Enamel: Composition, Formation, and Structure
Enamel

The enamel is creating form the first element of dental germ - enamel organ.

The cells responsible for the formation of enamel are ameloblasts.

They are lost as the tooth erupts, and hence enamel cannot renew itself.
Compensation

- To compensate for this inherent limitation, enamel has acquired a complex structural organization and a high degree of mineralization.

- These characteristics reflect the unusual life cycle of the enamel-forming cells, the ameloblasts.
Amelogenesis
This is the process of enamel formation
The amelogenesis begins after the final differentiation of the ameloblasts. The differentiation is a result of several changes in the enamel organ and the dental papilla. They stimulate the differentiation of preameloblasts into ameloblasts.
The preameloblasts begin to grow in height and turn into cylindrical cells.

The mitotic activity stops its division, but intracellular differentiation occurs.

The endoplasmic reticulum, Golgi apparatus, and mitochondria change are developing.

The preameloblasts receive signal stimulation from the dental papilla.

Until now, the source of the nutrients for preameloblasts has been dental papilla, since as a mesodermal tissue, it has blood vessels.

This transport occurs through the basal lamina between the enamel organ and the dental papilla.
The development of tooth structures is the result of complex and continuous mutual stimulation between the epithelial and ectomesenchymal cells.
Changes in the dental papilla

- Preameloblasts are the inner layer of the enamel organ.
- The preodontoblasts are situated in the periphery of the dental papilla. Between them is the basal lamina.
- The first is to differentiate the odontoblasts that will form dentin.
- They develop an outgrowth that connects to the dividing membrane between the ectoderm and the mesoderm, called membrane limitation.
- Cells form protoplasmic outgrowths, one of which is dominant.
- They attach to the dividing membrane. Some of them rupture this membrane and enter between the pre ameloblasts in the enamel organ to effect direct stimulation.
Formation of the dentin-enamel junction (DEJ)

- It is building on membrana limitans. The disintegration of the basement membrane allows the preameloblasts to come into contact with the newly formed predentin.
- This induces the preameloblasts to differentiate into ameloblasts.
- Ameloblasts begin deposition of enamel matrix.
- Pre odontoblasts and ameloblasts deposit an organic matrix that begins to mineralize.
- Then the odontoblasts begin production of very thin dentine, which is sufficient to stop nutrients from the dental papilla to the pre ameloblasts.
Changes in enamel organ

- Changing the food source is the main reason for the further differentiation of preameloblasts.
- They need to look for a new source of nutrients.
- The other closest source of mesoderm that has blood vessels in the tooth follicle is around the outer enamel epithelium of the enamel organ.
- Because the distance to the preameloblasts is very long, several changes occur:
Folding the outer cuboidal epithelium

- Many folds of this layer are forming, into which the blood vessels from the dental follicle are entering.
- The distance to the ameloblasts is reducing.
- Ameloblasts are enlarging and withdrawal from the dividing membrane.
- The preameloblasts increase in height to reach the source of the nutrients.
- At the same time, they move away and are forming the space between the preameloblast and the membrane.
Intracellular organelles of the ameloblasts are changing its positions

- The cell nucleus and the Golgi apparatus are replacing.
- Now the cell`s base is at the outer enamel epithelium and the distal end is at the dentin-enamel junction.
Formation of Tomes` process

- With the withdrawal of the ameloblasts to the outer enamel epithelium, the cells are extending to its lower end.
- This extension is called the Tomes` process and is the secretory part of the cell.
The stages of the amelogenesis

- Amelogenesis is a three-step process.
  - The first step is enamel matrix formation - 20-30% mineral content;
  - The second step is a process of mineralization;
  - The third is a maturation - after the full width of enamel has been deposited. This process includes a significant influx of additional mineral content, removal of the majority of organic material, water, and transformation of the remaining organic matter.
Ameloblasts

- Ameloblasts secrete matrix proteins and are responsible for creating extracellular environment favorable to mineral deposition;

- Ameloblasts exhibits a unique life cycle characterized by progressive phenotypic changes that reflect its primary activity at various times of enamel formation.
The ameloblasts are ectodermally derived cells;

In the process of tooth formation, they differentiate as a nice neat row of cells around the future "outside" of the tooth.

