

1 Structure of Bone

Aziz Nather, HJC Ong and Zameer Aziz

1.1 Introduction

Bone is a complex, highly organised and specialised connective tissue. It is characterised physically by the fact that it is a tissue that is hard, rigid and strong, and microscopically by the presence of relatively few cells and much intercellular substance formed of collagen fibres and stiffening substances. It is important to understand this complex structure in detail in order to comprehend how the complex process of bone healing occurs when fractures heal. Furthermore, it is only by understanding the biomechanical and biological properties of bone can we understand what type of bone grafts or bone substitutes could be best used to reconstruct large defects of normal bone. The best grafts and bone substitutes are naturally those with biomechanical and biological properties most closely resembling those of normal bone.

1.2 Functions of Bone

Bone is a rather unique tissue with many functions. All bones have a mechanical function providing attachment to various muscle groups. In addition, in some parts of the body, bones provide a protective function to vital structures — skull (brain), ribs (lungs, heart) and pelvis (bladder, pelvic viscera). Some bones retain their haematopoietic function in

adults — vertebrae, iliac crests, proximal parts of femur and humerus. All bones serve as a reservoir of calcium and actively participate in calcium homeostasis of the body.

1.3 Classification of Bones

Bones can be classified as one of the following types:

- LONG — Femur, tibia, humerus, radius, and ulna found in the limbs
- SHORT — Carpal, tarsal
- FLAT — Ribs, sternum, cranium, scapula
- IRREGULAR — Vertebra
- SESAMOID — Patella and smaller bones found in flexor hallucis longus and peroneus longus tendons

Long bone or tubular bone possesses a shaft made up of compact bone surrounding a central cavity containing cancellous bone together with marrow and fat. The cortical bone is thickest in the mid-portion of the shaft, the cancellous bone being relatively diminished in this portion of the bone. In contrast, the cancellous bone is more dense towards the ends of the bone where the cortical bone is less thick in this region. Long bones include the tubular long bones of the limbs (femur, tibia, fibula, humerus, radius and ulna) and the short tubular bones in the hands and feet (metacarpals, metatarsals and phalanges).

Each long bone can be divided into three regions, namely the epiphysis, the metaphysis and the diaphysis (Fig. 1). The epiphysis is the rounded end of the bone. The metaphysis is the part adjacent to the epiphysis in the adult (the growth plate or physis being closed). It is the part adjacent to the physis in children (growth plate being open). The diaphysis is the cylindrical shaft of the bone.

The **vertebra** consists of a vertebral body anteriorly resembling a tubular bone with a central portion surrounded by a thin cortical shell with cartilaginous end plates superiorly and inferiorly in continuity with the intervertebral discs. The posterior vertebral arch consists of the pedicles with dense cortices and relatively little intervening spongy bone and laminae

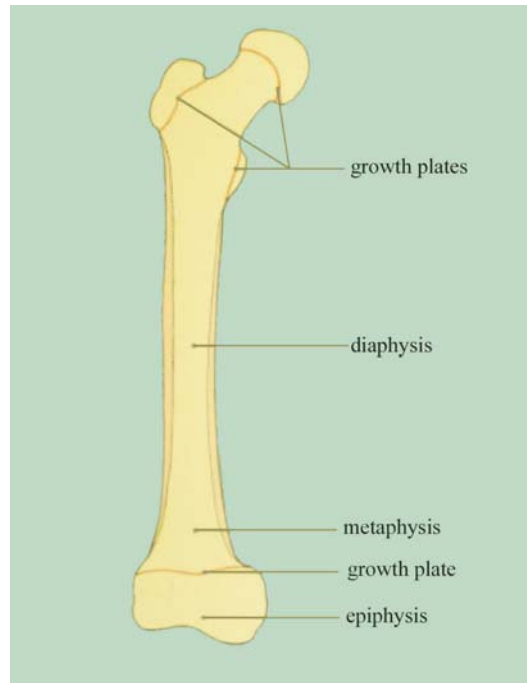


Fig. 1: Parts of a long bone.

which are flattened bones with also relatively dense cortex and less dense cancellous bone.

