ameloblasts. One ameloblast forms the rod head; a part of two ameloblasts forms the neck; and the tail is formed by a fourth ameloblast. Fig. 7-2 shows the six-sided design that is the shape of the ameloblast in contact with the forming keyhole- or racquet-shaped rod, which is columnar in its long axis. The head of the enamel rod is the broadest part at 5 μm wide, and the elongated thinner portion, or tail, is about 1 μm wide. The rod, including both head and tail, is 9 μm long. The enamel rod is about the same size as a red blood cell (Fig. 7-3).

Each rod is filled with crystals. Those in the head follow the long axis of the rod, and those in the tail lie in the cross axis to the head (Figs. 7-4 and 7-5). The upper right rod head of Fig. 7-4 indicates how the mineral is oriented during the rod’s development, which forms the rod head and tail as seen on the left side of the figure. The architecture of the mineral orientation is complex, especially when viewed in any direction other than cross section (see Fig. 7-5).
Rods form nearly perpendicular to the dentinoenamel junction and curve slightly toward the cusp tip. This unique rod arrangement also undulates throughout the enamel to the surface. Each rod interdigitates with its neighbor, the head of one rod nestling against the necks of the rods to its left and right (see Fig. 7-3). The rods run almost perpendicular to the enamel surface at the cervical region but are gnarled and intertwined near the cusp tips (Fig. 7-6). The surface of each rod is known as the rod sheath, and the center is the core. The rod sheath contains slightly more organic matter than the rod core (Fig. 7-7).

Groups of rods bend to the right or left at a slightly different angle than do adjacent groups (see Fig. 7-6). It is believed that this feature provides the enamel with strength for mastication and biting. When light is projected at the surface of a thin slab of enamel, light and dark bands appear. These bands are seen because the light transmits along the long axis of one group of rods but not along the adjacent rods, which lie at right angles. This is known as the Hunter-Schreger bands phenomenon (Fig. 7-8). These bands are named after the dental scientist who first noted the Schreger band effect microscopically, John Hunter. The repeating pattern from the cervical area to the incisal or occlusal areas can be seen along the long axis of the tooth. Hunter-Schreger bands extend through one half to two thirds of the thickness of enamel as shown in Fig. 7-6 (diagram) and Fig. 7-8 (a tooth section).

**CLINICAL COMMENT**

Enamel rods interlock to prevent fracture and splitting of the tooth. Enamel rod groups also intertwine, thereby preventing separation. The rod direction in the crown is normally perpendicular to the incisal surface, which provides additional support in preventing fracture.

**CONSIDER THE PATIENT**

A patient has attrition of cusp tips in the enamel of the crowns. What do you expect when you look at the root length radio graphically? Why would you see this?
**Fig. 7.6** Diagram of enamel rod orientation as shown in both longitudinal and cross section of the crown. Enamel rods are intertwined at the cusp tip; this is called *gnarled enamel*. Groups of outer enamel rods all run nearly perpendicular to the surface of the enamel, whereas inner groups of enamel rods alternate. Some appear in cross section, and adjacent groups appear longitudinal. *(Modified from Avery JK: Oral development and histology, ed 3, Stuttgart, 2002, Thieme Medical.)*

**Fig. 7.7** Enamel rods in cross section. Each rod has a sheath and core. The rod sheath surrounds rod head and tail. This enamel sample has been etched to reveal organic matrix.

**Fig. 7.8** Photomicrograph of enamel taken by reflected light and illustrating phenomena of light and dark (Hunter-Schreger) bands.

**Fig. 7.9** Photomicrograph of enamel taken by reflected light and illustrating phenomena of light and dark (Hunter-Schreger) bands.

**INCREMENTAL LINES**

The incremental lines in enamel are the result of the rhythmic recurrent deposition of the enamel. As the enamel matrix mineralizes, it follows the pattern of matrix deposition and provides the growth lines in enamel *(Fig. 7-9)*. These lines may be accentuated because of a variation in the mineral deposited at the point of enamel hesitation in deposition. In some cases, the incremental lines are not visible. With enamel development, a row of ameloblasts covering the crown hesitates during deposition. These hesitation lines mark the path of amelogenesis. The spaces between the crystals entrap air molecules, accentuating these lines. Dr. Retzius, who first noted these “growth lines,” termed them the *striae of Retzius*.