The ameloblasts require an inductive stimulus from the embryonic connective tissue just at the top of this field.
Life cycle of ameloblasts consists of six stages:

- Morphogenic stage;
- Organizing stage;
- Formative (secretory) stage (Tome's processes appear in secretory stage);
- Maturative stage;
- Protective stage;
- Desmolytic stage.
Phases of the amelogenesis:

- Amelogenesis has been described in as many as six phases but generally is subdivided into three main functional stages:
  - Presecretory stage;
  - Secretory stage;
  - Maturation stage.
1. Presecretory stage

- Differentiating ameloblasts acquire:
  - their phenotyp;
  - change polarity;
  - develop an extensive protein synthetic apparatus;
  - and prepare to secrete the organic matrix of enamel.
Morphogenetic Phase of the Presecretory Stage

- During the bell stage, the shape of the crown is determined.
- Cells of inner epithelium are separated from dental papilla by a basement membrane.
- They are cuboidal or low columnar, with large, centrally located nuclei, poorly developed Golgi elements in the proximal portion of the cells (facing the stratum intermedium).
Differentiation Phase of the Presecretory Stage

- As the cells of the inner epithelium differentiate into ameloblasts, they elongate, and their nuclei shift proximally toward the stratum intermedium.

- The basement membrane is fragmenting by cytoplasmic projections of odontoblasts and disintegrates during mantle predentin formation.

- This is the reason for the final stimulation of the ameloblasts by the odonoblasts.
Changes in the Dental Papilla

- Superficial cells are differentiating into odontoblasts. The odontoblasts secrete an organic matrix.
- They mineralize it to form the first layer of dentin.
Changes in the enamel organ

- When differentiation of the ameloblasts occurs, the dentin starts forming.
- A thin but mineralized barrier under the ameloblasts is forming.
- It stops the nutrients from the dental papilla to ameloblasts.
- The other closest source for nutrients is the dental follicle.
- Compensation for this distant vascular supply is achieved by blood vessels invaginating the outer dental epithelium.
- And by the loss of intervening stellate reticulum, which brings ameloblasts closer to the blood vessels.
Secretory stage

- As the ameloblast differentiates, the matrix is synthesizing within the RER, which then migrates to Golgy`s apparatus, where it is condensed and packaged in membrane-bound granules.
- Vesicles migrate to the apical end of the cell. Their contents are exteriorized and are deposited first along the DEJ.
- This first enamel deposition on the surface of the dentin establishes the dentin-enamel junction. In each cell, the Golgi complex and rough endoplasmic reticulum increases and migrated distally.
- A second junctional complex, called the terminal bar apparatus, develops at the distal extremity of the cell, dividing the ameloblast into the body and a distal extension, called Tomes’process.
- The dentin-enamel junction (DEJ) is forming. A small dentinal layer is forming, too. The content of the secretory granules is releasing over the newly formed mantle dentin.
Tall columnar ameloblasts like cells showing nuclear palisading.
Changes in the enamel organ

When differentiation of the ameloblasts occurs and dentin starts forming, these cells are distanced from the blood vessels that lie within the dental papilla;
* Compensation for this distant vascular supply is achieved by blood vessels invaginating the outer dental epithelium;
* And by the loss of intervening stellate reticulum, which blings ameloblasts closer to the blood vessels.
Vascular supply

- Compensation for this distant vascular supply is achieved by blood vessels invaginating the outer dental epithelium;
- And by the loss of intervening stellate reticulum, which blings ameloblasts closer to the blood vessels.
Superficial cells differentiate into odontoblasts; the odontoblasts secrete an organic matrix; they mineralize it to form the first layer of dentin; Changes in the Dental Papilla.
Presecretory stage

- Ameloblasts
- Forming enamel
- Odontoblasts
- Forming dentin
- Forming pulp cavity
Amelogenesis

I. Initial matrix formation

- Ameloblast
- Stippled matrix
- Dentinal surface

The pre-ameloblasts move from the surface of the dentine and secrete matrix via secretory vesicles.

