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The Alveolar Bone Provides Support to Teeth and Other Functions: A Review

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Abstract

Alveolar bone provides structural supports to teeth. The outer and inner compact bone are formed by osteons, the basic structure of cortical bone, with a central vertical Haversian canal and rings forming a lamellar bone (bundle or alveolar bone). The central cancellous bone is the spongiosa (spongy bone). Bundles of collagen fibers (Sharpey's fibers) provide attachment of the root to bone. Perforating Volkmann's canals, limiting the inner bone are forming "the cribriform plate". Oriented horizontally, the plate contains blood vessels and nerves issued from the periosteum. Alveolar bone associates intramembranous and endochondral bones. Mesenchymal stem cells (osteoprogenitor cells) initiate bone mineralization including a differentiation cascade. Alveolar bone includes pre-osteoblasts, osteoblasts, osteocytes, and bone lining cells, all these cells being derived from hematopoietic stem cells. The alveolar bone extracellular matrix (ECM) includes collagens, elastins, glycosaminoglycans and proteoglycans, small leucine-rich proteoglycans, small integrin-binding ligand N-linked glycoprotein (phosphorylated SIBLINGs) (DSPP [fragmented after cleavage into dentin sialoprotein, dentin glycoprotein, and dentin phosphoprotein], phosphorylated proteins such as bone sialoprotein, matrix extracellular phosphorylated protein (MEPE), and osteopontin], non-collagenous non-phosphorylated proteins (osteonectin), serum derived proteins (α_2 -HS-glycoprotein, and albumin), specific and non-specific alkaline phosphatase, metalloproteinases and tissue inhibitors of metalloproteinases (TIMPs -1 to -4) and enzymes that regulate components of the alveolar bone. Osteoclasts are stimulating osteoclastogenesis, and

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consequently bone remodeling. ECM molecules are involved in bone mineralization or acting as mineralization inhibitors. The major functions of the alveolar bone are the following

1. Providing structural support to teeth (Sharpey's fibers)
2. Act as mechanosensor
3. Supply vascular nutrition and innervation, releasing neuromediators to the periodontal ligament
4. Communicate with cells on the bone surface and with marrow cells
5. Regulate blood-calcium and phosphate metabolism. Interactions between integrins-dependent extracellular molecules and bone cells are essential for bone formation and resorption. Studies have addressed the importance of the lacunocanalicular system and the pericellular fluid for the adaptation of bone to mechanical forces.

Keywords

Bone Lining Cells; Osteoblasts; Osteocytes; Osteoclasts; Sharpey's Fibers; Collagens; Proteoglycans; SLRPs; SIBLINGs; MMPs; TIMPs; mineralization

Introduction

Alveolar bone provides structural support to teeth. Alveolar bone is formed alongside the teeth eruption (Fig. 1).

Alveolar bone structure is divided in two parts (Fig. 2):

- The cortical bone is composed by Haversian bone and compacted bone lamellae, forming thin layers of inner and outer compact bone or/and, composed of cortical plate (cribliform plate)
- The trabecular bone includes a central spongiosa (also named cancellous bone)-surrounding the lamina dura remains spongy and porous throughout life and it is lining the alveolus [1]

The cortical plates and inner socket wall bone are lining the socket and provide attachment (bundle bone) to bundles of the Periodontal Ligament (PDL).

Alveolar bone increases in high along eruption together with the root lengthening. Adult alveolar bone reach its functional formation but decreases along periodontitis and periodontal disease, leaving remnants of the mandible, namely the basal bone.

Figure 1: Tooth and alveolar crest.

Black arrows indicate oblique Sharpey's fibers, contributing to tooth eruption and root attachment to the socket.

Figure 2: The different parts of the alveolar bone.

Alveolar crest > alveolar bone proper. Cortical bone (Volkmann's canal) > cancellous bone. Basal bone is located in the basal part of the mandible, and/or to the palate of maxilla.

Nomenclature of Bone Cells

The cell lines consist of pre-osteoblasts, osteoblasts, osteocytes and bone lining cells. These cells are of mesenchymal origin, derived from the stroma of bone marrow and from pericytes adjacent to blood vessels. Growth factors are involved in the differentiation of these mesenchymal cells into osteogenic cells (TGF β -BMP-2). Osteoprogenitor cells take origin in the mesenchyme. (osteocalcin, osteonectin, alkaline phosphatase and BSP). They divide by mitosis and give all type of bone cells involved in bone formation.

Osteoclasts are also present and implicated in remodeling the bone at the inner and outer surfaces, but also along trabeculae. Growth factors such as the TGF β -2 are implicated in bone formation and remodeling (Fig. 3).