1.4 Structural Types of Bone

Macroscopically, there are two types:

- **Cortical (compact) bone**

With a dense outer layer — the cortex. This structure resists bending (Fig. 2).

- **Cancellous (spongy or trabecular) bone**

Present in the interior of mature bones. This structure resists compression (Fig. 2). Bone elements place or displace themselves in the direction of functional pressure according to Wolff's Law (Fig. 3).

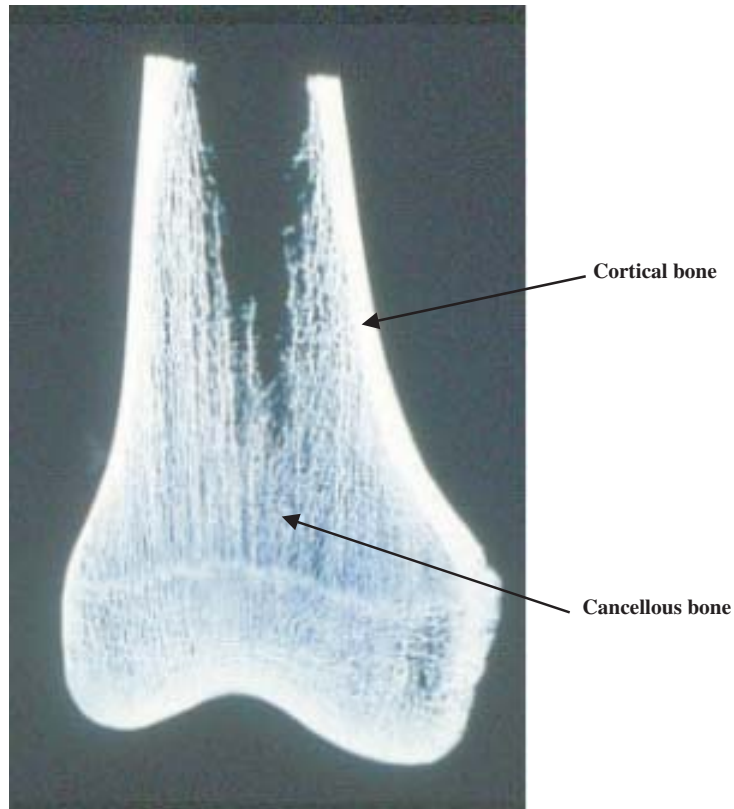


Fig. 2: Radiological appearance of cancellous and cortical bone.

1.5 Histological Types of Bones

Bone as a tissue consists of two main types:

- **Primary bone tissue (non-lamellar bone)**

This bone is also known as 'coarse fibred' or 'woven' bone or immature bone. It is characterised by the presence of randomly oriented coarse collagen fibres clearly visible by polarisation microscopy. Non-lamellar (woven) bone is seen in the bones of fetuses and young children. It is the osseous tissue first deposited on the calcified cartilage matrix in endochondral ossification. It is also the first tissue to appear in the repair of bone (fracture healing).

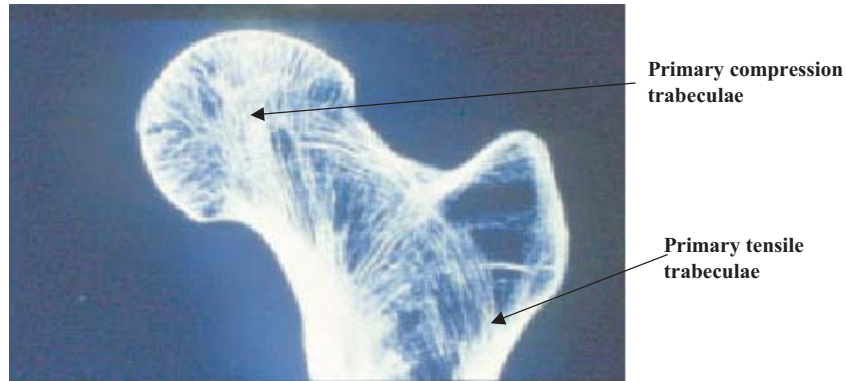


Fig. 3: Primary compression trabeculae appear in the direction the femur is subjected to most loading. Tensile trabeculae occur in the outer part subjected to most bending forces.