Part of the enamel of most deciduous teeth is formed before birth, and part is formed after birth. Because environment and nutrition change abruptly at the time of birth, a notable line of Retzius occurs at that time. This is known as the *neonatal line* *(Fig. 7-10)*. Although the neonatal line is an accentuated incremental line, it can be seen microscopically that this line is prominent for another reason. The enamel internal to this line is of a different consistency from that external to it because it was formed before birth, and the external was formed after birth. The prenatal enamel has fewer defects than the postnatal. The staining of the postnatal enamel has numerous minute spaces that are stained with pigment.

**CLINICAL COMMENT**

The rods that form enamel are woven during formation into a mass that resists average masticatory impact of 20 to 30 pounds per tooth. Enamel is thin in the cervical areas where masticatory impact is the least and thickest over the areas of crown cusps where impact is greatest.

**CLINICAL COMMENT**

Enamel is composed of mineral crystals that are the same as those found in dentin, cementum, and bone. Unlike bone and cementum, the mineral crystals in enamel are not replaced once deposited in enamel.
ENAMEL LAMELLAE

Enamel lamellae are cracks in the surface of enamel that are visible to the naked eye (see Fig. 7-9 and Fig. 7-11). Lamellae extend from the surface of enamel toward the dentinoenamel junction. Some lamellae form during enamel development, creating an organic pathway or tract. Spaces between groups of rods are another example of lamellae and may be caused by stress cracks that occur because of impact or temperature changes. Breathing cold air or drinking hot or cold beverages may cause small checks or cracks to develop in enamel. This is especially evident in enamel weakened by underlying caries. Lamellae are not tubular defects but appear leaflike, extending around the crown (see Fig. 7-11). Lamellae are a possible avenue for dental caries.

ENAMEL TUFTS

Enamel tufts are another developmental defect in enamel filled with organic material. They are located at the dentinoenamel junction and appear at right angles to it. They can extend one fifth to one tenth of the distance from the dentinoenamel junction to the occlusal surface of the tooth (Figs. 7-12 and 7-13). Tufts form between groups of enamel rods, which are oriented in slightly different directions at the dentinoenamel junction. These spaces are thus developed between adjacent groups of rods, which are filled with organic material termed enamelin. The interface of the junction of dentin and enamel is scalloped, and often tufts arise from these scalloped peaks (see Fig. 7-12).

ENAMEL SPINDLES

Spindles arise at the dentinoenamel junction and extend into enamel. These spindles are extensions of dentinal tubules that pass through the junction into enamel (see Fig. 7-13). Because dentin forms before enamel, the odontoblastic process occasionally penetrates the junction, and enamel forms...
Fig. 7.11 Enamel lamellae. A, Diagram of possible location of leaflike enamel lamellae extending from the cervical to incisal enamel. B, Scanning electron micrograph of lamellae in enamel. (Enamel was decalcified away, and lamellar space was impregnated with resin for its maintenance.) (Modified from Avery JK: Oral development and histology, ed 3, Stuttgart, 2002, Thieme Medical.)

Fig. 7.12 Transmitted light micrograph of the dentinoenamel junction area showing enamel tufts. In addition to tufts, scalloped dentinoenamel junction and fine enamel rod structure can be seen between tufts. Below the junction are dentinal tubules. (From Avery JK: Oral development and histology, ed 3, Stuttgart, 2002, Thieme Medical.)

Fig. 7.13 Enamel spindles at the dentinoenamel junction are extensions of dentinal tubules that may contain odontoblastic processes in enamel. (From Avery JK: Oral development and histology, ed 3, Stuttgart, 2002, Thieme Medical.)

SURFACE CHARACTERISTICS

The enamel surface may be smooth or have fine ridges. Such ridges result from the termination of the striae of Retzius on the surface of enamel (Fig. 7-14). These surface manifestations are around this process, forming a tubule. These small tubules may contain a living process of the odontoblast, possibly contributing to the vitality of the dentinoenamel junction. Tubules are found singularly or in groups and are shorter than tufts, only a few millimeters in length. The fingerlike spindles appear quite different than the broader and longer tufts.
ridges called perikymata or imbrication lines. Perikymata are produced by the ends of rod groups accentuated by hesitation of ameloblasts before the next group of rods contact the enamel surface (Fig. 7-15). This manifestation is more prominent on the facial surface of the tooth, near the cervical region (see Fig. 7-14). Another feature of outer enamel near its surface is the zone of prismless enamel, which is 20 to 40 μm thick. Throughout this zone, no Schreger band effect is noted. This zone is not accentuated except near the cervical region and in deciduous teeth. The prismless zone of enamel is important because it appears as a structureless microcrystalline environment of enamel rods oriented nearly perpendicular to the enamel surface. This enhances the integrity of the enamel surface and should be recognized when a bevel for restorations is prepared.