There are 3 types of bone:

1. Lamellar bone (compact bone and spongy bone) [2,3]. Arranged in 3 patterns. Circumferential, Haversian and Interstitial lamellae (Fig. 3,4)
2. Woven bone (or immature bone, formed during embryonic development)
3. Bundle bone

Osteon is the primary structure of the cortical bone (Fig. 3,4).

Figure 3: Osteons are the basic unit of compact bone. The central Haversian canal and horizontal canals (perforating Volkmann's canal) contain blood vessels and nerve from the

periosteum. It includes 5-20 lamellae, a varying number of concentrically arranged lamellae of bone matrix. Osteocytes are capable of local bone remodeling [4], blood-calcium homeostasis phosphate homeostasis [5].

Figure 4: Haversian systems (or osteons) are forming concentric rings around the central canal.

Horizontally oriented canals known as Volkmann canals are connecting adjacent osteons.

A major portion of the alveolar process begins with the formation and eruption of the teeth.

The various parts of the alveolar bone is made by thin lamellae of the cortical bone which surround the roots. The collagen fibers (Sharpey's fibers) are inserted in the bone (bundle bone perforated by many openings providing passage to blood vessels, lymphatics and nerves. This bone is also known as "cribliform plate"

Between the inner and outer cortical plates, trabeculae of the "spongy bone" are arranged in two patterns: A ladder-like fashion (seen mostly in mandible), and an irregular manner (seen mostly in maxilla) (Fig. 5- 7).

Osteoclasts are bone structural constituents.

Intramembranous (without the mediation of a cartilage phase) and endochondral bone formation that, occurs on a mineralized cartilage scaffold.

Figure 5: Bone cells Osteoclasts are bone structural constituents.

They are two modes of bone formation:

Intramembranous (without the mediation of a cartilage phase) and endochondral bone formation that occurs on a mineralized cartilage scaffold (Fig. 6,7).

Figure 6: Compact bone.

Woven bone is found in the foetus, in callus of fracture, and/or in the healing socket after a tooth extraction.

Figure 7: Bundle bone.

Alveolar bone proper lining the tooth socket or alveolus. Bone is also called cribriform plate (Volkmann's canals pass from the alveolar bone into the PDL).

Bone Formation

- Intramembranous bone formation starting with nodules. This bone is formed without the cartilage phase. Mesenchymal stem cells initiate the formation of an initial bone center, calcification, followed by the formation of trabeculae. The cells differentiate into osteoblasts, with deposition of osteoid at the site of bone formation
- Endochondral bone formation is occurring on a mineralized cartilage scaffold. Bone formation is initiated with the development of cartilaginous model follows by its growth. The primary ossification center is formed, giving rise to the final shape of the bone [6]
- Alveolar bone proper and the supporting alveolar bone: thin lamellae of bone which surround the root Cortical bone is lamellated and covered by the periosteum. The inner and outer cortical plates meet at the alveolar crest. The width of the cortical plates is about 1.5 to 3 mm, thicker in the mandible than in the maxilla. Between the two plates, spongy bone is present and organized in two different patterns (Fig. 8-11)

Bone Early Development

Figure 8: Early stage of mandible formation.

Figure 9: Prenatal developmental phase of the mandible.

Figure 10: Schematic representation of the first center of ossification of the mandible.

Figure 11: Intramembranous ossification steps: differentiation of mesenchymal cells or osteoprogenitor cells. invading the capillaries networks in the environment, formation of osteoblasts (bone-forming cells), secretion of the osteoid by osteoblasts cells, start mineralization, formation of collagen networks, transformation of osteocytes from osteoblasts, formation of the primary ossification center, formation of bony spicules or trabeculae, continue mineralization process, and the formation of spongy bone, periosteum, and compact bone.

Or it may be summarized as follow:

- Differentiation of mesenchymal cell
- Osteoblast and matrix formation
- Ossification and complete mineralization

Global Composition of the Alveolar Bone

The alveolar bone provides structural support for the dentition. For the maxilla, there are four processes: frontal, zygomatic, palatine and alveolar process. The two maxillary bones are fused in the midline of the inter-maxillary suture to form the upper jaw. The mandibular basal bone is parallel to the Meckel's cartilage. The formation of the mandible occurs along the Meckel's cartilage.

The pharyngeal arch, the second of the 5th pharyngeal arch is involved in the formation of the orbit, nose and palate (incus, malleus of the middle ear, and also the Meckel's cartilage). It comes from the Reichert's cartilage. The longer cranial or styloid segment depends of Reichert's cartilage. The palatine process is a thick horizontal process.