- **Secondary bone tissue (lamellar bone)**

This bone is also known as mature bone. It is characterised by the presence of collagen fibres arranged in parallel layers or sheets (lamellae) readily apparent when viewed by polarisation microscopy. Lamellar bone is present in both structured types of adult bone, cortical (compact) bone and cancellous (spongy or trabecular) bone.

1.6 Cortical Bone

Cortical or compact bone is made up of a structure of **Haversian systems** or **Osteons** (Fig. 4). Each Haversian System or Osteon is a cylinder running parallel to the long axis of the diaphysis. In the centre of each osteon is the **Haversian canal** which is lined by endosteum containing blood vessels, nerves and loose connective tissue. Surrounding each canal are 4–20 concentric lamellae of collagen fibres. The Haversian canals are round or oval in cross-section. They generally run in a longitudinal direction. Each osteon communicates with the marrow cavity, the periosteum and with each other through transverse or oblique canals — the **Volkman's canals** (Fig. 5). The **osteocytes** are arranged circumferentially around the central canal in parallel with the lamellae and are interconnected by fine processes of osteocyte

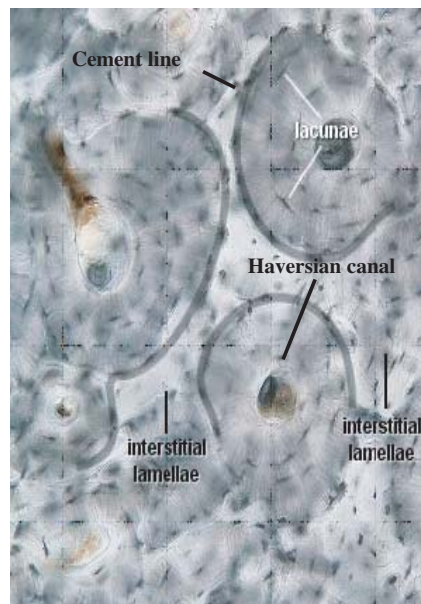


Fig. 4: Compact bone consisting of cylindrical units — **Osteons**, each Osteon with a Haversian canal in its centre and surrounded by a cement line. In between the Osteons are the interstitial lamellae.

cytoplasm — the **filopodia**. The osteocytes are housed in **lacunae** interconnected by **canaliculi** containing these fine cytoplasmic processes.

Irregular areas of lamellar bone are present between the Haversian systems — **interstitial lamellae**. These are remnants of previous Haversian systems which have been remodelled. Each osteon is separated from its neighbour and from interstitial lamellae by a **cement line** which stains darkly with Haematoxylin. The outermost and innermost layers of cortical bone contain no Haversian canals, and the lamellae are arranged parallel with the periosteal and endosteal surfaces to form the so-called **circumferential lamellae** (outer and inner circumferential lamellae).

1.7 Cancellous Bone

Cancellous or spongy bone consists of a series of interconnecting plates of bone — the **trabeculae**. Each bone trabecula contains collagen fibres