II. Formation of the Tomes process and early crystallization

- Tomes process
- Newly formed matrix
- Crystallization

After a thin layer of matrix has been secreted, the Tomes process forms and crystallization commences. The ameloblasts move away from the dentine.
In each cell the Golgi complex and rough endoplasmic reticulum increases and migrated distally;

A second junctional complex develops at the distal extremity of the cell, dividing the ameloblast into body and a distal extension called Tomes’ process, against enamel forms;
Ameloblast

- The ameloblasts elongate and are ready to become active secretory cells;

- Short conical Tomes` process develops at the apical end;

- Junctional complexes called the terminal bar apparatus appear at the junction of the cell bodies and Tomes` processes and maintain contact between adjacent cells.
The cell nucleus moved to the opposite end towards stratum intermedium;

Thus ameloblast becomes a polarized cell, with the majority of its organelles situated in the cell body distal to the nucleus
The Dentinoenamel junction is forming; A small dentinal layer is formed; Invagination of the outer dental epithelium.
Hand-points indicating Tome's process of ameloblasts.

- The content of the secretory granules is released against the newly formed mantle dentin along the surface of the process;
Scanning electron microscope image of the developing enamel secretory ameloblasts

- Separated ameloblasts;
- A honeycomb-like appearance with repetitive ridges and hollows is evident;
- Each hollow is a footprint of an ameloblast’s Tomes’ process that is responsible for the secretion of the extracellular matrix;
- Individual enamel crystallites can be seen.
The disintegration of the basement membrane allows the preameloblasts to come into contact with the newly formed predentin.

This induces the preameloblasts to differentiate into ameloblasts. Ameloblasts begin deposition of enamel matrix.
Ameloblasts;
The cell nucleus moved towards stratum intermedium;
The ameloblasts elongate; As the initial enamel layer is formed, ameloblasts migrate away from dentin.
Structureless enamel is forming on the mantel dentin

- The initial layer of enamel does not contain enamel rods.
- Little if any time elapses between the secretion of the enamel matrix and its mineralization.
Structureless enamel has formed on the mantle dentin.
- Junctional complexes called the terminal bar apparatus appear;
- The sites where enamel proteins are released extracellularly can be identified by the presence of abundant membrane infolding.
Tomes` process

Tomes' process

Ameloblast
Secretory stage

Secretion of enamel matrix becomes to two sites:

- The first site is on the proximal part of the process, close to the junctional complex, around the periphery of the cell;

- Secretion from this site, results in the formation of enamel portion that delimit a pit in which resides the distal portion of Tomes` process. This is called interrod enamel;

- Secretion from the second site (along the face of the distal portion of the Tomes` process) later fills this pit with matrix that regulates formation of the so-called rod enamel.
The ameloblasts develop the distal portion of Tomes` process as an outgrowth of the proximal portion.
The ameloblasts produce enamel rods. These rods have a cross-sectional shape reminding about a key.
Formation of interrod enamel is always a step ahead because the interrod enamel must delimit the cavity into which rod enamel is formed;

At both sites the enamel is of identical composition, and rod and interrod enamel differ only in the orientation of their crystallites;

The distal Tomes` process, creating a narrow space along most of the circumference between rod and interrod enamel that fills with organic material and forms the rod sheath.
The proximal portion of Tomes' process (ppTP) extends from the junctional complex to the surface of the enamel layer, whereas the more distal portion (dpTP) penetrates into enamel.
- Interrod enamel (IR) surrounds the forming rod (R) and the distal portion of Tomes` process (dpTP);
- This portion is the continuation of the proximal portion (ppTR) into the enamel layer;
- The interrod (IGS) and rod (RGS) growth sites are associated with membrane infolding (im) on the proximal and distal portion of TP;
- These foldings represent the sites where secretory granules (sg) release enamel proteins.
The way of enamel and dentin formation

The enamel is formed in the space provided by the enamel organ; The dentin is formed in the space provided by dental papilla.
Ameloblasts are cells which secrete the enamel proteins enamelin and amelogenin which will later mineralize to form enamel on teeth; each ameloblast is approximately 4 micrometers in diameter, 40 micrometers in length and has a hexagonal cross section; the secretory end of the ameloblast ends in a six-sided pyramid-like projection known as the Tomes' process.
Appositional stage of tooth development. During this stage of tooth development, both enamel and dentin are actively secreted until the crown is complete.
Enamel matrix

- Present in small quantities.
- It’s difficult to investigate.
- As gel-like which crystal is deposited.
- It composed large variety of amino acids.
- It can flow under pressure from the growing crystal.
The nature of enamel matrix
Early enamel matrix contain:

- 65% of water;
- Proteoglycans (small amount);
- Glycosaminoglycans;
- Lipid;
- Citrate;
- Inorganic ion (small percentage);
The organic matrix of enamel is made from non collagenous proteins only and contains several enamel proteins and enzymes.

