Bone Tissue Mechanics

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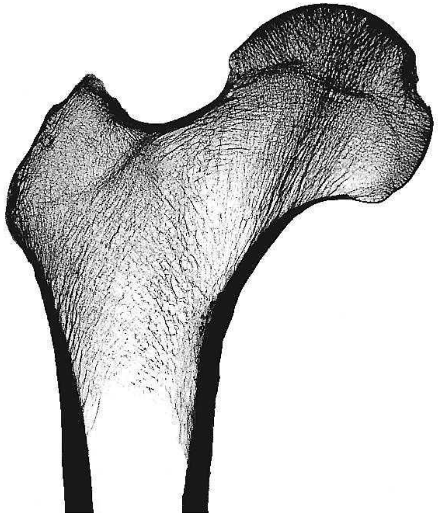
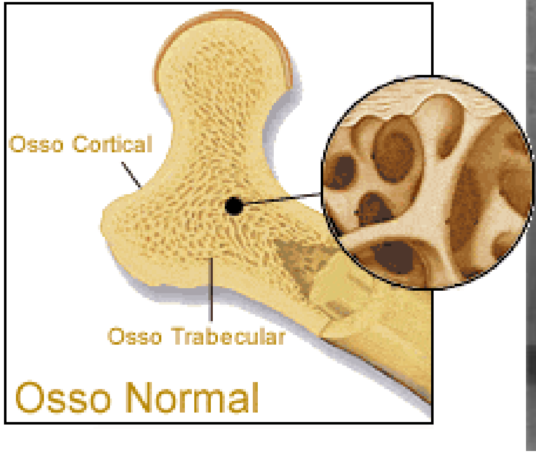
PART 3

Bone Biology

The Shapes of Bones



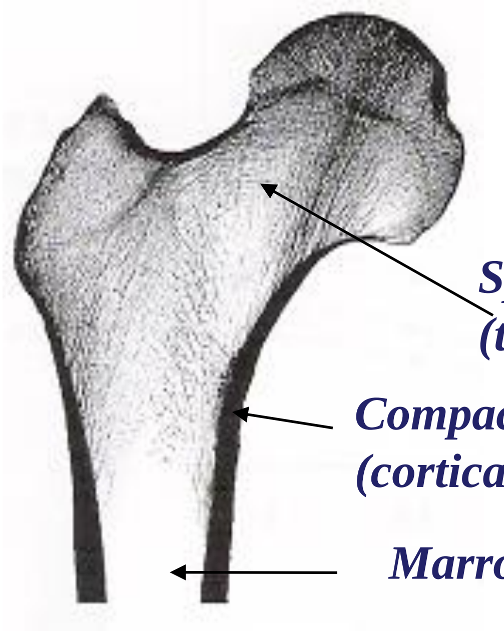


- different shapes for bones of the same individual

-Similarities between bones of different animals (we can recognize a femur, regardless of what animal it came from)

- Some specific characteristics for a specie. (it is possible to identify an isolated bone as a human bone).

Types of bone tissue: Trabecular vs. Compact bone



Spongy Bone (trabecular)

Compact Bone (cortical)

Marrow

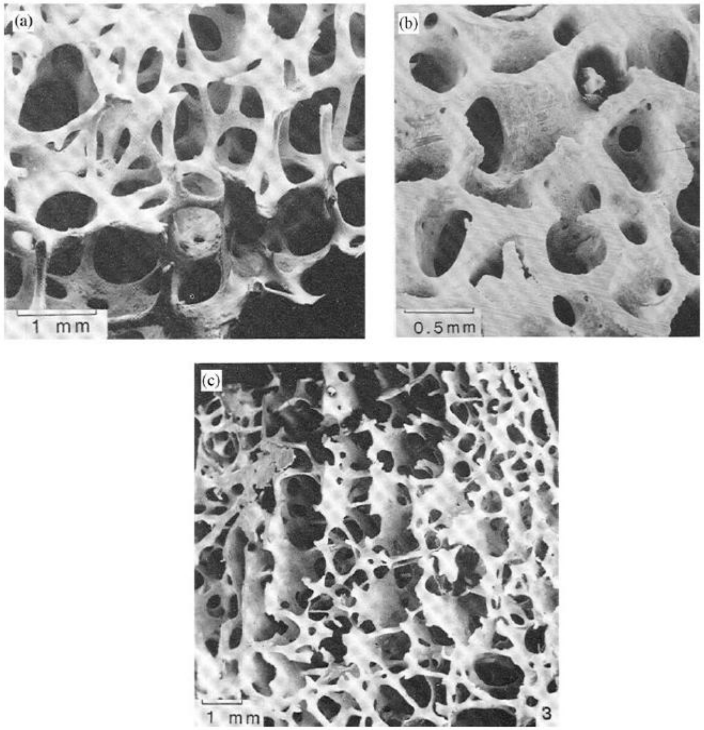
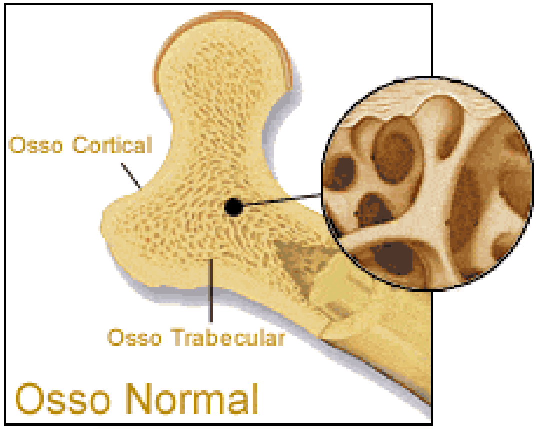


Fig. 12. Scanning electron micrographs showing the cellular structure of trabecular bone. (a) Specimen taken from the femoral head, showing low-density, open-cell, rod-like structure. (b) Specimen taken from the femoral head, showing a higher density, perforated plate-like structure. (c) Specimen taken from the femoral condyle, of intermediate density, showing an oriented structure, with rods normal to parallel plates. (Fig. 12a,b,c reprinted from Gibson, 1985 with permission of Elsevier.)