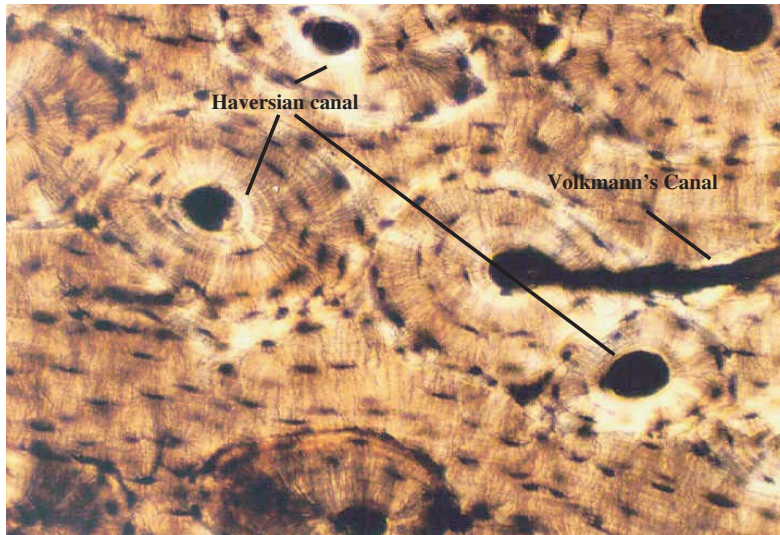


Fig. 5: Volkmann's canal connecting one Haversian canal to the other in another Osteon.

arranged in parallel lamellae. The surface of the trabecula is covered by an attenuated layer of flattened cells, the resting osteoblasts. Such a structure, in addition to providing a large surface area for metabolic activities of bone, gives mechanical strength without the disadvantages of undue weight. The thickest and strongest trabeculae are arranged in the direction subjected to the greatest stress (Wolff's Law).

1.8 Surfaces of Bone

The surfaces of bone are covered by a layer of bone-forming cells and the following connective tissues:

- **Periosteum** (outer layer)
- **Endosteum** (inner layer)

The outer surface of cortical bone is covered by the periosteum, a thin vascular membrane-like layer (Fig. 6). It blends with the fibres of ligaments and muscle insertions. The periosteum is absent at the sites of attachment of ligaments directly into bone e.g. at tuberosities and at the lines aspera

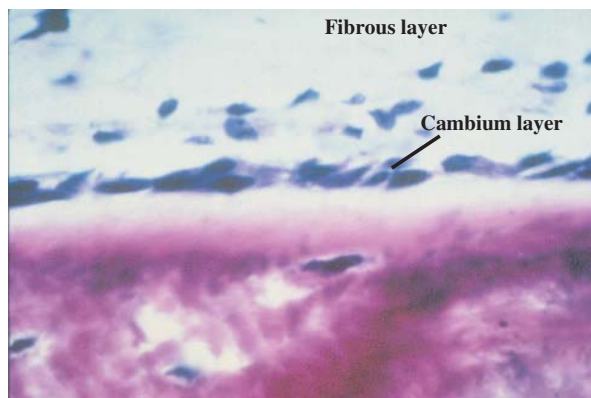


Fig. 6: Periosteum comprising of inner cambium layer and outer fibrous layer.

of the femur. The periosteum consists of an outer fibrous layer consisting of collagen fibres and fibroblasts and an inner cambium layer composed of flattened cells — the osteoprogenitor cells with the capacity to divide by mitosis and to differentiate into osteoblasts.

The endosteum lines the internal surface of bone. It is composed of osteoprogenitor cells and a very small amount of connective tissue. Both the surfaces, the periosteum and endosteum provide a continuous supply of osteoprogenitor cells or new osteoblasts for repair or growth of bone.

1.9 Cellular Components

Bone is a very specialised type of connective tissue consisting of cells and an intercellular matrix. There are three cell types:

- **Osteoblasts** — the bone forming cells, located on the surfaces of bone lying side by side like a simple cuboidal epithelium. These cells are responsible for the synthesis of organic components of the bone matrix. When active, they show high alkaline phosphatase activity.
- **Osteocytes** — the cells occupying the lacunae in the bone matrix. They possess long thin cytoplasmic processes — the **filopodia** located in thin cylindrical spaces or canals in the bone matrix — the **canaliculi**.

Nutrients and oxygen pass between the blood vessels and distant osteocytes by the arrangement of the canaliculi. Osteocytes also break down the bone matrix by osteocytic osteolysis to release calcium for calcium homeostasis.