Enamel proteins are:

- Amelogenins;
- Ameloblastins;
- Enamelin;
- Tuftelin.
The organic material forms a heterogeneous mixture, divided into two

- **Amelogenins** have large amount of histidine, proline, leucine, glutamic acid and absent hydroxyproline, hydroxylysine, and cystine.

- **Enamelins** contain less proline, glutamic acid, and histidine compared to amelogenins, while it contain greater glycine (enamel is devoid of both collagen and keratin).
- Vesicles in the ameloblasts filled with amelogenin;
- The red areas contain amelogenin.
Amelogenins

- 90% of the enamel proteins are a heterogeneous group of low-molecular-weight proteins known as amelogenins;
- Amelogenins are hydrophobic proteins rich in proline, histidine, and glutamine;
- They accumulate during the secretory stage;
- Undergo minor short-term and major long-term degradation;
- Regulate growth in thickness and width;
- May also nucleate crystals.
Taftelin

- This is a new, previously unknown acidic enamel protein;
- Believed to play an important role in enamel mineralization;
- In the C-terminal sites have their structures facilitating self-assembly and crystal formation.
- Self-assembly to form the supramolecular structural framework
The major extracellular events involved in enamel formation are:

- (a) delineation of space by the secretory ameloblasts and the dentino-enamel junction;
- (b) self-assembly of amelogenin proteins to form the supramolecular structural framework;
- (c) transportation of calcium and phosphate ions by the ameloblasts resulting in a supersaturated solution;
- (d) nucleation of apatite crystallites;
- (e) elongated growth of the crystallites.
II. Mineralization of the enamel matrix

- As enamel matrix is completed and amelogenin is deposited, the matrix begins to mineralize;
- 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 total enamel;
- The other 70% of mineral in enamel is result of growth of the crystals (5% of enamel is water).
The enamel organ cells during amelogenesis

- Amelogenesis is divided into the secretory stage and the maturation stage, being separated by a short period of morphological and functional transitions of ameloblasts (transitional stage).
- During the long-lasting process of enamel maturation, ameloblasts cyclically change structure and function between ruffle-ended ameloblasts (RA) and smooth-ended ameloblasts (SA).
- Here the enamel organ also comprises the papillary layer (PL) being deeply invaginated by a capillary network.
During the ‘maturation’ step:

- Rapid growth and thickening of the crystallites take place, which is concomitant with progressive degradation and eventual removal of the enamel extracellular matrix components (mainly amelogenins).
- This latter stage during which physical hardening of enamel occurs is perhaps unique to dental enamel.
Maturation stage

Starting with the initial mineralization:
- Formation of crystals;
- Arranged in prisms;
- Forming enamel prisms cross-architecture;

Mineralization continues:
- Increasing amounts of minerals;
- Increasing the size of the crystals;
- Maturation of crystals.

Maturation of the organic matrix.
Mineralization and maturation of enamel.

- Two mineralization occurred:
  - **Primary mineralization**: deposited enamel matrix, needle shaped crystals appear after deposition of thickness, 50 nm of matrix initially thin widespread dispersed, rapidly increase in size and become hexagonal.
  - **Secondary mineralization**: occurs at amelo-dentinal junction, rapid process, cannot be easily distinguish from initial phase, enamel are transformed from soft material into hard substance, large quantities inorganic material deposited in matrix
A. Enamel crystals to a distal portion of Tomes` process. The elongating extremity of the rod crystals about the infolded membrane (im) at the secretory surface; B - In cross section, newly formed crystals appear as small, needle-like structures surrounded by granular organic matrix. Secretory granules (sg).
The time between enamel matrix deposition and its mineralization is short; the first matrix deposited is the first enamel mineralized, occurring along the dentinoenamel junction. Matrix formation and mineralization continue peripherally to the tips of the cusps and then laterally on the sides of the crowns, following the enamel incremental deposition pattern. Finally, the cervical region of the crown mineralizes.
Initial mineralization

- Arrangement of crystals in the rods;
- Lengthwise jointing of the crystals;
- Crossing the rods.
Growth of cusps to predetermined point of completion
Growth and mineralization along the side of a tooth.

