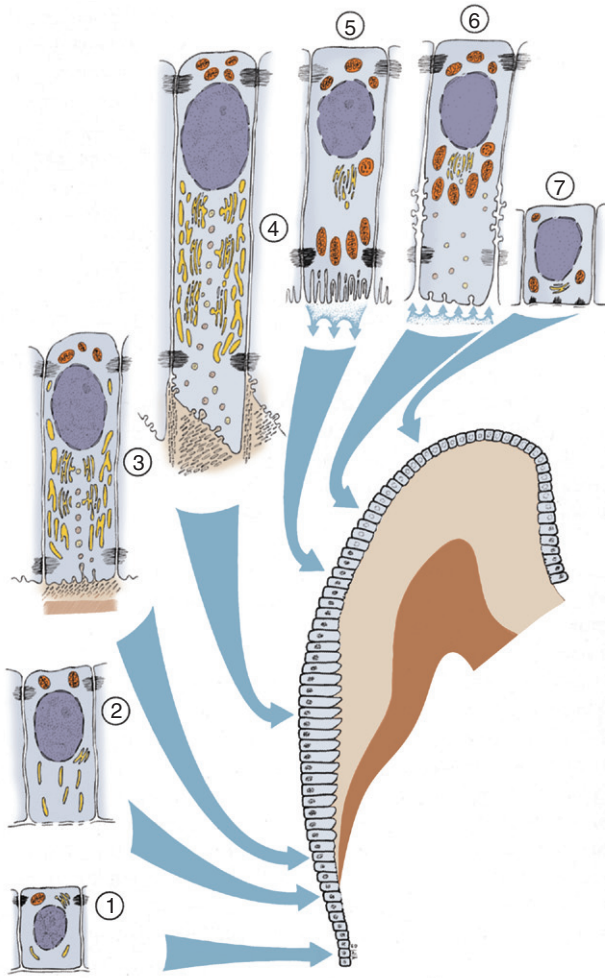


Fig. 5.15 Diagram of Tomes process, the specialized secretory process of the ameloblast during enamel formation. *(From Nanci A:* Ten Cate's oral histology, *ed 8, St. Louis, 2013, Mosby.)*

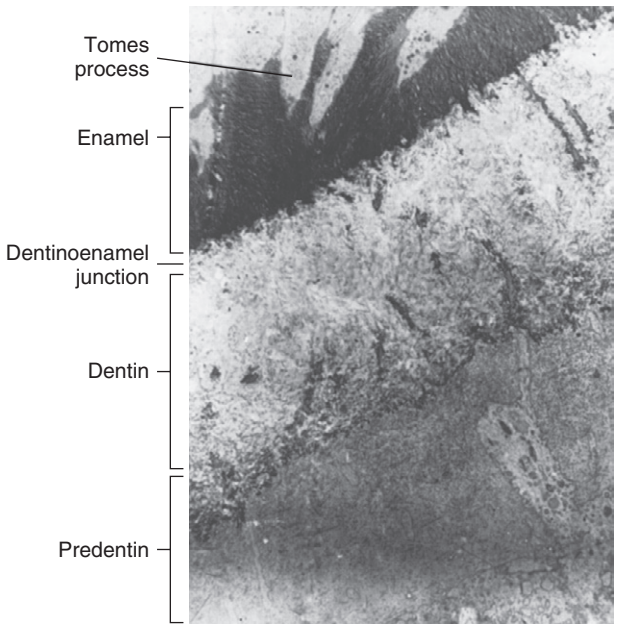
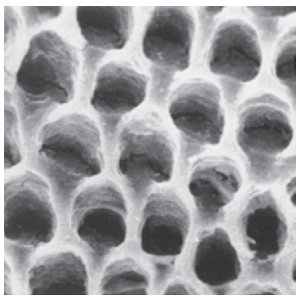


Fig. 5.16 Ultrastructure of the dentoenamel junction showing early enamel and dentin matrix formation.



Human deciduous molar

Developing enamel surface

Height of field, 15-18 μm

Fig. 5.17 Scanning electron micrograph showing interface between ameloblast and enamel matrix during amelogenesis. Pits are result of presence of Tomes process.

CLINICAL COMMENT

Amelogenesis imperfecta is a genetic problem in which the enamel is poorly developed and mineralized. This can be the result of cellular malfunction resulting in defective enamel matrix formation.

CROWN MATURATION

As amelogenesis is completed and amelogenin is deposited, the matrix begins to mineralize (see Fig. 5-10, *F* to *H*). As soon as the small crystals of mineral are deposited, they begin to grow in length and diameter. The initial deposition of mineral amounts to approximately 25% of the total enamel. The other 70% of mineral in enamel is a result of growth of the crystals (5% of enamel is water). The time between enamel matrix deposition and its mineralization is short. Therefore the pattern of mineralization closely follows the pattern of matrix deposition. The first matrix deposited is the first enamel mineralized, occurring along the dentinoenamel junction. Matrix formation and mineralization

Growth of cusps to predetermined point of completion

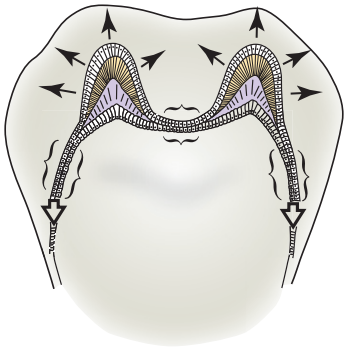


Fig. 5.18 Diagram of growth areas of developing crown. Growth occurs at cusp tips, then intercuspal zones and the cervical zone.