- **Osteoclasts**— the large, multi-nucleated cells formed by fusion of monocytes. They lie in shallow depressions on the bone surface called the **Howship's lacunae**.

1.10 Bone Matrix

The bone matrix is composed of:

- **Organic matter**

Consisting of **type I collagen fibres** embedded in the ground substance containing proteoglycans and glycoproteins. The collagen fibres are made up of bundles of fibrils to resist pulling forces.

- **Inorganic matter**

Made up of **stiffening substances** to resist bending and compression. The bone mineral is an analogue of crystals of calcium phosphate — **hydroxyapatite** $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ a substance that can only be seen under electron microscopy (Fig. 7). It is this association of hydroxyapatite with collagen fibres which is responsible for the hardness of bone.

1.11 Marrow

This tissue fills the cylindrical cavities of long bones and occupies the spaces of cancellous bones. In long bones, the marrow is yellow in colour consisting mainly of fat cells and some marrow cells. In contrast, the marrow in flat and short bones is red in colour containing connective tissue, blood vessels and numerous “marrow cells” — myelocytes, erythroblasts, giant cells and some fat cells (Fig. 8).

The marrow is the organ of haematopoiesis. This process occurs in all bones at birth. With maturation, haematopoiesis is confined to the vertebral column, the bones of the pelvic girdle, the ribs, skull and the proximal end of long bones.

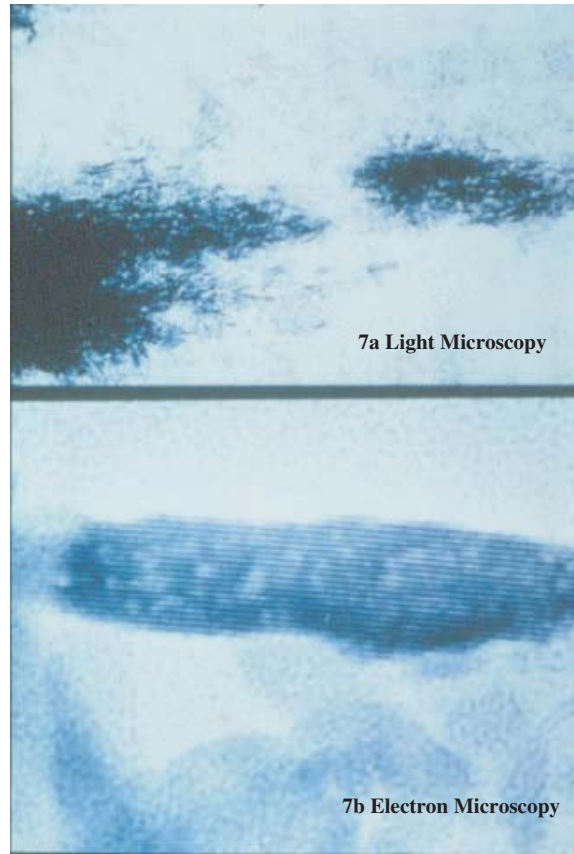


Fig. 7: (a) Crystals of hydroxyapatite as seen under light microscopy. (b) Each crystal can only be visualised under electron microscopy.

1.12 Histogenesis

There are two types of histogenesis of bones namely intra-membranous ossification and endochondral ossification.

1.13 Intra-Membranous Ossification

This occurs in flat bones such as the skull and clavicle. In this process, the bone is developed from a condensation of mesenchymal tissue — the