- Compact bone – porosity 5%-10%
- Trabecular bone – porosity 75%-95%

Some features of bone tissue

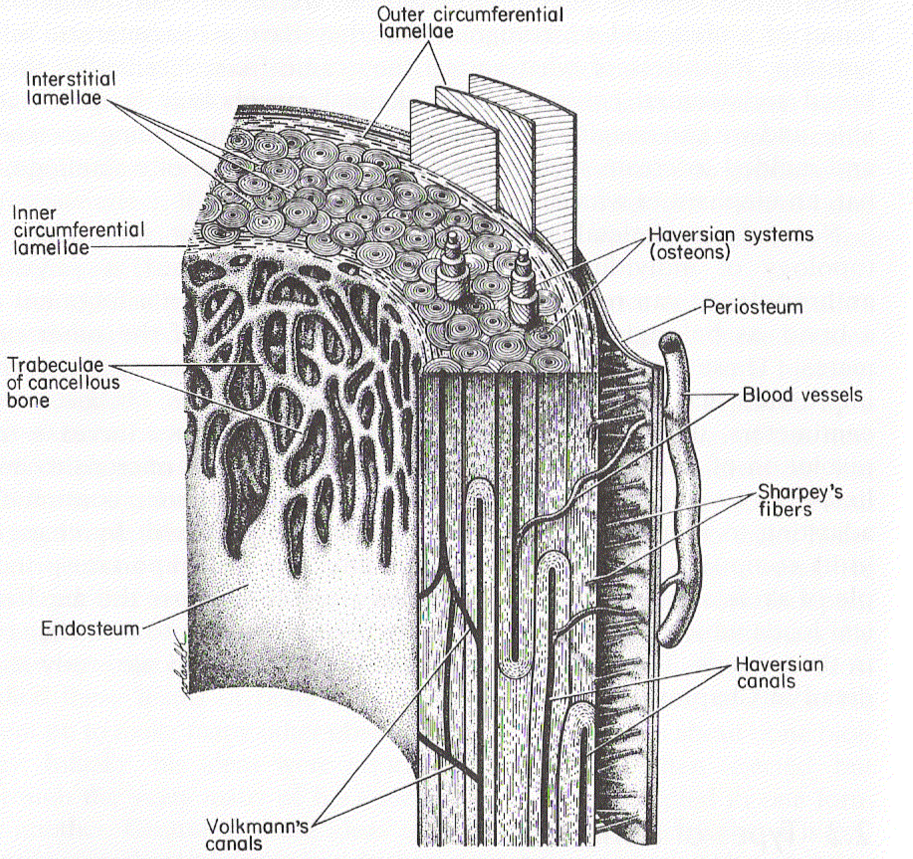
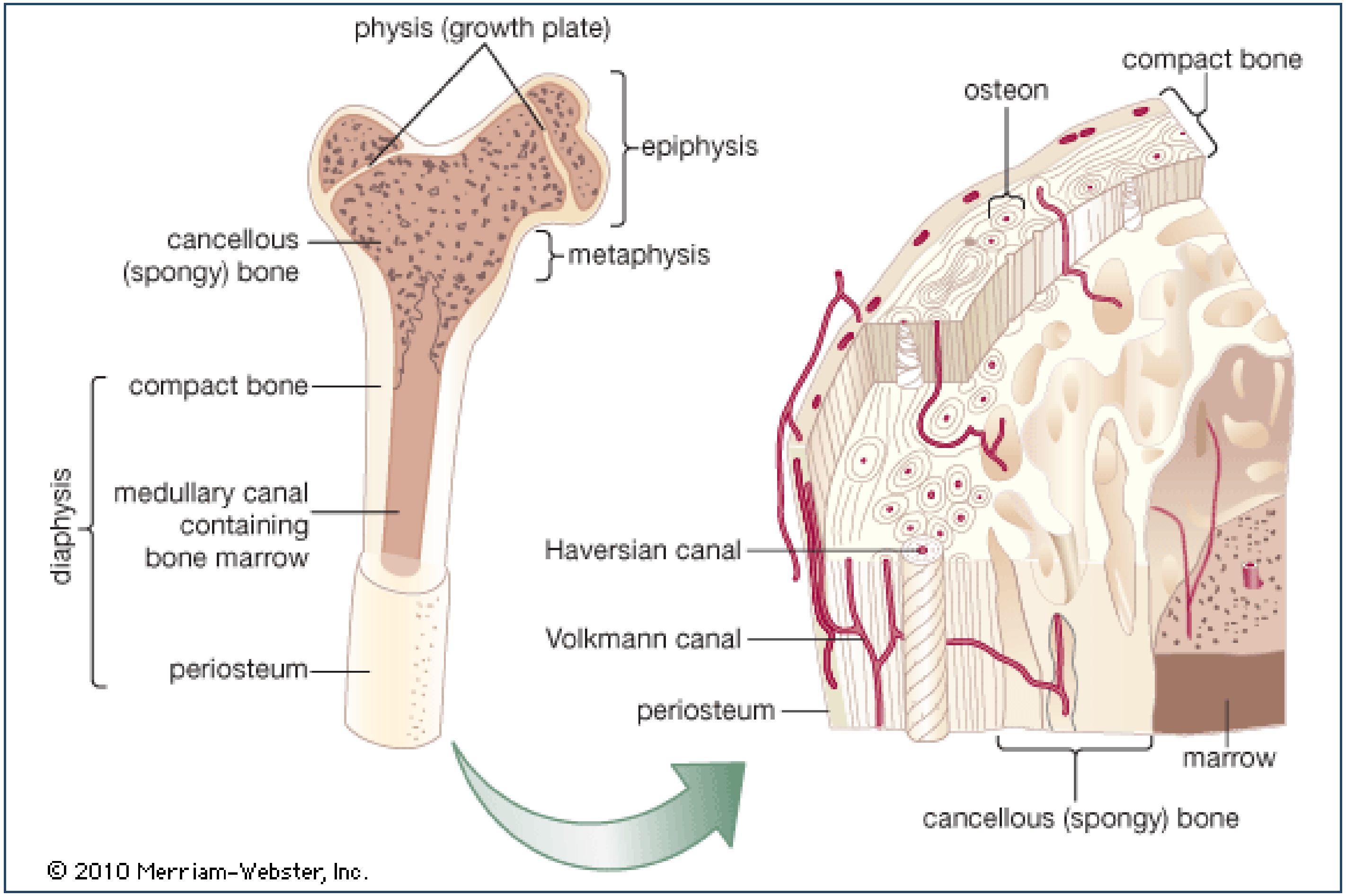


FIGURE 2.1. Sketch of some important features of a typical long bone. (After Benninghoff, 1949.)

Bone Surfaces

- *periosteum* (external surface of bone)
- *endosteum* (internal surface of bone)
- *Haversian* canals
- Trabeculae

<u>Bone surfaces </u>are important because is there that bone activity take place in order to renew bone tissue.



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osteons –lamellar structure

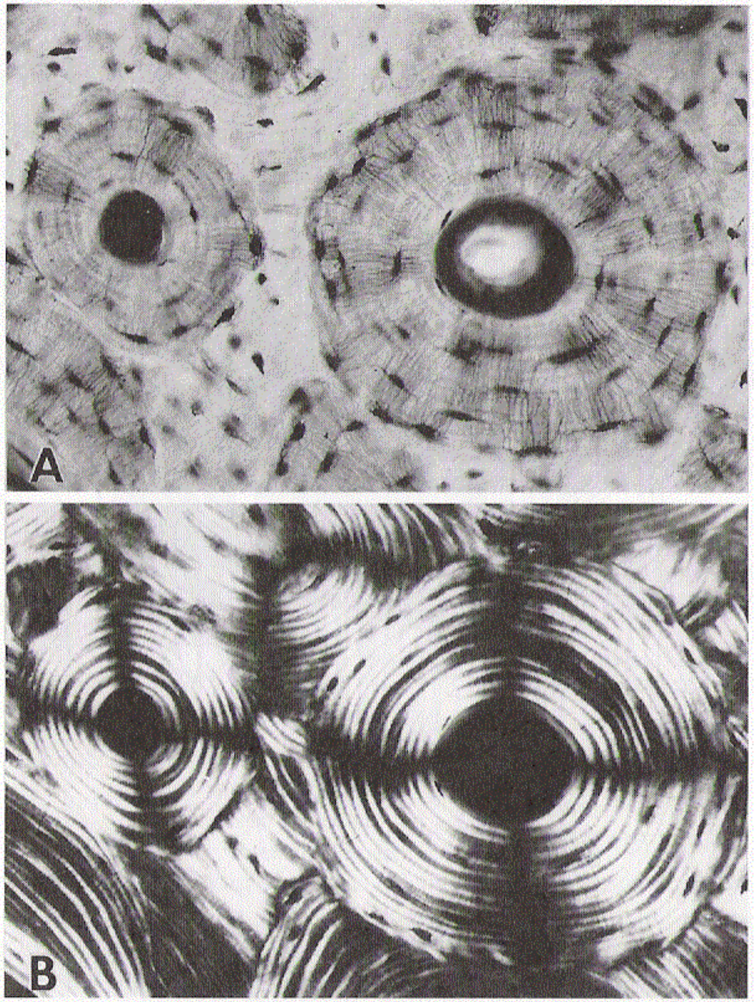


FIGURE 1.4 (A) Cross section of cortical bone showing osteon with its lacunae and canaliculi and Haversian canals. Note intervening interstitial lamellae between osteons. (B) Same section in polarized light. Note the osteons composed of numerous lamellae. (From Royce, P. M. and Steinmann, B., Eds., *Connective Tissue and Its Heritable Disorders, Molecular, Genetic and Mineral Aspects,* John Wiley & Sons, New York, 1993. With permission.)