continue peripherally to the tips of the cusps and then laterally on the sides of the crowns, following the enamel incremental deposition pattern **(Fig. 5-19)**. Finally, the cervical region of the crown mineralizes. During this process, protein of the enamel changes or matures and is termed **enamelin.**

The mineral content of enamel is approximately 95% as it rapidly surpasses that of dentin (69%) to become the most highly calcified tissue in the human body. Because of the high mineral content of enamel, almost all water and organic material are removed during maturation (see Fig. 5-10, *E* to *H*).

As the ameloblast completes the matrix deposition phase, its terminal bar apparatus disappears, and the surface enamel becomes smooth (see Fig. 5-10, *F* and *G*). This phase is signaled by a change in the appearance of the cell, as well as by a change in the function of the ameloblast. The apical end of this cell becomes ruffled along the enamel surface. The length of the ameloblast decreases, as does the number of organelles within it. The enamel has now reached the maturation phase, and the ameloblast becomes more active in absorption of the organic matrix and water from enamel, which allows mineralization to proceed (see Fig. 5-10, *F* to *H*).

The increased mineral content in enamel is dependent on the removal of fluid and protein. This process of exchange occurs throughout much of enamel maturation and is not limited to the final stage of mineralization. Even after the teeth erupt, mineralization of enamel continues.

Finally, after the ameloblasts have completed their contributions to the mineralization phase, they secrete an organic cuticle on the surface of the enamel, which is known as the **developmental** or **primary cuticle.** The ameloblasts then attach themselves to this organic covering of the enamel by **hemidesmosomes** (see Fig. 5-10, *H*). A hemidesmosome is half of a desmosome-attachment plaque. Whereas a desmosome functions in attaching a cell to an adjacent cell, a hemidesmosome relates to the attachment of a cell to a surface membrane. The hemidesmosome-attachment plaque is developed by the ameloblast, and this stage of plaque formation and attachment is known as the **protective stage** of ameloblast function. The ameloblasts shorten and contact the stratum intermedium and other enamel epithelium, which fuse together to form the **reduced enamel epithelium.** This cellular organic covering remains on the enamel surface until the tooth erupts into the oral cavity.

With mineralization of enamel complete and its thickness established, the crown of the tooth is formed **(Fig. 5-20)**. The nearly completed crown with the reduced enamel epithelium is seen in **Fig. 5-21**. Meanwhile, dentin formation proceeds. The next stage of development will be root formation.

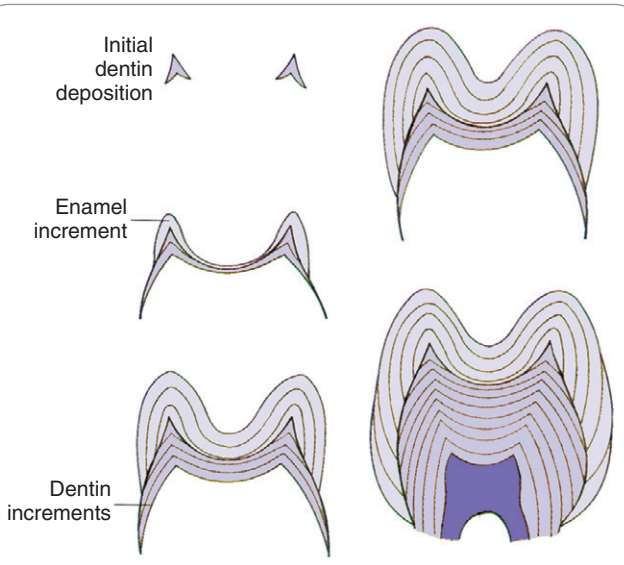


Fig. 5.19 Incremental pattern of enamel and dentin formation from initiation to completion. Development is shown vertically, proceeding from upper left to lower right.

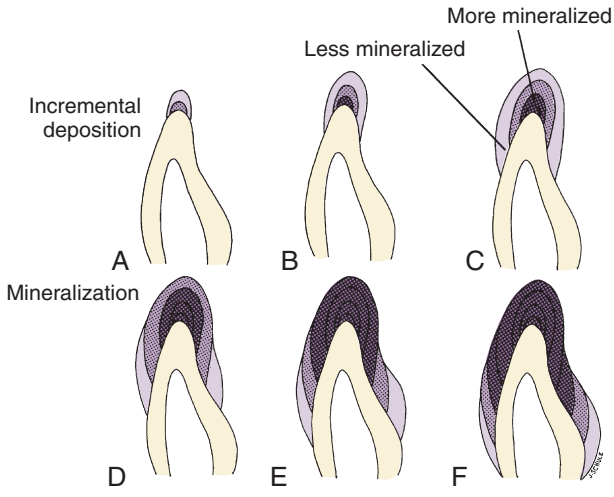


Fig. 5.20 Summary of enamel mineralization stages. **A,** Initial enamel is formed. **B,** Initial enamel is calcified as further enamel is formed. **C,** More increments are formed. **D,** Matrix deposition and mineralization proceeds. **E** and **F,** Matrix is formed on the sides and cervical areas of the crown.