Daily growth front:
At regular intervals, these growth fronts become more prominent and are termed Striae of Retzius.

Cross-striations:
Lines formed by connecting daily intervals of adjacent enamel prisms. Typically less evident than Striae of Retzius.

Outer surface of tooth:
Where striae of Retzius contact the surface, perikymata may be visible.

Occlusal Surface  Root
Incremental pattern of enamel and dentin formation from initiation to completion

- Initial dentin deposition
- Enamel increment
- Dentin increment
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.
Mineralization

- After the initial primary mineralization starts fast secondary and tertiary mineralization;
- Mineralization starts from the top of the crown and go laterally to the cervix.
Maturation of the matrix

- After the full thickness of immature enamel has formed, ameloblasts undergo significant changes in preparation for their next functional role, that of maturing enamel;
- At this stage, they change shape and size;
  - A brief transitional phase involving a reduction in height and decrease in their volume and organelle content occurs;
  - They lose Tomes` process;
- During this stage, ameloblasts undergo programing cell death (25% during the transitional phase and 25% die as enamel maturation proceeds);
- The initial ameloblast population thus is reduced by roughly half during amelogenesis.
Maturation Proper

- The ameloblasts become involved in the removal of water and organic material from the enamel;
- Additional inorganic material is introduced;
- The dramatic activity of ameloblasts is modulation, the cyclic creation, loss, and recreation of a highly invaginated ruffle-ended apical surface;
- The modulation seem to be related to calcium transport and alterations in permeability of the enamel organ;
- This process continuously alkalize the enamel fluid to prevent reverse demineralization of the growing crystallites and maintain pH conditions optimized for functioning of the matrix degrading enzymes.
The ameloblasts cyclically change between RA and SA. The present model assumes that ameloblasts and papillary cells (PL) act as a functional syncytium allowing free diffusion of ions via the numerous connected gap junctions. Carbonic anhydrase (CA II or other isoforms) together with vacuolar $\text{H}^+$-ATPase, acidified enamel surface (ES) in the RA stage. *In SA cells, they preclude this acidification and the intercellular spaces between SA cells open toward the enamel surface. This allows acidified, decomposed enamel matrix proteins (DEMP) to escape from the bulk enamel and neutralize the enamel surface. bl, Basal lamina.
Secretory stage of enamel formation

Early maturation

Late maturation

Protection

Amelogenin and H$_2$O

Ca$_2$(PO$_4$)$_6$
After the mineralization occurs:

- Maturation of enamel is remarked by loss of water from matrix.
- Final stage of maturation:
  - Loss of Tomes process;
  - Mitochondria aggregate will increase in acid phosphate activity;
  - Many enzyme undergo catabolic activity;
  - Ameloblast degrade material is selective withdrawn from maturing enamel;
Ameloblasts in the maturation

- Its terminal bar apparatus desappears, and the surface enamel becomes smooth;
- This phase is signaled by a change in the appearance of the cell as well as by change in the function of the ameloblasts;
- The apical end of this cell becomes ruffled along the enamel surface.
1. Ruffle-ended maturation stage;
2. Smooth-ended maturation stage.
Final function of the ameloblasts

- The ameloblasts shorten and contact the stratum intermedium and outer 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.
Apex to apex junction between the outer enamel epithelium and the inner enamel epithelium or ameloblasts.
Reduced enamel epithelium and enamel cuticle

- Last phase of ameloblast function;
- After enamel formation completed, before tooth erupts, ameloblast shorten to cuboidal cell form the inner component of reduced enamel epithelium called Nasmyth’s membrane.
- It is a homogenous layer over enamel surface described as thin layer of unmineralized enamel matrix called primary enamel cuticle.
- Secondary enamel cuticle occur before tooth eruption - a basal lamina type junctional region between inactive ameloblast, enamel surface and oral mucosa.
Reduced enamel epithelium

- Following the formation of the crown, the enamel organ collapses to form the **reduced enamel epithelium** which covers the tooth through eruption.