- *osteons* are made of several lamellae

Orientation of colagen fibers

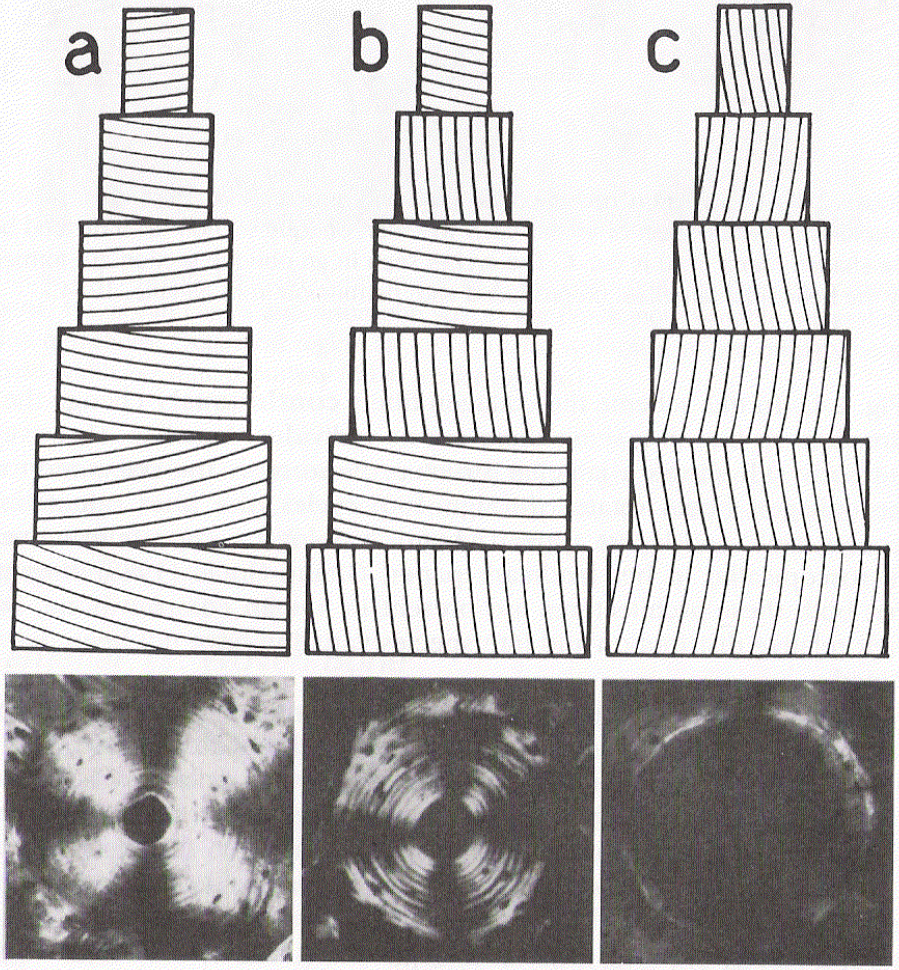


FIGURE 2.5. Three osteon types as defined by Ascenzi and Bonucci. Photomicrographs at *bottom* show appearance in plane-polarized light; diagrams *above* show hypothesized fiber arrangements in successive lamellae. *a*, Type T or transverse (i.e., circumferentially wrapped) fiber orientatio; *b*, type A or alternating fiber orientations; *c*, type L or longitudinal fiber orientation. (Reproduced with permission from Ascenzi and Bonucci, 1967.)

Ascenzi and Bonucci :

- fibers are paralel within lamellae
- different orientation between lamellae

a = type T (transverse fiber orientation)
b = type A (alternating)
c = type L (longitudinal)

Cortical bone structure

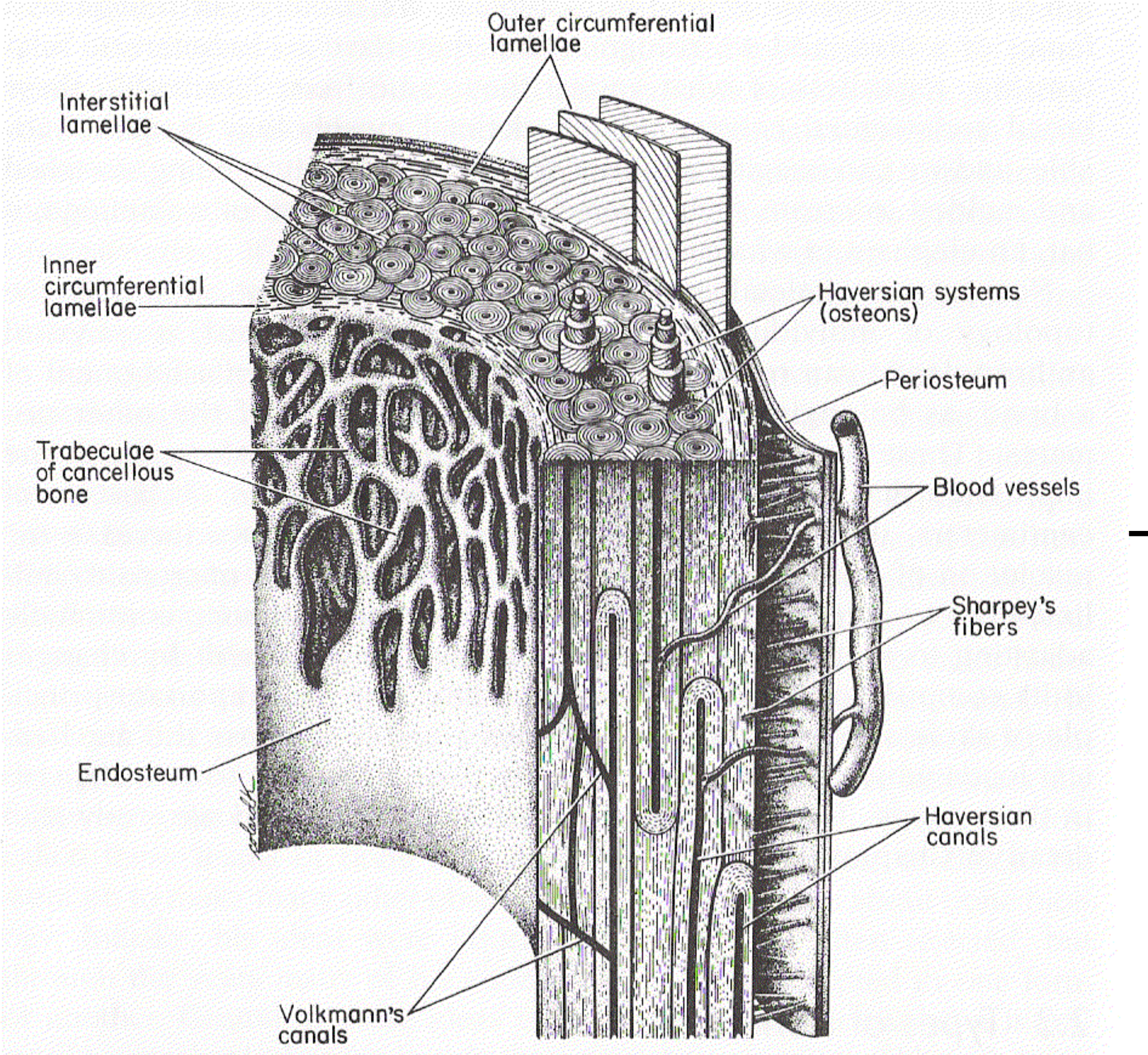
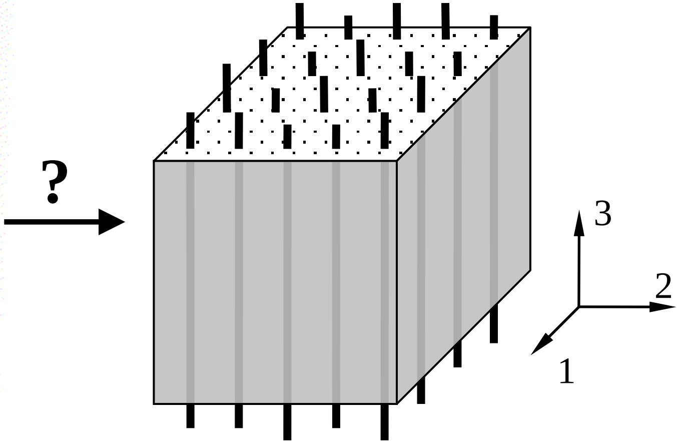
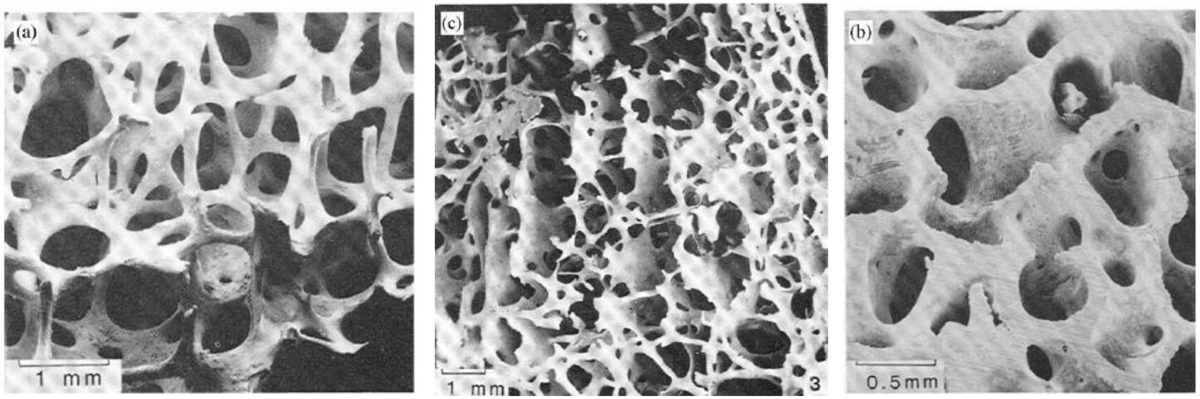