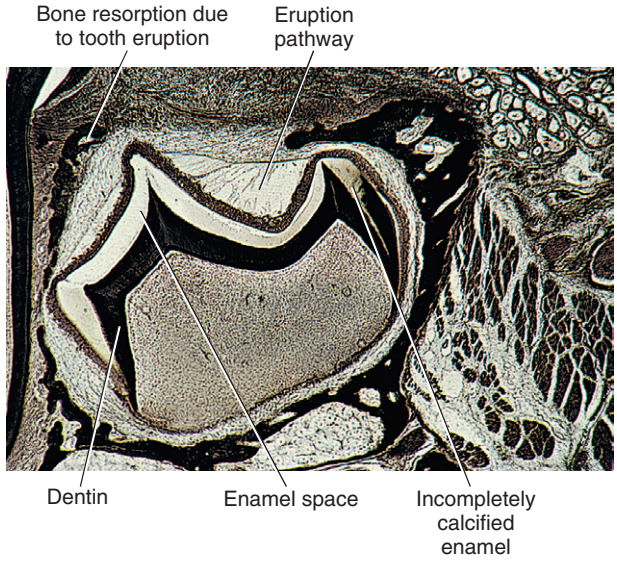


Fig. 5.21 Demineralized section of enamel of crown showing loss of mineralized enamel. Enamel matrix is present only at the cervical region where the matrix still contains developmental enamel proteins.

CONSIDER THE PATIENT

A patient complains that white, chalky areas appear in the cervical enamel of some of his crowns. He asks what could cause this condition.

DEVELOPMENT OF THE TOOTH ROOT

Root Sheath

As the crown develops, cell proliferation continues at the cervical region or base of the enamel organ, where the inner and outer enamel epithelial cells fuse to form the root sheath **(Fig. 5-22)**. When the crown is completed, the cells in this region of the enamel organ continue to grow, forming a double layer of cells termed the **epithelial root sheath,** or **Hertwig's epithelial root sheath (HERS)** (see Fig. 5-22, *A*). The inner cell layer of the root sheath forms from the inner enamel epithelium or ameloblasts in the crown, and enamel is produced. In the root, these cells induce odontoblasts of the dental papilla to differentiate and form dentin. The root sheath originates at the point that enamel deposits end. As the root sheath lengthens, it becomes the architect of the root. The length, curvature, thickness, and number of roots are all dependent on the inner root sheath cells. As the formation of the root dentin takes place, cells of the outer root sheath function in the deposition of **intermediate cementum,** a thin layer of acellular cementum that covers the ends of the dentinal tubule and seals the root surface and is composed of a keratin-like protein.

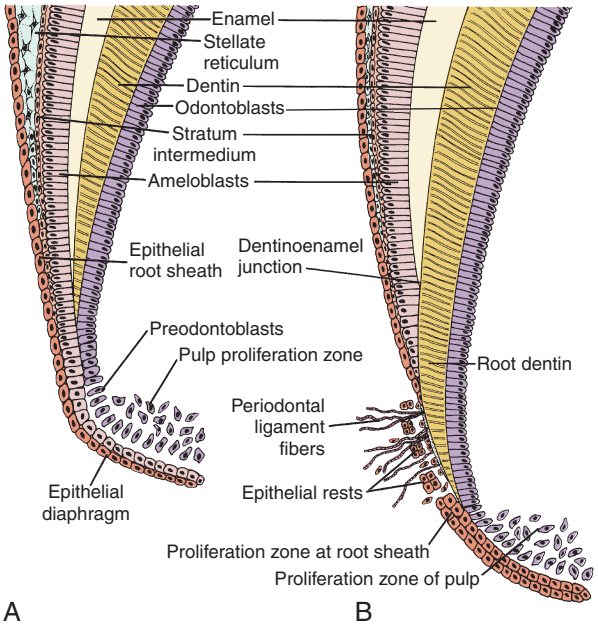


Fig. 5.22 Root formation, showing root sheath and epithelial diaphragm. A, Time of epithelial root sheath formation showing fusion of outer and inner enamel epithelium to form the epithelial root sheath, which includes the vertical epithelial root trunk and inward bending epithelial diaphragm. **B,** Later stage of root sheath development. Root dentin has formed below the cervical enamel on the surface of the pulp organ. Cementoblasts, periodontal ligament fibers, and epithelial rests are present in the ligament.

Then, the outer root sheath cells disperse into small clusters and move away from the root surface as **epithelial rests** (see Fig. 5-22, *B*). At the proliferating end, the root sheath bends at a near 45-degree angle. This area is termed the **epithelial diaphragm** (see Fig. 5-22). The epithelial diaphragm encircles the apical opening of the dental pulp during root development. It is the proliferation of these cells that allows root growth to occur.

As the odontoblasts differentiate along the pulpal boundary, root dentinogenesis proceeds and the root lengthens. Dentin formation continues from the crown into the root **(Fig. 5-23)**. The dentin tapers from the crown into the root to the apical epithelial diaphragm. In the pulp adjacent to the epithelial diaphragm, cellular proliferation occurs. This is known as the **pulp proliferation zone** (see Fig. 5-22). It is believed that this area produces new cells needed for root lengthening. Dentinogenesis continues until the appropriate root length is developed. The root then thickens until the apical opening is restricted to approximately 1 to 3 mm, which is sufficient to allow neural and vascular communication between the pulp and the periodontium.

