HARD TISSUE BIOMECHANICS

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Contents

Summary

Bone tissue is described as a material and as a biological system. The extracellular matrix of bone tissue, the “material” of bone, is described first in terms of the types of bone tissue, then in terms of the interfaces, porosities and fluids that fill those spaces. The cells that make the abundant extracellular matrix of bone a living tissue are described and their functions delineated. Many of these cells are part of a connected cellular network in bone tissue, a network whose life maintenance functions have not all been revealed. Bone is a porous solid whose physiological range of function is at strain levels classified as infinitesimal. Anisotropic linear elasticity is an adequate model for many mechanical aspects of bone function, anisotropic linear poroelasticity being required in the important situations where pore fluid pressure of pore fluid movement occurs. The values of the basic physical parameters of anisotropic linear elasticity and anisotropic linear poroelasticity appropriate for bone tissue are summarized. Representation of the architecture and elastic properties of cancellous bone tissue is given special attention.

1. Introduction

Bone is a remarkable and extremely complex connective tissue. It has at least two major functions. First, it is the material from which the skeleton is made and the skeleton provides mechanical support and protection for the organism. The bone tissue of the skeleton is continually changing to adapt its form and structure to this task. From the birth to the death of the organism it modifies its structure by laying down new bone

tissue and resorbing old. A second function of bone is to store the minerals, particularly Ca^{++}, needed to maintain a mineral homeostasis in the body by regulating the concentrations of the key blood electrolytes including Ca^{++}, H^{+} and HPO_4^{-}.

Bone differs from the other connective tissues because of its greater stiffness and strength due to its mineralization. These properties stem from its being a composite material formed by the deposition of a mineral, apatite or hydroxyapatite, in a frame of collagen. The stiffness of bone is the key to understanding why it differs so greatly from other tissues. While other connective tissues grow interstitially, bone grows only by the addition of tissue on a cell-laden surface. Bone does not retain its scar tissue like other tissues do, and long bones have a very complicated mechanism for growing longer.

After the next two sections, in which the gross- and micro-anatomy of a long bone is briefly described, there is a short description of the five types of cells associated with bone tissue. This is followed by four sections on cortical bone (elastic symmetry, poroelastic model, electrokinetic effects and strength) and two sections on cancellous bone (architecture and elastic properties). The last four sections concern the structural adaptations that occur in living bone tissue to accommodate changes in the environmental loading the whole bone is subjected to. The final section concerns the relevant literature.

2. The Types of Bone Tissue

At the macroscopic level there are two major forms of bone tissue, called *compact* or *cortical* bone and *cancellous* or *trabecular* bone. The location of these bone types in a femur is illustrated in Figure 1. Cortical or compact bone is a dense material with a specific gravity of almost two in humans and a little over two in cattle; see Figure 2. It forms most of the outer shell of a whole bone, a shell of variable thickness. The external surface of bone is smooth and is called the periosteal surface or periosteum. The periosteum is a specialized membrane, a layered and highly vascularized structure, covering most of the external surface of a bone. It consists of an outer dense layer of collagenous fibers and fibroblasts. This relatively impermeable fiber stocking is attached to the exterior surface of bone and is always under tension. The longitudinal central tubular passage in a long bone (illustrated but not labeled in Figure 1) is called the medullary canal. The surface of this canal is called the endosteal surface or the endosteum. The endosteum is mainly a cell layer; it does not contain the extensive collagenous structure of the periosteum. The diaphysial region of a long bone is the mid-shaft and the epiphysial regions are the ends of the bone. The flared regions in between are called the metaphysial regions.

Each of the bone tissue types described above is mineralized. As noted, the mineralization is orderly except in the case of woven bone. The deposition of the mineral in the collagen template is illustrated in Figure 3. There exist spaces in the hierarchical structure of collagen that are designed to receive the mineral deposition. The mineral is apatite or hydroxyapatite ($[Ca_{10}(PO)_4](OH)_2$) or some amorphous or approximate form of hydroxyapatite. The simultaneously occurring interactive growth of collagen, apatite and bone tissue is illustrated in Figure 4. Each of the bone tissue

types is described below: cancellous bone and the three types of cortical bone, lamellar, osteonal (Haversian) and woven.

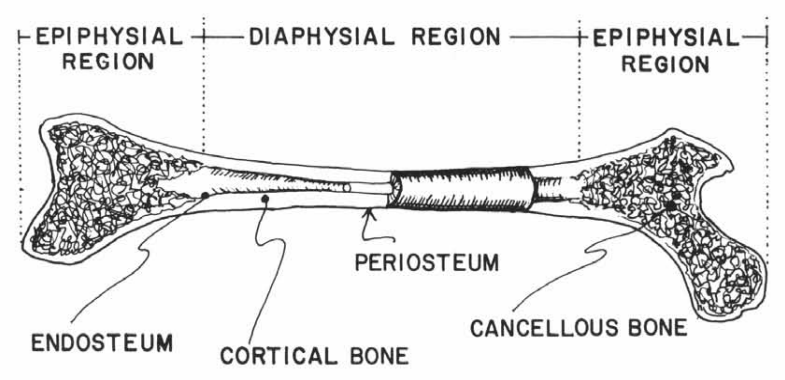

Figure 1. Longitudinal section of the femur illustrating cancellous and cortical bone types