Alveolar bone composition: it comprises 65-70% inorganic (calcium and phosphate, sodium, magnesium and fluorine) and for 35% the organic matrix:

- Collagenous proteins (namely Type I collagen and type V collagen)
- Non-collagenous proteins, including hyaluronan, proteoglycans, GAGs (CS and KS) adhesive glycoproteins (osteonectin, sialoproteins I and II), osteopontin, growth factors and cytokines

Cellular Components

Osteoblasts arise from mesenchymal stem cells. They express parathyroid hormone receptors. They are derived from pluripotent mesenchymal stem cells differentiation controlled by RUNX2 (also known as CBFA1 (OB-cadherin)). They are generating new bone matrix. They secrete various secretory vesicles, MMPs and TIMPs, cytokines and growth factors. They have a cuboidal or columnar shape. Osteoblasts: express parathyroid hormone (PTH), controlled by the master transcription factor RUNX2, also known as CBFA1 (core binding factor A1). Permissive conditions include Bone Morphogenetic Proteins (BMPs) including Transforming Growth Factor β (TGF- β) and members of the Wingless (Wnt) pathways. The expression of Runt-related transcription factor 2, Distal-less homeobox 5 (Dlx 5) and Osterisx (Osx) are crucial for osteoblast differentiation, as demonstrated by the fact that Runx -null mice are devoid of osteoblasts. FGF, microRNAs and connexin 43 also play important role in the

osteoblast differentiation. The most common integrins present in osteoblasts are $\alpha1\beta1$, $\alpha2\beta1$, and $\alpha5\beta1$ [7].

The cells are cuboidal or have columnar shape. They attach to plasma membrane attachment plaque. They bind to collagen, attach to the underlying bone via integrins. TUNEL-positive structures have been observed inside osteoblasts vacuoles, demonstrating that osteoblasts engulf and degrade apoptotic bodies during alveolar bone formation. They produce Osteoprotegerin (OPG) and the receptor activator of nuclear factor kappa-B ligand (RANKL). Bone is rebuilt by osteoblasts and broken down by osteoclasts both communicating through cytokine signaling (TGF- β , IGF) [8].

Osteocytes are osteoblasts entrapped into the bone lacunae during bone deposition. The life span of these cells is about 10 years up to 25 years. Osteocytes, showing a dendritic morphology, are connected by canaliculi containing cytoplasmic processes, hence providing nutrition and communication to these cells. Osteocytes are involved in collagen synthesis. Osteocytes can send signals to osteoclasts during bone remodeling. It is a terminally differentiated cell, acting as a mechanosensor in bone [(re)modeling functions]. Direct contact via cell-cell and gap-junctions and indirect (paracrine signals). Role in the endocrine control of systemic phosphate metabolism. Depending on the lacunar-canalicular system. Both Dmp1-null mice and individuals with a newly identified disorder, autosomal recessive hypophosphatemic rickets, manifest rickets and osteomalacia with isolated renal phosphate-wasting associated with elevated Fibroblast Growth Factor 23 (FGF23) levels and normocalciuria. Absence of DMP1 results in defective osteocyte maturation and increased FGF23 expression [9,10].

They serve as endocrine cells and regulate the phosphate homeostasis. They control bone remodeling through regulation of both osteoclasts and osteoblasts. They act as mechanosensors [11]. They target distant organs such as kidney, muscle and other tissues [12]. Among the functions attributed to osteocytes, the regulation of phosphate metabolism is important [13] (Fig. 12). During bone remodeling there is intricate communication among bone cells. Osteocyte apoptosis is followed by osteoclastic bone resorption [14].

Figure 12: From the osteoblasts to mature osteocyte.

Osteoclasts are bone resorbing cells. They are multinucleated cells. Critical factors are the macrophage colony stimulating factor (M-CSF) along with a RANK/RANKL system, PGE₂, IL-A, 1,25-(OH)₂D₃, PTH and PTH-related protein stimulate osteoclastogenesis. Calcitonin inactivates osteoclasts.

The plasma membrane facing the bone matrix become ruffled. Carbonic anhydrase and vacuolar-type H⁺-ATPase in ruffled border contribute to the formation of erosive pits (Howship lacunae). The organic content of the bone matrix is degraded by lysosomal enzymes such as cathepsin K and MMP-9. The resorption phase lasts as long as the lifespan which is around 8 to 10 days. Myeloid cells become pro-monocytes and afterward pre-osteoclasts. Later they differentiate into osteoclasts. They are components of the mononuclear phagocyte system. Multinucleated cells are 150-200 µm in diameter. Cathepsin K is secreted by the ruffled border into the resorptive pit. MMP-9 is associated with the bone microenvironment. Required for osteoclast migration, it is a powerful gelatinase. Resorption by the osteoclasts require 2 steps:

1. Dissolution of inorganic components (mineral)
2. Digestion of organic components of the bone matrix (Fig. 13,14) [15]

Figure 13: From the pre osteoclast to a functional osteoclast.