With the increase in root length, the tooth begins eruptive movements, which provide space for further lengthening of the root. The root lengthens at the same rate as the tooth eruptive movements occur **(Fig. 5-24)**.

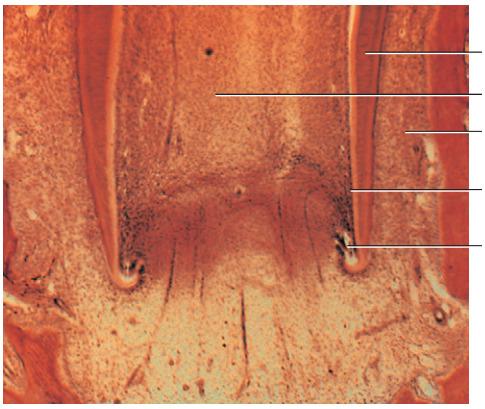


Fig. 5.23 Histology of root formation, showing root sheath and epithelial diaphragm. The highly cellular pulp proliferative zone is shown in the apical pulpal zone.

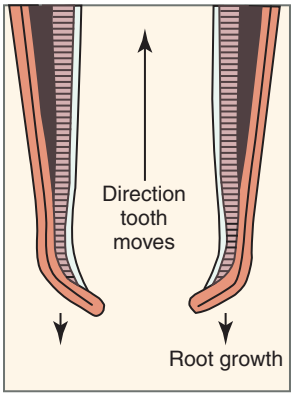


Fig. 5.24 Direction of root growth versus eruptive movements of the tooth.

CLINICAL COMMENT

The presence of the epithelial root sheath determines whether a root will be curved or straight, short or long, or single or multiple.

Single Root

The root sheath of a single-rooted tooth is a tubelike growth of epithelial cells that originates from the enamel organ, enclosing a tube of dentin and the developing pulp (see Fig. 5-23). As soon as the root sheath cells deposit the intermediate cementum, the root sheath breaks up, forming epithelial rests (see Fig. 5-22, *B*; **Fig. 5-25**). The epithelial rests persist as they move away from the root surface into the follicular area. Mesenchymal cells from the tooth follicle move between the epithelial rests to contact the root surface. There they differentiate into cementoblasts and begin secretion of **cementoid** on the surface of the intermediate cementum. Cementoid is noncalcified cementum that soon calcifies into mature cementum **(Fig. 5-26)**. The root sheath is never seen as a continuous structure, because its cell layers break down rapidly once the root dentin forms. However, the area of the epithelial diaphragm is maintained until the root is complete; then it disappears.

Multiple Roots

The roots of multirooted teeth develop in a fashion similar to those of single-rooted teeth until the furcation zone begins to form **(Fig. 5-27)**. Division of the roots then takes place through differential growth of the root sheath. The cells of the epithelial diaphragm grow excessively in two or more areas until they contact the opposing epithelial extensions. These extensions fuse, and then the original single opening is divided into two or three openings. The epithelial diaphragm surrounding the opening to each root continues to grow at an equal rate. When a developing molar is sectioned through the center of its root, it shows the root sheath as an island of cells **(Fig. 5-28)**.

As the multiple roots form, each one develops by the same pattern as a single-rooted tooth. After the root is complete and the sheath breaks up, the epithelial cells migrate away from the root surface as they do in a single-rooted tooth. Cementum then forms on the surface of the intermediate cemental surface. The cementum usually appears cellular, although the cementum near the cementoenamel junction is less cellular than that at the apices of the root **(Fig. 5-29)**. Because the apical cementum is thicker, it is said to require more cells to maintain vitality. The primary function of this cementum involves the attachment of the principal periodontal ligament fibers.

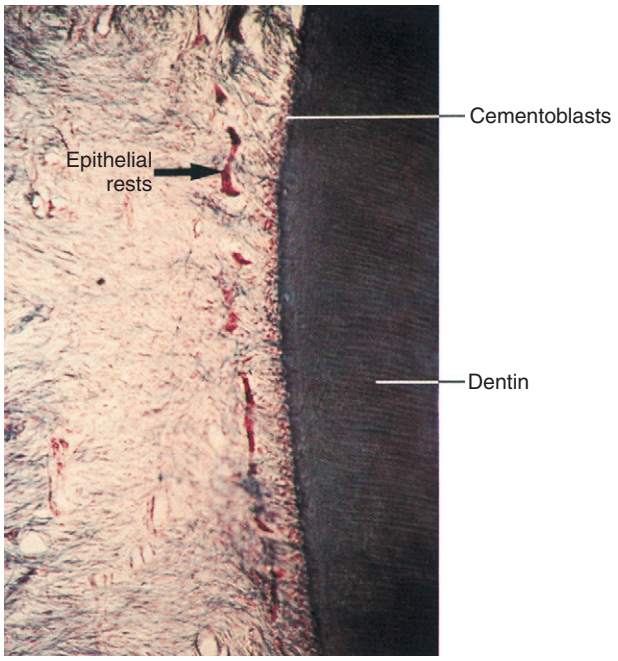


Fig. 5.25 Epithelial rests resulting from breakup of epithelial root sheath.