- The reduced enamel epithelium consists of the **mature/protective ameloblasts** and remanants of the outer layers of the enamel organ.

- Numerous **capillaries**, which had formed to supply oxygen and nutrients to the ameloblasts following dentin formation, surround the reduced enamel epithelium.

Legend: A, Reduced enamel epithelium; B, Maturative/protective ameloblasts; C, Capillary
Different stages of development of the enamel

1. morphogenetic stage; 2. histodifferentiation stage; 3. initial secretory stage (no TP); 4. secretory stage (TP); 5. ruffle-ended ameloblast; 6. smooth-ended ameloblast; 7. protective stage.
Ruffled border of ameloblasts attaches to the basal lamina by means of hemidesmosomes (HD)
Four phases of enamel mineralization.
Protein changes in the enamel

- Amelogenins and ameloblastins are removed from the newly formed enamel;
- In the enamel remain enamelinns and taftelins;
- At the end of maturation the enamel is completely mineralized.
Immature enamel

The red areas indicate partially mineralized enamel.
Theories for the mineralization of the enamel

- Various theories which explains mechanism of mineralisation:
  1. Booster mechanism;
  2. Seeding mechanism/nucleation theory;
  3. Matrix vesicle concept.
- Epitaxy theory
- Nanosphere theory - 1994 г. - Fincham;
- Confirmed by Du and Fallini in 1998 г.;
1. Booster mechanism

- According to this mechanism, due to the activity of certain enzymes the concentration of calcium and phosphate ions would raise further leading to precipitation.
Robinsons alkaline phosphatase theory based on Booster mechanism

- The discovery of enzyme alkaline phosphates in mineralizing tissues suggests that this enzyme is responsible for mineralisation.
Mechanism

- Alkaline phosphatase releases inorganic phosphates from organic phosphates (hexose phosphates) and thus raise locally the concentration of phosphate ions in the tissue fluid which reacts with calcium ions in tissue fluid leading to precipitation of insoluble calcium phosphate.

- This theory is not well accepted.
2. Seeding mechanism

- According to this mechanism, there are certain substances called seeding or nucleating having resemblance to apatite.
- These substances act as mold or template upon which crystals are laid down, after which crystallization proceeds automatically.
- This process is known as epitaxy.
3. Matrix vesicle concept

- Matrix vesicles were discovered simultaneously by Anderson and Ermanno Bonucci;
- Matrix vesicles (MV) are organelles of cellular origin that can be observed in the ameloblasts;
- Histochemical and biochemical studies have shown that matrix vesicle contain most of these substances that are believed to play a role in calcification process, esp AlkPh and related enzymes.
4. Nanosphere theory of mineralization of enamel

- Enamel biomineralization involves secretion of the enamel specific amelogenin proteins that through self-assembly into nanosphere structures provide the framework within which the initial enamel crystallites are formed.
Amelogenins have the remarkable spontaneous self-assembly and hierarchical organization of amelogenin ‘microribbons’ and their ability to facilitate oriented growth of apatite crystals.
Secretion

Aggregation of bipolar amelogenin molecules:

24kDa Amelogenin

Aggregates associate with HAP crystallites controlling growth

Core-polypeptides are released

HA crystallite nucleated at DEJ
Amelogenins are organized in "nanospheres"
Self-assembly and hierarchical organization of amelogenin in ‘micro ribbons’ and oriented growth of apatite crystals.
First occurrence of enamel crystals
Structural and Organizational Features of Enamel
Morphology of enamel

1. Enamel rods;
2. Enamel interrod space;
3. Rod sheath;
4. Striae of Retzius;
5. Bands of Hunter and Schreger;
6. Cross-striation of the rods;
7. Gnarled enamel;
8. Enamel Tufts and lamellae;
9. Dentinoenamel junction and enamel spindles;
10. Enamel surface.
Enamel rod structures