FIGURE 2.1. Sketch of some important features of a typical long bone. (After Benninghoff, 1949.)

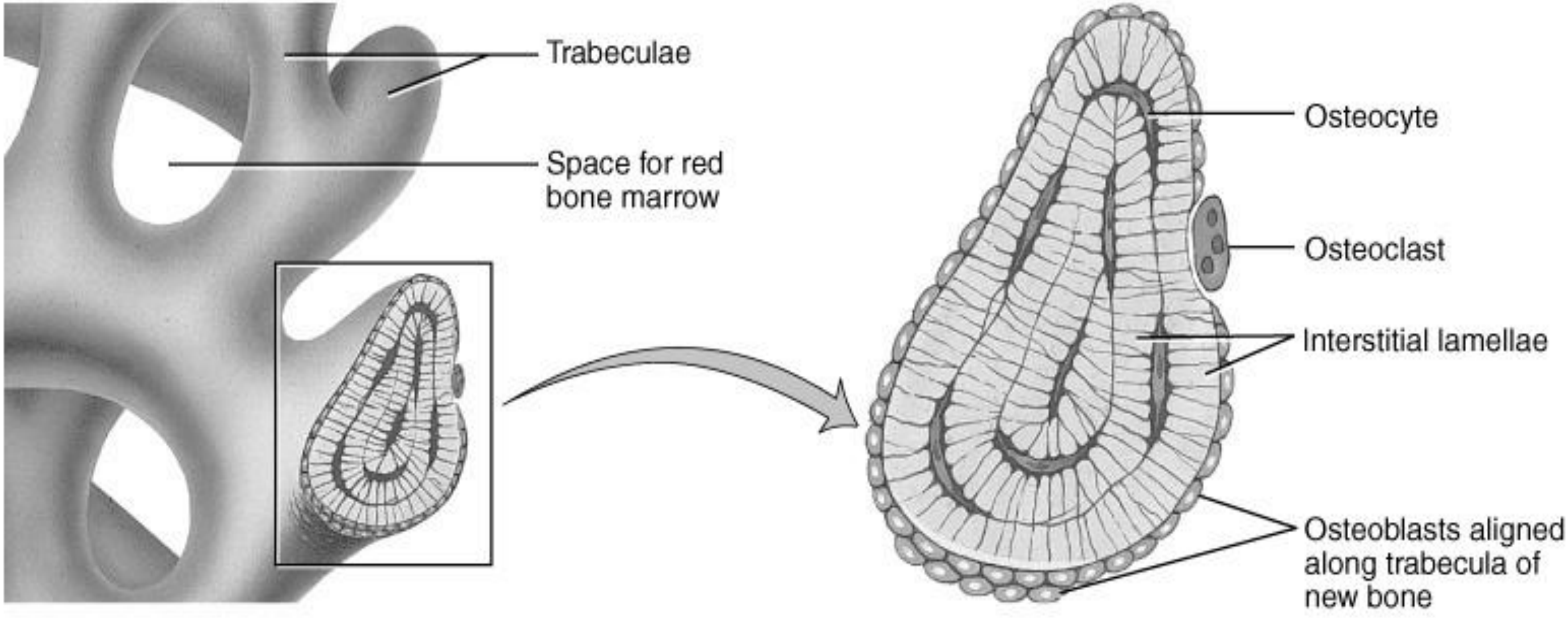


Trabecular bone



- here we have trabeculae instead od osteons.
- trabeculae thickness less than 200μm and length about1000μm=1mm
- trabecular bone is less stiff than cortical bone.
- Bone *turnover* is faster in trabecular bone

Trabecular bone



Compact bone vs trabecular

propertie	Cortical	trabecular
Volume fraction	0.95	0.20
surface / bone volume (mm^2/mm^3)	2.5	20
Total bone volume (mm^3)	1.4×10^6 (80%)	0.35×10^6 (20%)
Total internal surface (mm^2)	3.5×10^6 (33%)	7.0×10^6 (67%)

- the surface of trabecular bone is one reason to have more bone remodelling.
- This can be a consequence of a higher necessity of remodelling.
- the higher remodeling rate can explain the fact of trabecular bone being less stiff.

Types of bone tissue: Lamelar vs. Woven

At a refined scale we can distinguish between lamelar and woven bone.

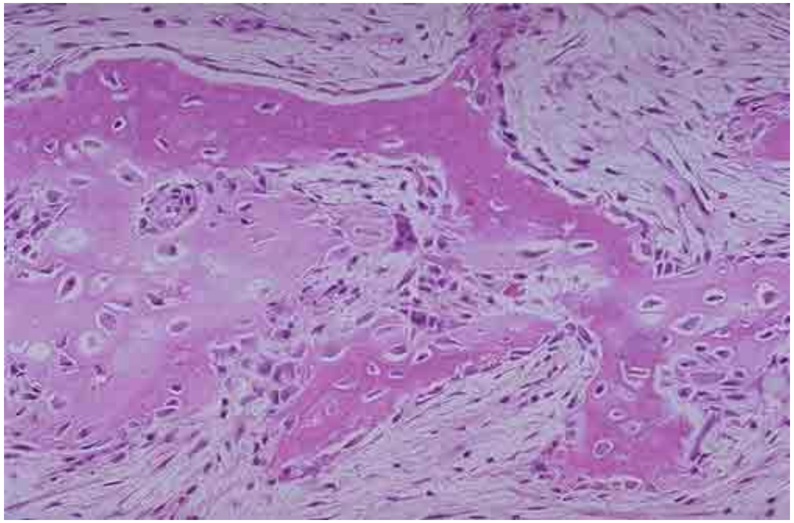
Lamelar – highly organized bone

Woven – poorly organized bone

Types of bone tissue: Primary vs. Secundary

Primary – appears during growth (modelling)

Secundary – appears due to remodelling



Woven bone

- Quickly formed, poorly organized tissue

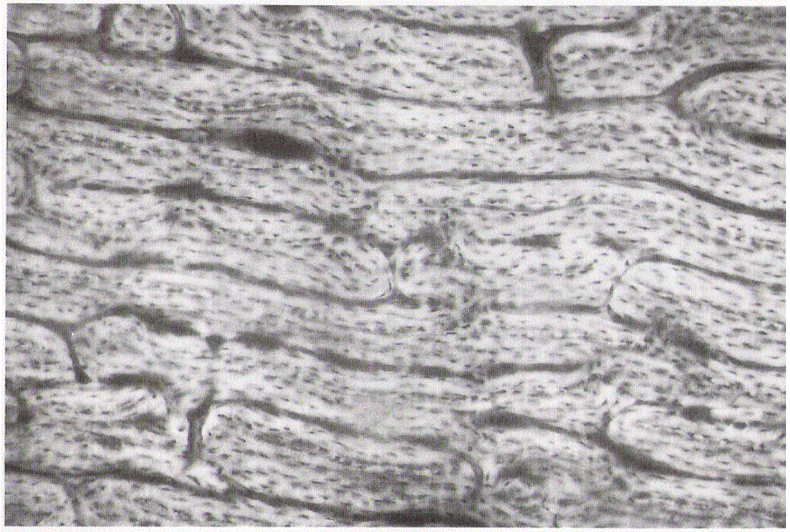


FIGURE 2.7. Photomicrograph of plexiform bone. Field width, ~500 μm.