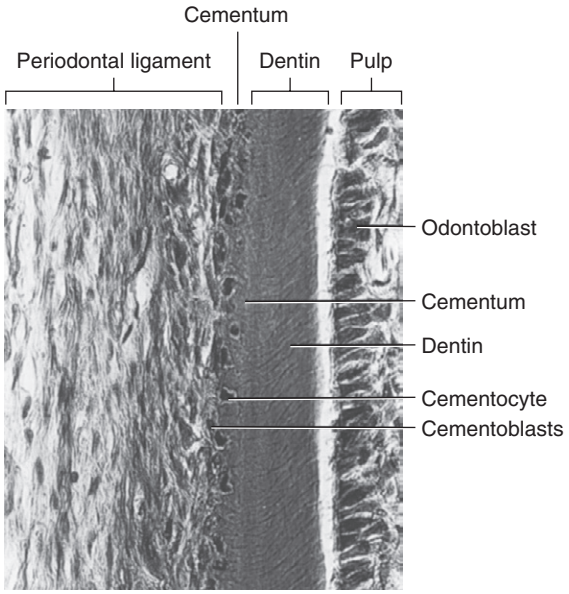


Fig. 5.26 Cementum formation on the root surface after breakup of the epithelial root sheath. Cementocytes can be seen on the surface as well as within the cementum.

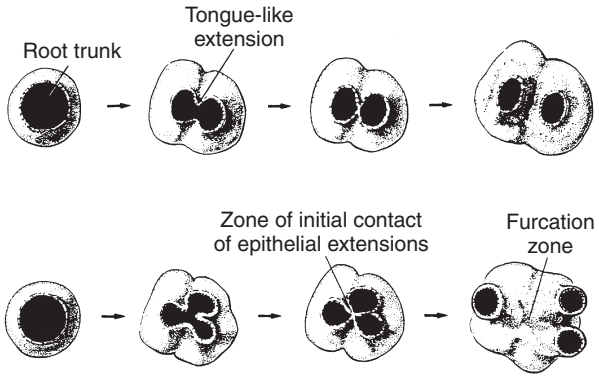


Fig. 5.27 Development of multirooted teeth. As the epithelial diaphragm grows, it may make contact and fuse to develop one-, two-, or three-rooted teeth.

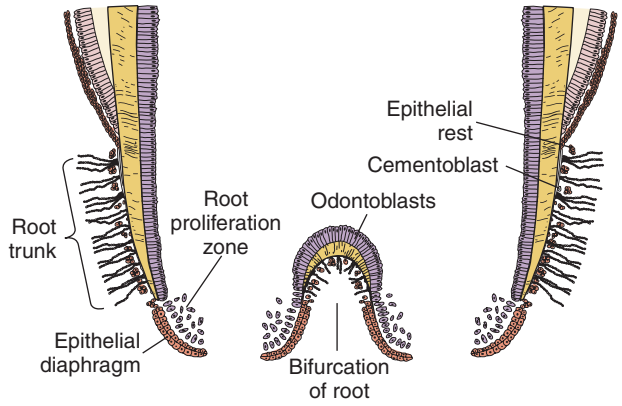


Fig. 5.28 Bifurcation root zone in multiple root formation. The root trunk is the junction area between the crown and the root bifurcation area.

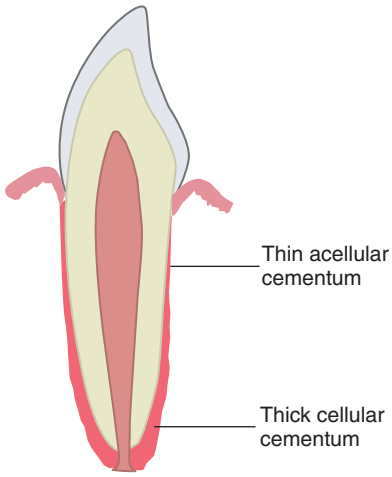


Fig. 5.29 Location of thin cementum on cervical area of root (younger individual) and additional apical cementum in an older individual.

DEVELOPMENT OF PRIMARY AND PERMANENT TEETH

Primary and permanent teeth develop very similarly, although the time needed for development of primary teeth is much less than for the permanent teeth. Primary teeth begin development in utero, and the crown undergoes complete mineralization before birth, whereas the permanent teeth begin formation at or after birth. In Figs. 6-1 and 6-2, the formation of the primary and permanent incisors is compared, as is the first primary second molar and the permanent premolar. Any prenatal systemic disturbance will affect mineralization of the primary tooth crowns, whereas postnatal disturbances may affect the permanent tooth crowns.

Primary teeth function in the mouth approximately 8.5 years; this period of time may be divided into three periods: crown and root development, root maturation and root resorption, and shedding of the teeth. The first period extends for about a year, the second for about 3.75 years, and the final stage of resorption and shedding lasts for about 3.5 years. In contrast, some of the permanent teeth may be in the mouth from the fifth year until death. One must also consider the permanent molars, which may be in the mouth only from the 25th year on until they are lost or death occurs. The permanent teeth may function seven or eight times as long as the primary teeth. This time of function of permanent teeth includes 12 years of development, 3 years longer than the primary teeth.