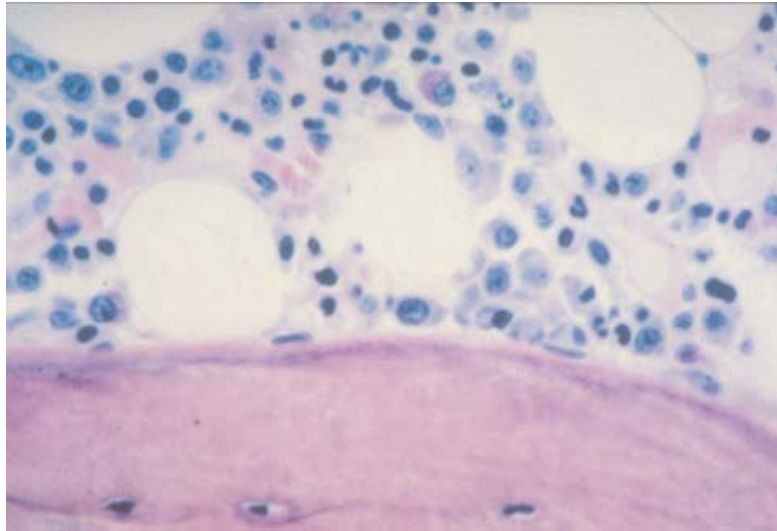


Fig. 8: Marrow cells in medullary canal of long bone. The empty vacuoles indicate spaces previously occupied by fat cells.

ossification centre. This tissue differentiates directly into **osteoblasts** which synthesise osteoid which then undergoes calcification.

1.14 Endochondral Ossification

This type of histogenesis occurs in long bones and short bones. The primary ossification centre appears in the middle of the long bone and produces **chondrocytes**. The chondrocytes then undergo hypertrophy and the cartilage matrix undergo calcification. The chondrocytes are then invaded by primitive mesenchymal cells and blood vessels to differentiate into **osteoblasts** and blood-forming cells of bone marrow.

1.15 Growth Plate

This highly specialised tissue is responsible for the rapid longitudinal growth that occurs in long bones. A more accurate term for it is the epiphyseal plate. Since the epiphysis is moving away from the centre of the bone

whilst growth occurs in the metaphysis, it is the shaft and not the end of the bone which grows.

The growth plate is circular or oval in cross-section. It has the shape of an irregular disc. Indeed, the diameter of the long bone is greatest at the level of the growth plate.

The growth plate is divided into various zones according to their morphology and function (Fig. 9). Just beneath the epiphysis is the reserve zone ('resting zone') and adjacent to this the proliferation zone, the hypertrophic zone and the zone of provisional calcification.

In the reserve zone or 'resting zone' (even though the cells are not resting) are cells spherical in shape and present singly or in pairs. They are separated by more extracellular matrix than in other zones. The **chondrocytes** show little or no proliferation activity. This zone provides the source of chondrocytes.

The flattened cells in the proliferation zone are arranged in longitudinal columns. The cartilage cells in this zone are the only ones that divide. It is the top most cells of each column which acts as the source of those lower down.

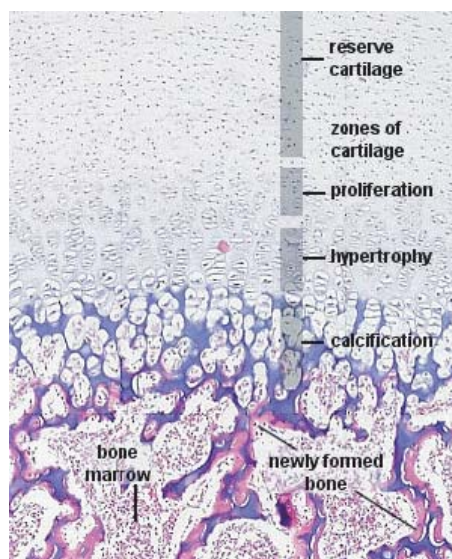


Fig. 9: Layers of physis.

It is the production of the cartilage cells that is responsible for the increase in length of a tubular bone though the cartilage columns are converted at their metaphyseal ends into bone.

In the hypertrophic zone, the flattened cells on the metaphyseal side of the cartilage columns are transformed into large spherical cells. The cells increase in size by about five to six times. The upper part of the hypertrophic zone has been shown to have the highest content of alkaline and acid phosphatase, phosphate, calcium and lysosomal enzymes. Degradation of proteoglycan occurs **due to** lysosomal enzymes. The initial calcification which occurs in the growth plate occurs within the longitudinal septa of the matrix.