Plexiform bone

- Quickly formed
- “brick wall” appearence
- layers of lamelar and *woven bone*
- appears in large, fast-growing animals (cows, sheeps)

Primary bone – *Primary osteons*

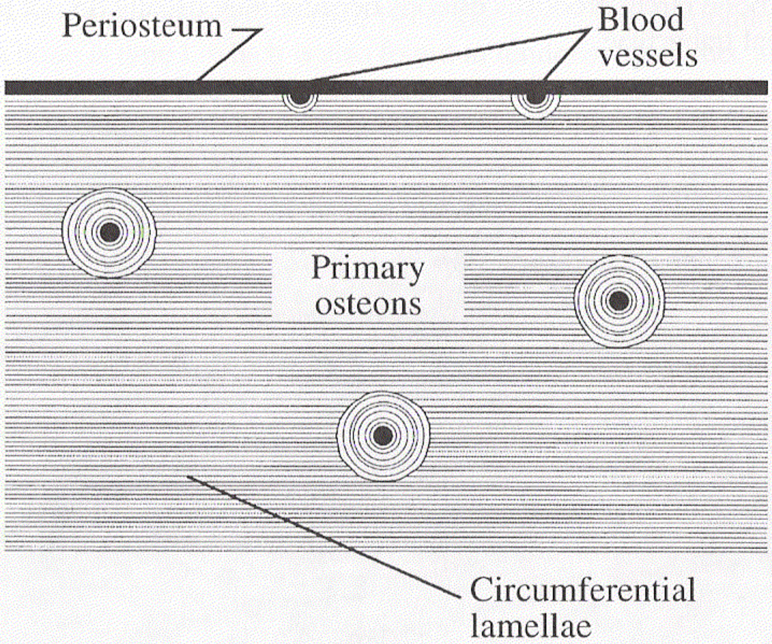
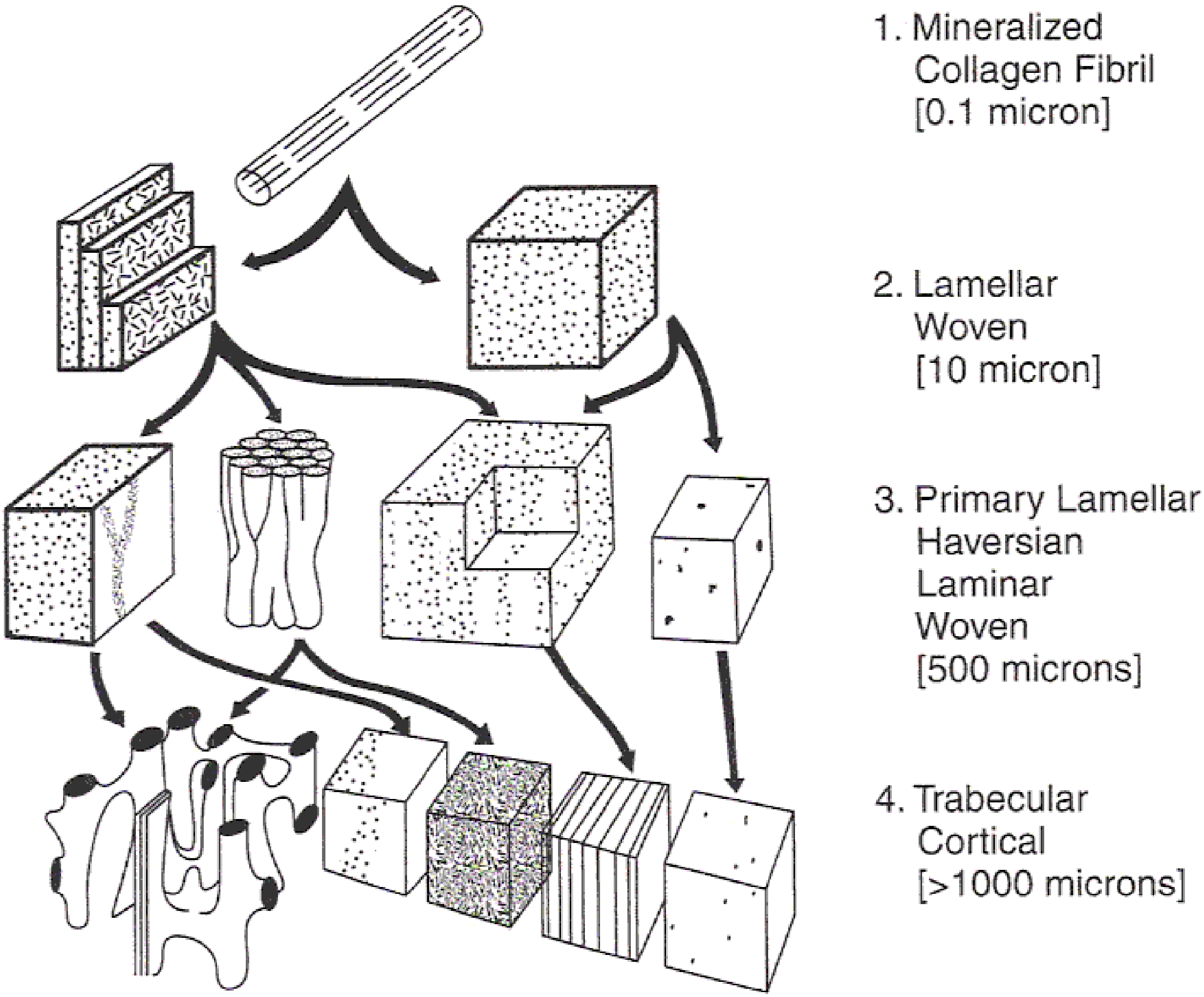


FIGURE 2.6. Sketch of primary circumferential lamellar bone structure. Primary osteons form when blood vessels on the bone surface become incorporated into the new periosteal bone. They usually have several concentric lamellae, but their cement line is not scalloped.

- primary bone is also called as immature bone
- primary *osteons* are formed by the mineralization of cartilage
- primary *osteons* have less lamellae than the secundary osteons.

Bone is a hierarchical material

FIGURE 3.2 The four levels of bone microstructure, from the level of mineralized collagen fibrils to cortical and trabecular bone. It is generally assumed that, at the former level, all bone is equal, although there can be subtle differences in the nature of the lamellar architecture and degree of mineralization between cortical and trabecular bone. (Adapted from Wainwright et al., *Mechanical Design in Organisms*. Halsted Press, New York, 1976.)