- Enamel is composed of rods that extend from DEJ, to the enamel outer surface;
- 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 four ameloblasts.
Cross-section of the rods

- **A** - rod - a package of tightly arranged crystals;

- **B** - Interrod space - packaged crystals lose their shape and go in different directions;

- **C** - Tail of the rod;

- **D** - Head of the rod.
- One ameloblast (1) forms the rod head;
- A part of two ameloblasts forms the neck (2 and 3);
- And the tail is formed by four ameloblasts (1, 2, 3, 4);
Crystal orientation of the rods

- In the rods - longitudinally;
- In the tail - diagonally or perpendicular (lower mineralization);
- The rod sheats - the least mineralized place. There the crystals are meeting with different directions.
- The rod has keyhole-shape form.
The rod is columnar in its long axis

- The head is the broadest part at 5 µm wide;
- Elongated thinner portion, or tail, is about 1 µm wide;
- The rod, including both head and tail, is 9 µm long;
- The rod is about the same size as a red blood cell.
Longitudinal section of the enamel

- A- A cross section of the crystals forming the interrod space;
- B- longitudinally arranged cristals in the rod core;
Enamel rods interlock to prevent fracture and splitting of the tooth.

Enamel rod groups also intertwined, thereby preventing separation;

The rod direction in the crown is normally perpendicular to the enamel surface which provides additional support in preventing.
Different groups of crossing rods
Cross section of the rods

- Enamel rods appear wavy;
- It can be seen keyhol-shape form of the rods.
- The surface of each rod is known as the rod sheath;
- The rod center is the core;
- The rod sheath contains slightly more organic matter than the rod core.
Direction of the rod

- Rods form nearly perpendicular to the DEJ and curve slightly toward the cusp tip;
- This unique rod arrangement also undulates throughout the enamel surface;
- Each rod interdigitates with its neighbor, the head of one rod nestling against the neck of the rods to its left and right;
- The rods run almost perpendicular to the enamel surface at the cervical region;
- Near to the cusp tips they are gnarled and intertwined.
The diagram shows orientation of crystals in the forming rod Head and tail;

And forming crystals pack in the rod from the cell complex.
One rod is pulled out to illustrate how individual enamel rods interdigitate with neighboring rods.
Orientation of crystals in a mature enamel rod as indicated by cross section and side of cut rod.
Striae of Retzius

- In a longitudinal section of the tooth, they are seen as a series of dark lines extending from the dentinoenamel junction toward the tooth surface;
- They are ascribed to a weekly rhythm in enamel production resulting in a structural alteration of the rod;
- Another proposal suggests that they reflect appositional or incremental growth of the enamel layer;
Striae of Retzius in a cross section

- In cross section they appear as concentric rings;
When present, is an enlarged striae of Retzius that apparently reflects the great physiologic changes occurring at birth;

Accentuated incremental lines also are produced by systematic disturbances that affect amelogenesis.
Lungitudinal section of enamel

- The enamel rods and striae of Retzius are seen.
Cross Striations

- Human enamel is known to form at a rate of approximately 4 µm per day;
- Ground sections of enamel reveal what appear to be periodic bands or cross striations at 4-µm intervals across so-called rods.
Undulating (wavy) rods

- In the cross section of the rods they are differently cut because their wavy course;
- One part is cut longitudinally, another - transversely;
- The phenomena of light and dark - (photomicrograph) Hunter-Schreger bands.
Bands of Hunter and Schreger

- They are optical phenomenon produced by changes in direction between adjacent groups of rods;
- They are seen most clearly in longitudinal sections viewed in the inner thirds of the enamel.
Enamel rods

Cross section of the rods

Longitudinal section of the rods
Bands of Hunter and Schreger
Gnarled enamel

- Near the DE junction especially in the cuspal regions, the enamel rods form intertwining bundles (A);
- This arrangement of enamel rods, close to their origin at the DE junction, is referred to as gnarled enamel.
Dentinoenamel junction

- The junction between these two hard tissues as a scalloped profile in cross section;
- The shape and nature of the junction prevent shearing of the enamel during function.
Enamel Tufts and Spindles