Many separate events occur within a few millimeters during development of the dentition. For a single primary tooth and its successor, an example of two possibly simultaneous events could be eruption with root formation of the primary tooth and mineralization of the crown of the permanent tooth. Other examples of complex events during this mixed dentition stage are root resorption of the primary tooth root and formation of the root of the permanent tooth. In a 6-year-old child, one or more of these formative processes may be occurring in up to 28 of 32 permanent teeth, while some degree of resorption is occurring in the 20 primary teeth. Timing and coordination of myriad events allow continual function within the growing jaws.

In addition to the formative events, the primary teeth undergo root resorption and pulp degeneration.

DEVELOPMENT OF SUPPORTING STRUCTURES

The mesenchymal cells surrounding the teeth are known as the *dental follicle (dental sac)* (see Fig. 5-7). Some of these follicular cells, which lie immediately adjacent to the enamel organ, migrate during the cap and bell stages from the enamel organ peripherally into the follicle to develop the alveolar bone and the periodontal ligament **(Fig. 5-30)**. These cells have been traced from this origin to the site where they differentiate into cementoblasts, osteoblasts that form the alveolar bone proper, or fibroblasts that form the principle fibers of the periodontal ligament. After tooth eruption, these tissues serve to support the teeth during function.

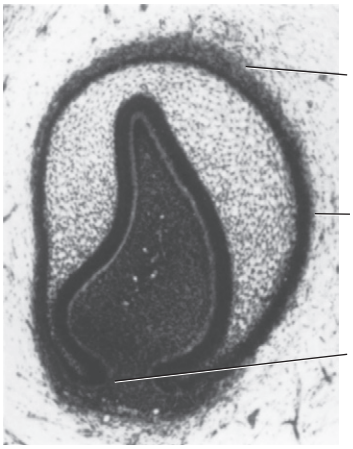


Fig. 5.30 Histology of enamel organ at time of cervical loop development. At this time, mesenchymal cells develop adjacent to the enamel organ on the external surface of the developing enamel organ and differentiate into follicular cells.

Periodontal Ligament

Cells of the dental follicle differentiate into collagen-forming fibroblasts of the ligament and cementoblasts, which synthesize and secrete cementum on surface of the tooth roots. Some cells of the ligament invade the root sheath as it breaks apart. Other cells of the ligament area form delicate fibers, which appear along the forming roots near the cervical region of the crown. These are probably the stem cell fibroblasts that form the principle fiber groups, which appear as the roots elongate **(Fig. 5-31)**. As these fibers become embedded in the cementum of the root surface, the other end attaches to the forming alveolar bone. Evidence suggests that these fibers turn over rapidly and are continually renewed as the location of origin is established. Collagen fiber turnover takes place throughout the ligament, although the highest turnover is in the apical area and the lowest is in the cervical region. Maturation of the ligament occurs when the teeth reach functional occlusion. At this time, the density of fiber bundles increases notably.

Alveolar Process

As the teeth develop, so does the alveolar bone, which keeps pace with the lengthening roots. At first, the alveolar process forms labial and lingual plates between which a trench is formed where the tooth organs develop. As the walls lining this trench increase in height, bony septa appear between the teeth to complete the crypts **(Fig. 5-32)**. When the teeth erupt, the alveolar process and intervening periodontal ligament mature to support the newly functioning teeth **(Fig. 5-33)**. Bone that forms between the roots of the multirooted teeth is termed **interradicular bone.** In the mature form, alveolar bone is composed of **alveolar bone proper** and **supporting bone.** Alveolar bone proper lines the tooth socket, sustained by supporting bone, which is composed of both spongy and dense or compact bone **(Fig. 5-34)**. Supporting bone forms the cortical plate, which covers the mandible. The interactions of the tooth with the surrounding alveolar bone is necessary, because if the tooth is lost, the bone will resorb. The exact biological mechanisms are unknown.

In summary, tooth development involves the interactive events of two types of tissues: epithelial and mesenchymal. These tissues develop through the soft-tissue stages of bud, cap, and bell. This level is followed by the hard-tissue formative stages of dentinogenesis and amelogenesis. Root formation logically follows crown development. Each developmental progression includes morphologic changes in shape and size that are coordinated with microscopic changes in cell shape and function. Most of these relationships are seen in **Fig. 5-35**.

CLINICAL COMMENT

Accessory root canals may connect the pulp with the periodontal ligament at any point along the root, although it usually appears near the root apex. Pulp or periodontal infection can spread by means of this route to the adjacent tissue. A periodontal pocket that is resistant to treatment could be caused by this defect.

CLINICAL COMMENT

Dentinogenesis imperfecta is an autosomal dominant genetic disorder of tooth development which often makes the teeth susceptible to excessive wear. It can affect the primary and permanent teeth with an incidence of between 1 in 6000 to 1 in 8000 people. Current evidence suggests this disorder is caused by a mutation in the gene that produces dentin sialophosphoprotein (DSPP), a substance necessary for the proper mineralization of dentin by the odontoblasts.