Cortical bone – hierarquical levels

level	structure	dimensions	
0	Solid material		> 3000 µm
1	Secundary *osteons* (A) Primary *osteons* (B) plexiform (C) *woven bone* (D)	$\varnothing$=200 ~ 300µm $l \approx 150$ µm	100 – 300 µm
2	lamellae (A,B*,C*) lacunae (A,B,C,D) *cement lines* (A) *canaliculi*	$t \approx 3 \sim 7$ µm $\varnothing_{\text{max}}$ =10~20µm $t \approx 1 \sim 5$ µm	3 – 20 µm
3	Collagen-mineral composite (A,B,C,D)		0.06 – 0.6 µm

Composition of Bone – Quantitative representation

- Water – 25%
- Organic Matrix – 32% (mainly collagen)
- Mineral – 43 % (mainly hydroxyapatite)

$V_T = V_m + V_v$

V_T – total volume

V_m – Bone matrix

V_v – volume of voids

B_v – volume fraction ($B_v = 0 \sim 1$)

p_v – porosity ($p_v = 0 \sim 1$)

$$B_v = \frac{V_m}{V_T} \quad , \quad p_v = \frac{V_v}{V_T}$$

ρ – apparent density

ρ_m – density of bone tissue ≅ 2.0 g/ml

ρ_v – density of soft tissue in the void spaces ≅ 1.0 g/ml

$$\rho = \frac{\rho_m V_m + \rho_v V_v}{V_T}$$

$$\rho = 1.0 \sim 2.0\ g/ml$$

Porosity:

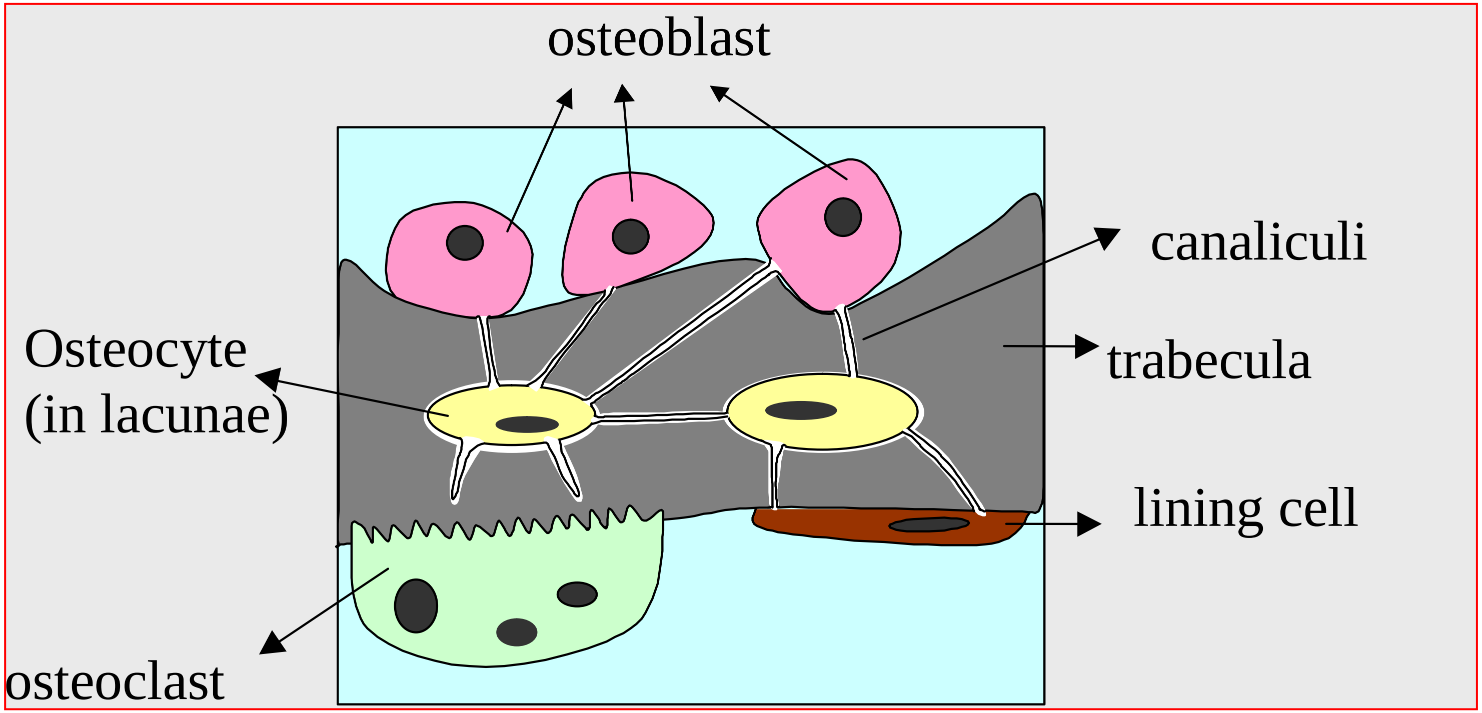
- cortical bone → $p_v = 5\% \sim 10\%$
- trabecular bone → $p_v = 75\% \sim 90\%$

<u>Ash fraction:</u> ratio between the ash mass and dry mass. It is a measure of the degree of mineralization of bone tissue

Bone cells

Bone cells:

- osteoclast s(bone resorption)
- osteoblasts (bone formstion)
- osteocytes
- *lining cells*



Bone Modelling vs. Remodelling

osteogenesis – bone production from soft tissue (fibrosis tissue or cartilage). Bone formation in a early stage of growth. It also happens in bone healing.

bone modelling – Modelling results in change of bone size and shape. The rate of modelling is greatly reduced after skeletal matutity. Involves independent actions of osteoclasts and osteoblasts.

- ***bone remodelling*** – Process of replacement of "old bone" by "new bone". It repairs damage and prevent fatigue damage. Usually does not affect size and shape. Occurs throughout life, but is also substantially reduced after growth stops. A combined action of osteoclasts and osteoblasts (BMU - *Basic multicellular unit*).

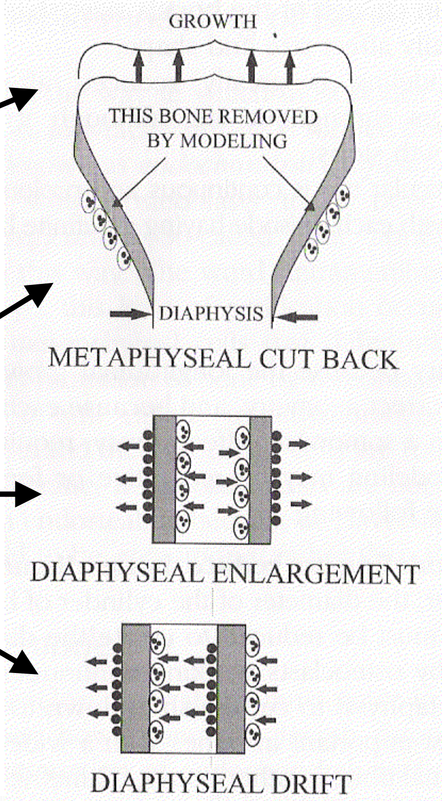


FIGURE 2.19. *Top:* Resorptive modeling beneath the growth plate to form the diaphysis from the metaphysis. *Middle:* Formative (periosteal surface) and resorptive (endosteal surface) modeling to enlarge the diaphysis. *Bottom:* Modeling to "drift" the diaphysis to the left (thereby altering diaphyseal curvature).

BMU – Basic Multicellular Unit

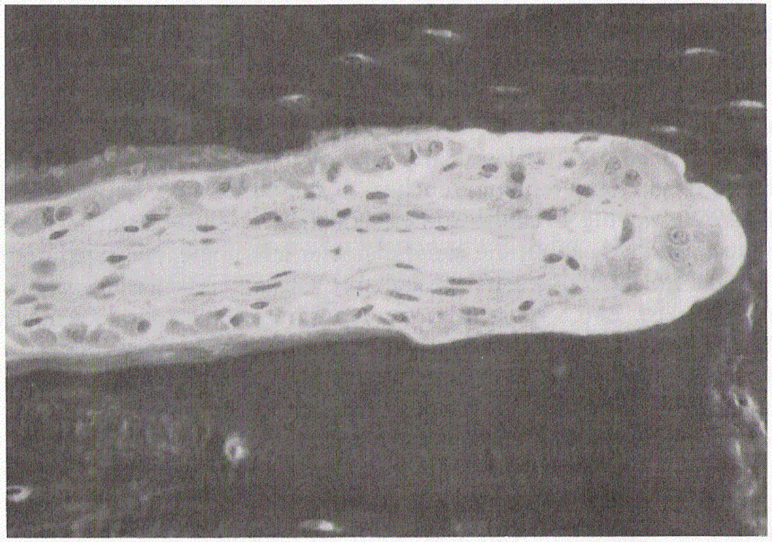


FIGURE 2.20. Photomicrograph of an osteonal basic multicellular unit (BMU). Two multinuclear osteoclasts are visible at *right*, tunneling through the bone; osteoblasts are on bone surfaces to left. Field width, ~1 mm. (Courtesy of Dr. Jenifer Jowsey.)