Figure 14: The different bone cells.

Bone lining cells (bordering cells) cover inactive bone surfaces: surface osteocytes, inactive osteoblasts, and flattened mesenchyme cells. These cells are joined by adherens junctions. The primary function of these cells is mechanosensation [16].

Non-Collagenous Extracellular Matrix Components of Alveolar Bone

Genes such as Msx-1 and Msx-2, DLx (Dlx1/2, Dlx -5/6 and Runx-2) regulate the expression of osteocalcin. RUNX activate the expression of collagen type 1, BSP, osteocalcin and osteopontin [17].

Reciprocal interactions between the epithelium and mesenchyme play a key role, mediated by seven signaling pathways: WNT, BMP, FGF, SHH, EDA, TNF and NOTCH, which affect gene expression networks regulated by Transcription Factors (TF).

Proteins

PHEX and DMP1 contribute to hypophosphatemic rickets. Alkaline phosphatase, sclerostin (blocking the stimulatory actions of BMP-2, -4, -5, -6 and BMP-7 or blockage of Wnt signalling and MEPE [18-20]. Phospho 1 is a phosphatase enriched synthesized by osteoblasts.

Irisin, BSP, OPN, Osteonectin, Periostin, PP1, TNAP, Osteocalcin, MGP. FGF23 is a dimer that acts as a hormone-like myokine.

Three members of the SIBLING family of integrin-binding phosphoglycoproteins. BSP, OPN and DMP-1 activate three different MMPs (MMP-2, MMP-3, and MMP-9), that are respectively DSP and MEPE. They do not form complex with any MMPs.

Woven bone are bony structures, versus lamellar bone present in the facial bones [17].

Proteins (osteopontin, osteocalcin), structural proteins (collagens, elastins , plasma proteins (α 2HS glycoprotein (fetuin), albumin).

Collagens (I to XXVIII) are endocytosed in their precursor form (procollagen), and further cleaved by proteases [21].

Fibrillar (type I, II, III, V, XI)

Facit (type IX, XII, XIV)

Short chain (Type VIII, X)

Basement membrane (Type IV)

Other (type VI, VII, XIII)

Elastins are synthesized by fibroblasts. Tropoelastin de-aminated are incorporated into elastin

Osteopontin, DMP1 and MEPE are expressed in osteocytes

Cell adhesion proteins:

Fibronectin, secreted by cells in an unfolded inactive form, binding to platelet.

Laminins found in the basal laminae, assists in cell adhesion, and binding to collagens and nidogens.

Extracellular Matrix Proteins

Proteoglycans

- Heparan sulfate include a variety of biological activities, developmental processes, angiogenesis, blood coagulation and tumor metastasis.
- Chondroitin sulfate affect neuroplasticity
- Keratan sulfate is present in cornea, cartilage, bones, horns of animals
- Hyaluronic acid control the swelling of bonny tissues.
- Small proteoglycans (decorin and biglycan), gamma carboxyglutamic acid proteins (Matrix gla protein and osteocalcin (bone gla protein) facilitate the attachment of bone cells.
- Bone sialoprotein and osteopontin are the last PGs of the list [22-24]
- Enzymes such as Sclerostin and DKK1: are osteocyte

Functions of Alveolar Bone

- Give shape and support of the body (mandible or maxilla)
- Insertion for muscles and ligaments
- Alveolar bone hold the teeth in position to masticate
- Supplies vessels to periodontal ligaments
- Houses and protects developing permanent tooth while supporting primary teeth

Conclusion

Alveolar bone is a complex structure that contribute to maintain the teeth inside bonny sockets. It is linked to the root formation (lengthening, insertion of collagen-rich fibers (Sharpey's fibers), binding to platelets, providing cell adhesion. The cribriform plate allows to irrigate the periodontal ligament and provide nerve mediators.

The major functions of the alveolar bone are:

1. To provide structural support to teeth (Sharpey's fibers)
2. Act as mechanosensors
3. Supply vascular nutrition and innervation, releasing neuromediators to the periodontal ligament
4. Communicate with cells on the bone surface and with marrow cells
5. Regulate calcium and phosphate metabolism. Studies have addressed the importance of the lacunocanalicular system and the pericellular fluid for the adaptation of bone to mechanical forces. Osteoblasts are mainly implicated in ECM synthesis and its turnover. Studies carried out on osteocytes have addressed the importance of the lacunocanalicular system and the pericellular fluid for the adaptation of bone to mechanical forces

Conflict of Interest

The author declares no conflict of interest.

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