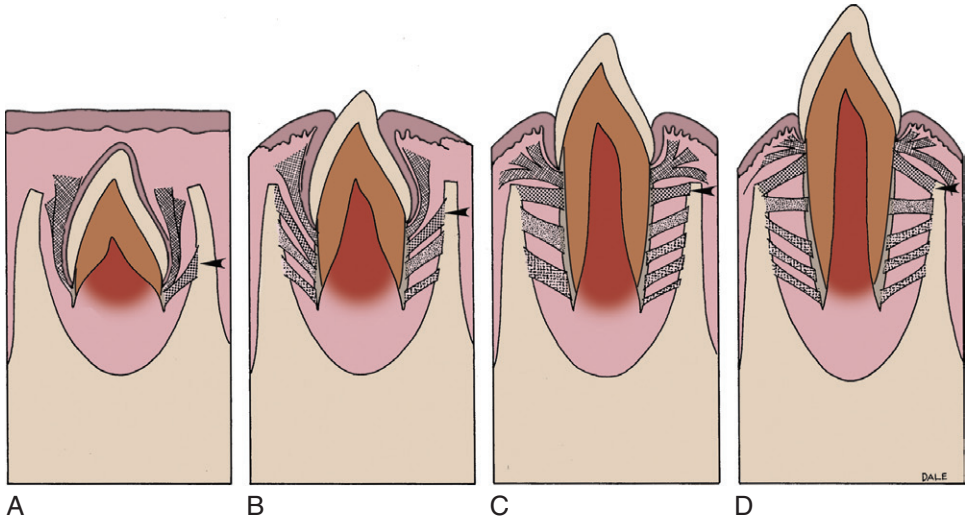


Fig. 5.31 Development of principal fibers of the periodontal ligament. A, Initial fiber development during preeruptive movements. **B,** Secondary fiber development below alveolar crest as tooth moves into prefunctional occlusion. **C,** Further fiber development and maturation of the principal fibers and the gingival group of fibers occurs when the tooth reaches towards functional occlusion. **D,** Although the apical foramen is still open at this point the principal fibers of the PDL and gingival group are full formed enabling the tooth, the PDL and the alveolar bone proper to react to the stresses of the maturing individual including the larger muscles of mastication and concomitant increased occlusal forces. *(From Nanci A:* Ten Cate's oral histology, *ed 8, St. Louis, 2013, Mosby.)*

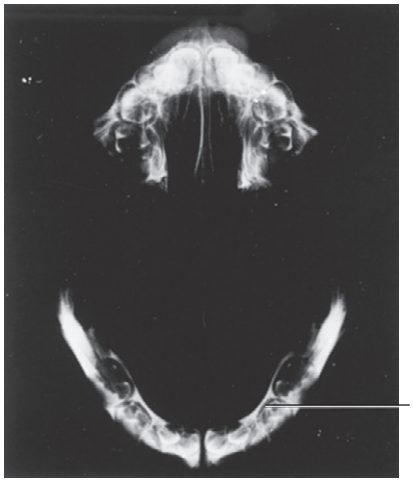


Fig. 5.32 Microradiograph of maxillary and mandibular arches showing alveolar bone and primary tooth crypts enclosing developing teeth.

Fig. 5.33 Developing periodontal ligament fibers. Density of fibers similar to *C* in Figure 5-31.

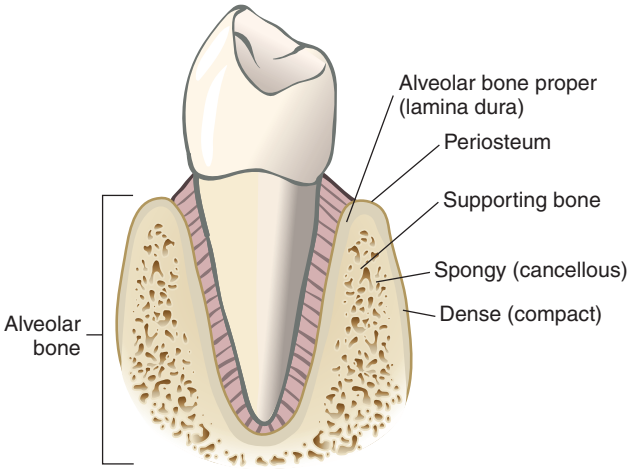


Fig. 5.34 Tooth in alveolar bone. Alveolar bone is composed of alveolar bone proper, which lines the socket, and supporting bone, which consists of spongy or cancellous bone and compact bone.

CONSIDER THE PATIENT

Discussion: White, chalky areas in the cervical enamel of some crowns are caused by a lack of mineralization of the enamel. The chalkiness occurs in this location because this is the last area of the crown to calcify, and sometimes the crown erupts before the cervical enamel has completely mineralized.

Self-Evaluation Questions

1. What two cell types interact in tooth development?
2. Describe two characteristics of the bell stage of tooth development.
3. List and describe each stage of tooth development.
4. Describe the dental papilla. When does it become the dental pulp organ?
5. Describe the differentiation of the odontoblast and the initiation of dentin formation.
6. Why is dentinogenesis called *the two-phases process?*
7. What are the five phases of enamel production?
8. What structures enable the ameloblasts to move in a row rather than individually during enamel production?
9. What areas of enamel are first and last to calcify in the crown?
10. What two processes signal enamel completion?

ACKNOWLEDGEMENTS

Dr. Nicholas P. Piesco and Dr. N.M. EINesr contributed to the production of chapters in Avery JK: *Oral development and histology,* ed 3, Stuttgart, 2002, Thieme Medical. Some of the figures in that text have been used in preparation of this chapter.