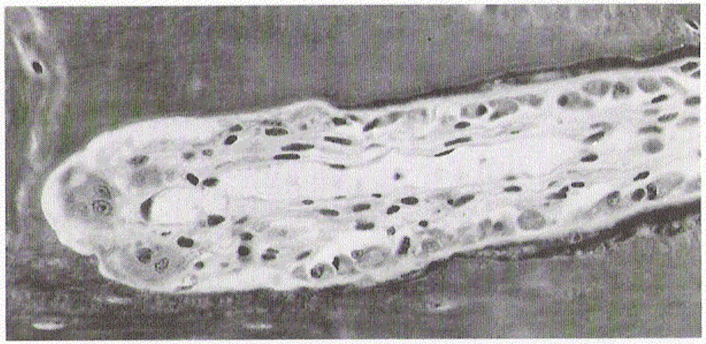
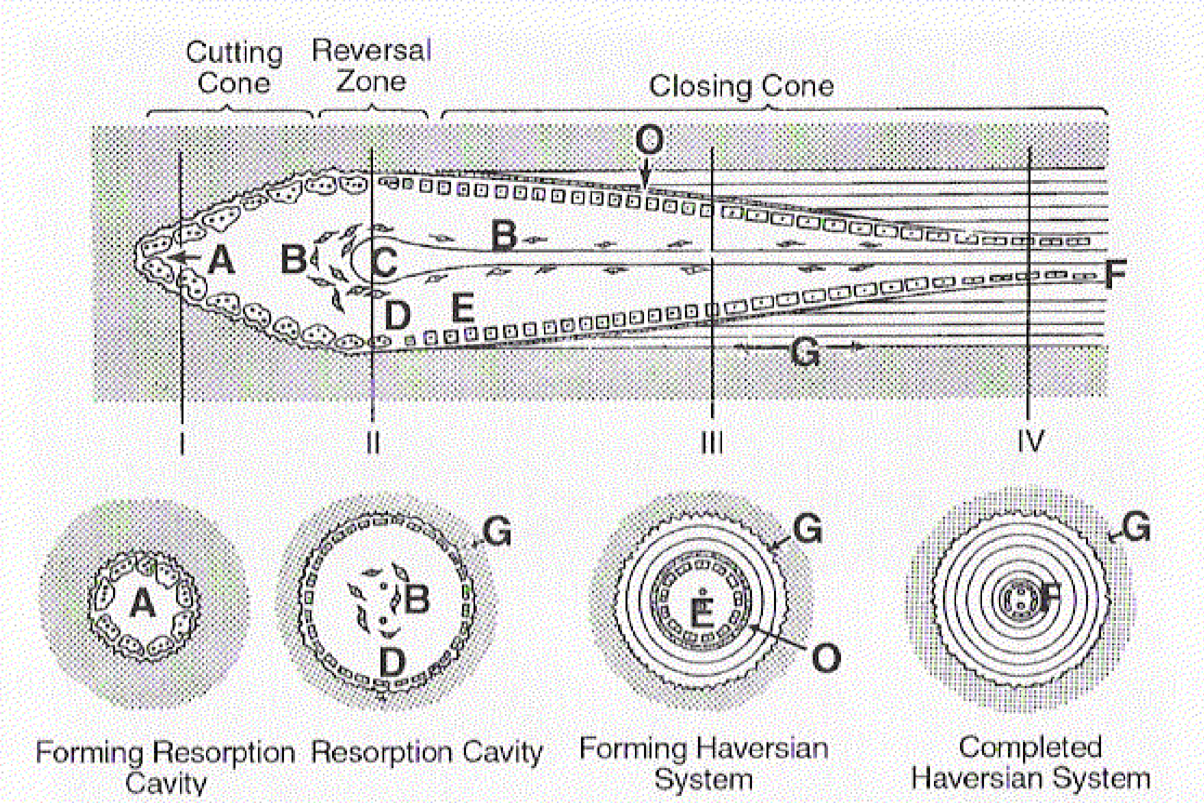


FIGURE 1.26 Cortical bone remodeling. Osteoclasts resorbing a tunnel and osteoblasts filling it. (From Royce, P. M. and Steinmann, B., Eds., *Connective Tissue and Its Heritable Disorders, Molecular, Genetic and Mineral Aspects*, Wiley-Liss, New York, 1993. With permission.)

In compact bone the BMU works in order to create a secundary osteon

BMU – tunneling and forming an *osteon*



Forming Resorption Cavity

Resorption Cavity

Forming Haversian System

Completed Haversian System

FIGURE 1.24 Diagram showing a longitudinal section through a cortical remodeling unit with corresponding transverse sections below. (A) Multinucleated osteoclasts in Howship's lacunae advancing longitudinally from right to left and radially to enlarge a resorption cavity. (B) Perivascular spindle-shaped precursor cells. (C) Capillary loop delivering osteoclast precursors and pericytes. (D) Mononuclear cells (osteoblast progenitors) lining reversal zone. (E) Osteoblasts apposing bone centripetally in radial closure and its perivascular precursor cells. (F) Flattened cells lining Haversian canal of completed Haversian system or osteon. Transverse sections at different stages of development: (I) resorption cavities lined with osteoclasts; (II) completed resorption cavities line by mononuclear cells, the reversal zone; (III) forming Haversian system or osteons lined with osteoblasts that had recently apposed three lamellae; and (IV) completed Haversian system or osteon with flattened bone cells lining canal. Cement line (G); osteoid (stippled) between osteoblast (O), and mineralized bone. (From Parfitt, A. M., *Metabolism,* 25, 909, 1976. With permission of author and Grune and Stratton, Inc., publisher.)

Bone remodelling on trabecular surface

- remodelling on trabecular surface

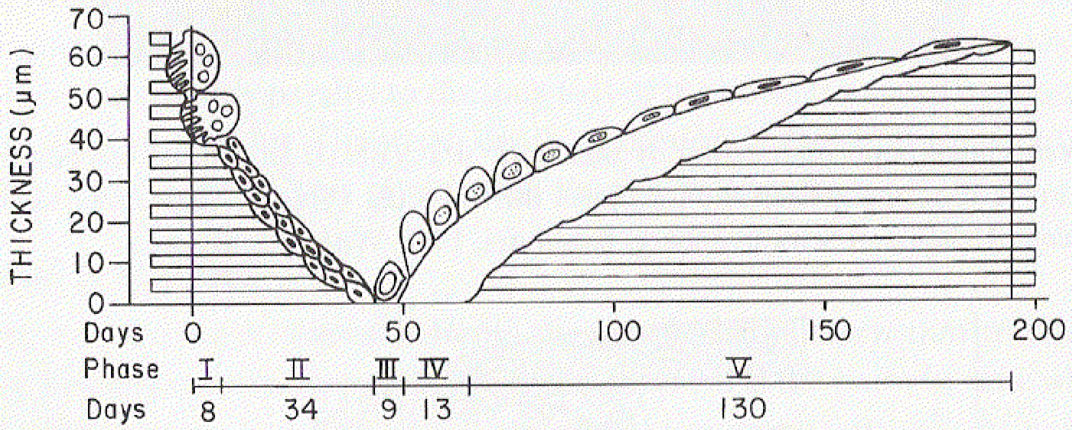


FIGURE 1.25 Cancellous bone remodeling. The total remodeling period in 20 normal individuals (19 to 60 years of age). The remodeling period is subdivided into osteoclastic resorption phase (I, 8 days), mononuclear cell resorption phase (II, 34 days), preosteoblastic or reversal phase (III, 9 days), initial mineralization lag time (IV, 13 days), and mineralization phase (V, 130 days). Total remodeling period of 196 days. Osteoclast depth, 19 ± 4.9 μm; mononuclear cells depth, 49.1 ± 10.2 μm; and preosteoblasts, 62.6 ± 12.5 μm. (Modified from Eriksen, E. F. et al., *Metab. Bone Dis. Relat. Res.*, 5, 243, 1984. With permission of authors, Pergamon Press, and Société Nouvelle de Publications Medicales et Dentaires.)