The septum becomes calcified by the deposition of crystals in the bottom of the hypertrophic zone, also called 'the zone of provisional calcification.' The hypertrophic zone functions in preparing the matrix for calcification.

Small vessels appear in the upper part of the metaphysis immediately adjacent to the growth plate and invades the calcified cartilage. Plump oval osteocytes appear and form within the calcified cartilage. Osteoclasts are present to resorb both calcified cartilage and bone in the remodelling process.

Longitudinal growth of bone occurs from the physis or growth plate. Appositional growth occurs from the periosteum.

1.16 Blood Supply of Bone

Bone is a highly vascular structure. Like all other living tissues, it is supplied by several blood vessels.

The normal blood supply of a long bone is best considered in terms of vascular systems (Rhineland, 1972; 1974) according to its function as listed below:

- **Afferent vascular system**

The afferent vascular system comprises of arteries and arterioles carrying nutrients to bone. These include the principal nutrient artery, the metaphyseal arteries, the epiphyseal artery and the periosteal arterioles.

The principal nutrient artery enters the long bone through its nutrient foramen and divides into an ascending and descending branch to supply the whole length of the medullary bone in the long bone.

The old concept of a single periosteal artery supplying the whole of the long bone and dividing into similar ascending and descending branches is no longer true. Instead, it is now well established that there are numerous musculo-periosteal vessels entering the bone at multiple points over its entire surface. These vessels are present in the various muscles attached to the bone surface. Likewise, the old taboo of applying a cerclage wire and strangulating the periosteal blood supply to a bone no longer holds true since we now know there are numerous periosteal vessels supplying bone at multiple entry points instead of just one vessel supplying it through a single portal of entry.

The epiphysis and metaphysis have separate circulations, divided by the growth plate. They unite at maturity. After maturity, the three sources of blood supply to the diaphysis are:

- Nutrient artery
- Metaphyseal arteries (proximal, distal)

These arteries enter the metaphysis on all sides at ligamentous attachments.

The branches of the nutrient artery anastomose at each end of the medulla with the metaphyseal arteries to form the **medullary arterial supply** — the major supply to the diaphyseal cortex.

- Periosteal arterioles

This arterioles enter at fascial attachments to supply the external third of the cortex locally.

- **Efferent vascular system**

This system comprises of the veins and venules carrying waste products away from bone. These include the metaphyseal veins and in the diaphysis, the cortical venous channels from deep cortex to periosteal venules, the venae comitantes accompanying the nutrient artery and large emissary veins which completely traverse the cortex.

- **Intermediate vascular system**

There is no true capillary network in bone as is present in soft tissues between the afferent and efferent vascular systems.

The ultimate vascular channels in the cortex are blood vessels of capillary size in rigid bony canals (usually one in each canal). They form a very important system, each vessel conveying nutrients to the osteocytes each in its own otherwise very much isolated separate fluid compartment.

1.17 Blood Flow in Bone

The basic components of the afferent vascular system, the principal nutrient artery and the metaphyseal arteries carry blood from the circulation almost exclusively into the medulla. The intravascular pressure in the medulla is higher than in the periosteal area. This pressure gradient is the chief factor maintaining the blood flow in bone **centrifugally** (Brookes, 1971). The periosteal arterioles convey blood to the diaphyseal cortex only along the heavy fascial attachments. Their terminal branches anastomose in the cortex with the terminal branches of the medullary arterial system. The medullary arterial supply provides circulation to the inner two-thirds of the cortex leaving the periosteal arterial supply to provide circulation to the remaining outer third of the cortex.

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References

- Brookes M (1971) *The Blood Supply of Bone*, Butterworths, London.
- Rhineland FW (1972) Circulation in bone, in: Bourne GH (ed.), *The Biochemistry and Physiology of Bone*, second edition. Academic Press, London, New York, pp. 2–77.
- Rhineland FW (1974) Tibial blood supply in relation to fracture healing, *Clin. Orthop.* **105**:34–81.