QUANDARIES IN SCIENCE

Neural crest cells (NCCs) contribute to many structures in the oral-facial complex from development through adulthood and have a major role in tooth development. Before the neural tube fuses to form the spinal cord, NCCs begin to migrate on predetermined pathways to aggregate under specific areas of the oral ectoderm that have high concentrations of specific homeobox genes, where they interact with the ectoderm to initiate tooth development through a complex series of well-orchestrated epithelial-mesenchymal interactions and end in a functional tooth and supporting apparatus. However, at times deficits can occur such that the teeth do not develop or there are multiple copies of the same tooth. Science is just beginning to understand the genetic basis for many of the anomalies associated with tooth development, but many developmental processes are still enigmatic. For example, the sequence of growth factors, transcription factors, and genes for inducing tooth development is the same as for inducing hair, mammary and salivary glands, and more. What type of molecule or signaling event is critical for just tooth induction is still a mystery and presently unanswered, although many candidates have been suggested.

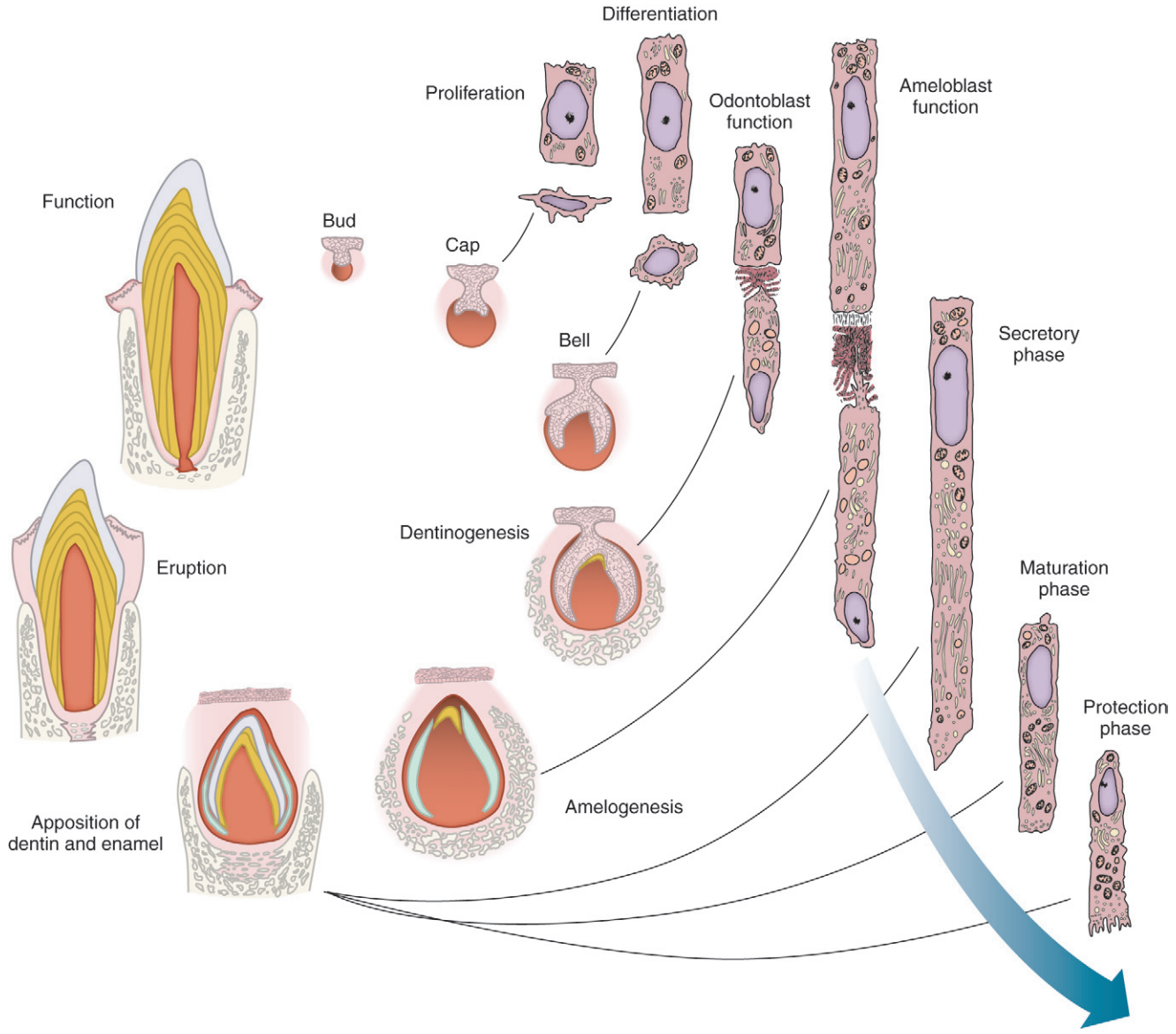


Fig. 5.35 Changes in formative cells of developing teeth shown on the right and correlated with morphologic changes of tooth organ on the left. Cell proliferation relates to the cap stage, whereas cell differentiation relates to the bell stage. Odontoblast function relates to dentinogenesis and ameloblast function to amelogenesis. The labels *Secretory phase, Maturation phase,* and *Protection phase* relate to ameloblast function.

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