Bone remodelling on trabecular bone

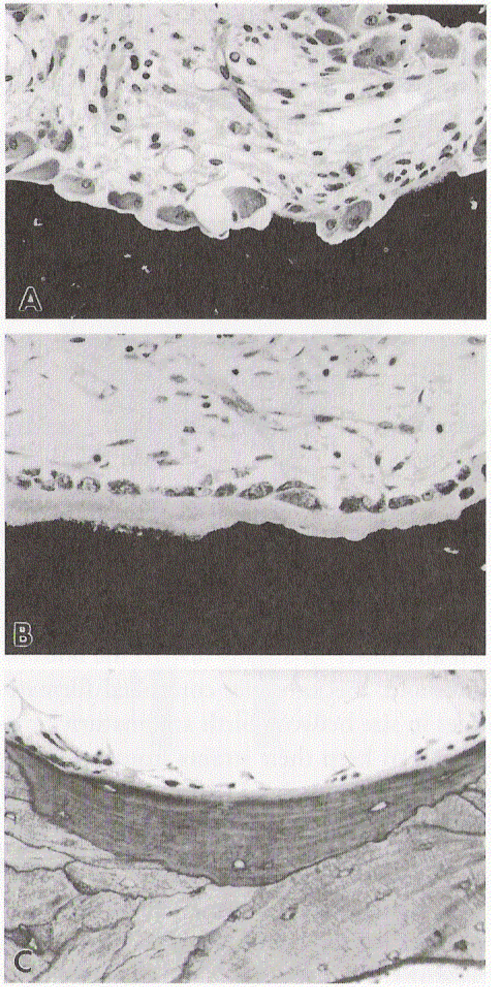


FIGURE 1.23 Cancellous bone remodeling to form a trabecular packet or hemiosteon. (A) The resorption phase—osteoclasts eroding a parcel of bone (black); (B) formation phase with osteoblasts and osteoid seam; and (C) completed trabecular packet or hemiosteon showing bone lining cells and scalloped cement line. (From Royce, P. M. and Steinmann, B., Eds., *Connective Tissue and Its Heritable Disorders, Molecular, Genetic and Mineral Aspects*, Wiley-Liss, New York, 1993. With permission.)

BMU activation and Turnover rate

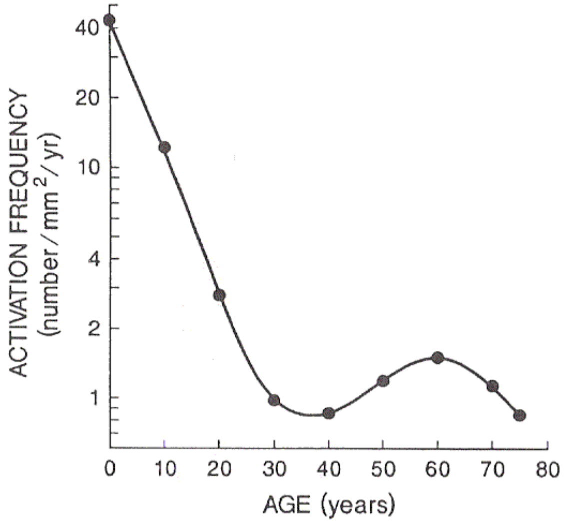


FIGURE 2.21. BMU activation rate vs. age for human ribs. (From data by Frost, 1964b.)

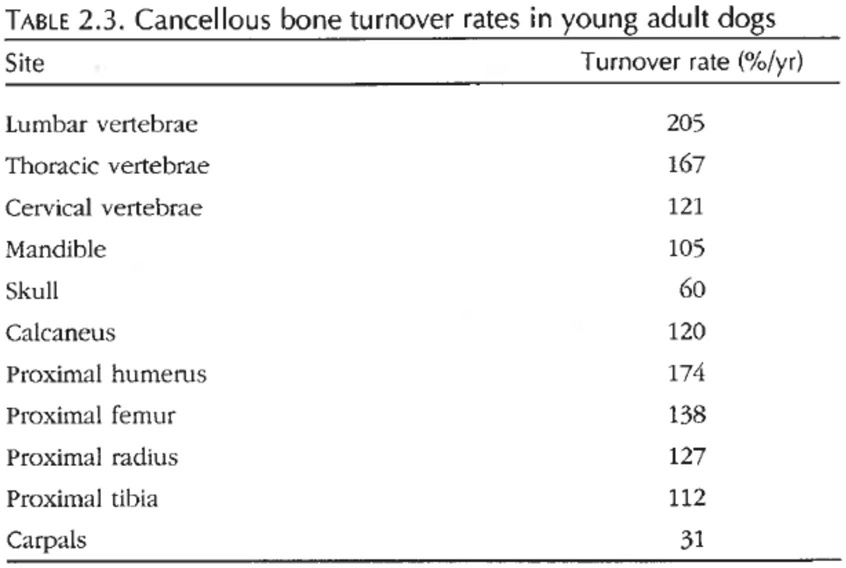


TABLE 2.3. Cancellous bone turnover rates in young adult dogs

Site	Turnover rate (%/yr)
Lumbar vertebrae	205
Thoracic vertebrae	167
Cervical vertebrae	121
Mandible	105
Skull	60
Calcaneus	120
Proximal humerus	174
Proximal femur	138
Proximal radius	127
Proximal tibia	112
Carpals	31

After Jee et al., 1991.

Fracture healing

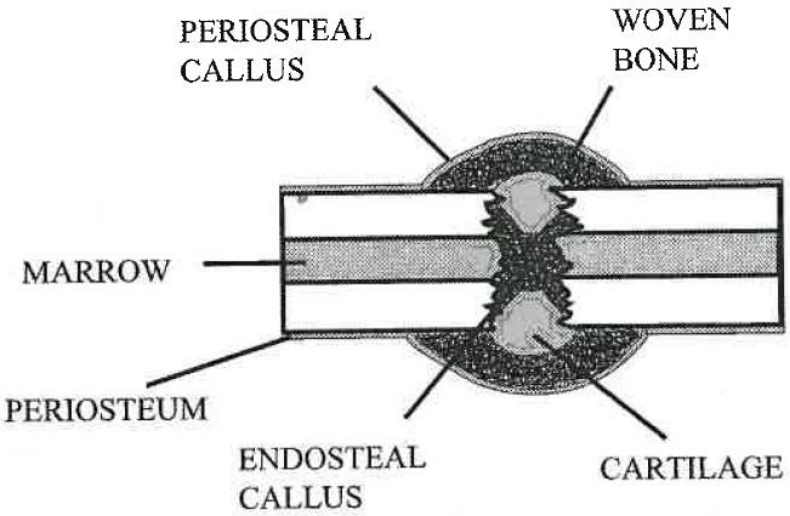
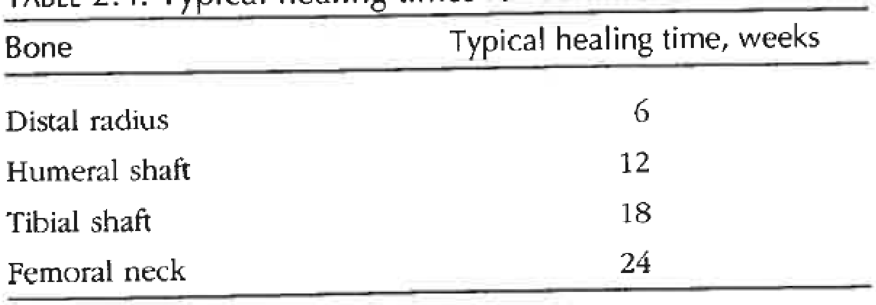


FIGURE 2.22. Diagram of a healing fracture.

TABLE 2.4. Typical healing times for common fractures



Bone	Typical healing time, weeks
Distal radius	6
Humeral shaft	12
Tibial shaft	18
Femoral neck	24

Fracture healing

Three Biological Phases

- Inflammatory Phase
- Reparative Phase
- Remodeling phase

Four Biomechanical Stages

- Stage I – No stiffness is seen, failure occur through the original line of the fracture.
- Stage II – Substantial stiffness is now encountered, but failure still occur through the original line of the fracture
- Stage III – There is no further increase on stiffness but failure is now partially through the original line and partially through the intact bone.
- Stage IV – Failure occurs through the intact bone rather than the callus at the fracture site.

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