**PERMEABILITY**

Enamel permeability is a feature of clinical importance. The passage of fluid, bacteria, and bacterial products through enamel is an important consideration in clinical therapy. Permeability of enamel is caused by several factors, some of which are evident as they relate to leakage around faulty restorations and decomposition of the tooth by dental caries. These latter examples need no further explanation, but fluid and fine particles can also pass through unbroken enamel by way of pathways described previously in this chapter, such as lamellae, cracks, tufts, and spindles. These all contribute to the microporosity of enamel. The minute spaces between or around enamel rods and through crystal spaces within rods are also important and are called microlamellae. Differences in crystal orientation can cause enamel to have minute spaces, which can be seen at high magnification (Fig. 7-16). Also, surface irregularities, such as those found in central fissures and near the cervical region, are important in influencing permeability.

Enamel and dentin are both composed of hydroxyapatite crystals, although the crystals in enamel are about 30 times larger than those in dentin (Fig. 7-17). Crystal size is a factor in the extreme hardness of enamel in contrast to dentin.

**CLINICAL COMMENT**

Decalcifying agents such as lemon juice and sodas can remove the mineral from the surface of the enamel crystals. However, the various constituents of saliva, including calcium and phosphate, help to maintain the integrity of the enamel surface.
Etching with dilute acids, such as citric acid, may alter the surface of enamel. This dilute acid selectively etches the ends of the enamel rods and provides adherence of a plastic sealant to the surface of enamel rods (Fig. 7-18). The rod sheath resists demineralization to a greater extent than the rod core. The core of the crystal is rich in coronated apatite and is more sensitive to demineralization than the peripheral hydroxyapatite (Fig. 7-19). The purpose of this procedure is to produce an intact surface and thus prevent caries.

CLINICAL COMMENT

Some etched areas of enamel can be remineralized by solutions of sodium fluoride or stannous fluoride. Tests show that the fluoride ion penetrates the porous etched surface enamel. Low levels of fluoride stimulate remineralization.

CLINICAL COMMENT

The use of sealants, especially in children, can help prevent caries in susceptible areas of the teeth. In order for the sealant to be effective and retained, the surface enamel must be etched to improve adhesion.
CONSIDER THE PATIENT

Discussion: A radiograph would reveal a lengthened root with excessive cemental deposition that is the result of hypereruption of the tooth. Because of the hypereruption, space is provided for compensating cemental deposition.

QUANDARIES IN SCIENCE

Enamel is a unique tissue that does not have the ability to heal after it matures. Although it is the most mineralized tissue in the body, it is still subject to challenges by bacteria and wear by occlusal attrition. The dental practitioner has a complete armamentarium of techniques and materials to treat caries and occlusal attrition and restore function. Whereas the mechanical issues of enamel are easily fixed, the genetic issues are not well understood, and therefore the resultant treatments are technical and not usually related to the genetic basis of the specific dental problem. Many scientists are actively researching the genetic basis of various enamel disorders such as amelogenesis imperfecta with the hopes of treating this genetic disorder in utero or informing the patient of what to expect when their children inherit the genes. Active researchers have a much clearer understanding of the biology of enamel formation and the proteins involved in enamel growth and maturation. The precise mechanisms involved in the synthesis, secretion, and maturation of enamel crystals are beginning to be elucidated, and perhaps in the future the practicing dentist will be able to use natural enamel as a restorative agent.

Self-Evaluation Questions

1. Describe the shape and size of the enamel rods.
2. Define Hunter-Schreger bands.
3. Define striae of Retzius. What is a synonym?
4. Describe gnarled enamel. Where is it located?
5. What are perikymata and imbrication lines?
6. What are the location and importance of tufts?
7. Define and give the cause of neonatal lines.
8. What is prismless enamel?
9. What is the inorganic component of enamel, dentin, and bone?
10. What is the organic component of enamel?

SUGGESTED READING