A - Before enamel forms, some developing odontoblast processes extend into the ameloblast layer and, when enamel formation begins, become trapped to form enamel spindles;

B - Enamel tufts are believed to occur developmentally because of abrupt changes in the direction of groups of rods that arise from different regions of scalloped DEJ.
Dentinoenamel Junction
Enamel tufts

- A - Enamel tufts;
- B - dentinoenamel junction;
- C - Dentin.
Enamel lamellae

- **A** - enamel lamellae. They are faults in development of enamel and extend for varying depths from the surface of the enamel;
- They are consist of linear, longitudinally oriented defects filled with organic material;
- **B** - Enamel tufts;
- **C** - Neonatal line.
- A - Enamel lamellae;
- B - Enamel tufts.
Enamel spindles

A - Enamel spindles

B - Odontolast process in dentin.
Enamel spindles

A - enamel spindle - odontoblast processes extend through the DEJ into the enamel;

B - Branched odontoblast processes in the dentin;

C - Enamel rod.
Enamel surface

- Enamel surface is characterized by several structures:
  - Perikymata - the striae of Retzius often extend from DEJ to the outer surface of enamel, where they end in shallow furrows known as perikymata;
  - Final enamel - the enamel surface consist of a structurless surface layer (without rods);
  - As the tooth erupts, it is covered by a pellicle consisting of debris from enamel organ that is lost rapidly and salivary pellicle is formed.
Prismless layer - 20-30 µm thick (only with crystals)

- Enamel rods do not reach the surface;
- Enamel surface contains only a crystals arranged almost at right angles to the surface;
- These crystals are big and tall and with small intercrystal spaces.
Final enamel

Final enamel provides greater resistance of the enamel surface.
Enamel surface
Chemical composition of teeth

- In the permanent teeth inorganic phase of the enamel is 96%;
- In the primary teeth - 93%;
- The mineral composition of enamel is:
  - Hydroxyapatite - $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$;
  - Fluorapatite - $\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$;
  - Carbonate Apatite;
- In the intercrystalline spaces there are:
  - Amorphous calcium carbonate;
  - Manganese (Mn), zinc (Zn), copper (Cu), magnesium (Mg), aluminum (Al) and etc.
Apatite crystals

- The height of the crystal is - 1600 Å;
- The crystal width is 200 Å;
- A single crystal portrayed as a ;
  - carpenter-shaped pencil configuration;
  - Ribbons;
  - Needles;
  - Hexagonal.
- The water in the enamel is in two forms:
  - Loosely connected;
  - Firmly attached to the apatite crystal.
Organic matter

- Soluble in acids - 2/3;
- Insoluble in acids - 1/3;
- Organic matter of the enamel is highly organized and similar to the keratin;
- It contains enamelin, tuftelin and Carbohydrate-protein complexes.
Ionic exchange in the enamel

- Ion exchange in enamel is weak and slow;
- Ions in the crystal may undergo ionic exchange with ions in the environment - saliva;
- One third of the ions in apatite can exchanged by replacement of different ions - “heteroionic exchange”;
- It is possible for one ion to be replaced by another of the same kind - “isoionic exchange”.
Structure of the crystal

- The inside of the crystal is a mosaic of mutually neutralize electrical charges;
- On the crystal surface there are electrical asymmetry;
- The crystal is covered with a double water layer of Helmholtz.
Electrical double layer (EDL) of Helmholtz

- The DL refers to two parallel layers of charge surrounding the enamel crystals.

- The first layer, the surface charge (either positive or negative), comprises ions adsorbed directly onto the object due to a host of chemical interactions.

- The second layer is composed of ions attracted to the surface charge via the coulomb force, electrically screening the first layer. This second layer is loosely associated with the object, because it is made of free ions which move in the fluid under the influence of electric attraction and thermal motion rather than being firmly anchored. It is thus called the diffuse layer.
Ionic exchange in the enamel

1. The first stage of the ionic exchange is reversible - the ions diffuse into the superficial hydration layer;

2. The second stage is easily reversible - the ions enter into subsurface layer of absorbed ions and neutralize their charges;

3. The third stage is difficult to reversed - the ions are included in the surface of the crystal;

4. The fourth stage is irreversible - the ions replace defects inside of the crystal lattice.