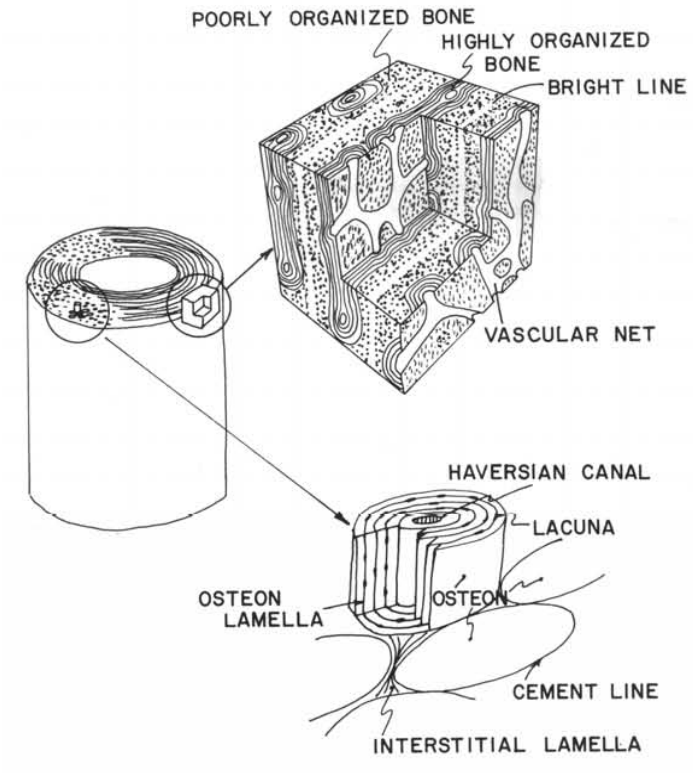

Figure 2. Typical bone structures in the diaphysis of the femur; two types of cortical bone are illustrated: lamellar and osteonal.

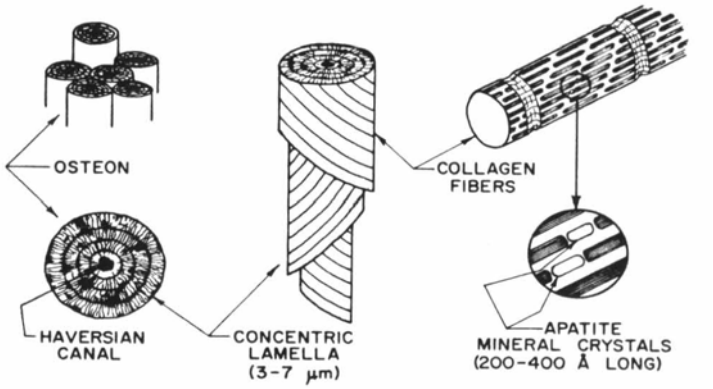

Figure 3. Detailed structure of an osteon

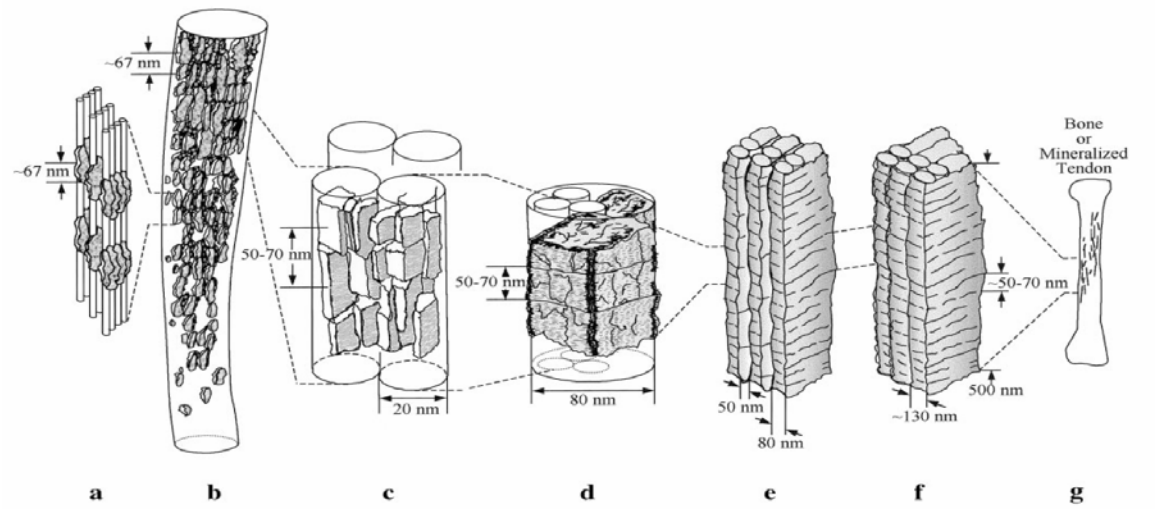

Figure 4. A schematic diagram of the organization and interaction of collagen and mineral at different structural levels of hierarchy for a calcified vertebrate tissue. (a) Based on the current model of collagen assembly and the manner of its association with mineral, crystal platelets nucleate in collagen channels or gaps created by periodic (≈ 67 nm) hole and overlap zones. (b) Crystal platelets grow in length along their crystallographic *c*-axes and in width through the channel or gap spaces (c) As collagen macromolecules grow as well to microfibrils and fibrils (≈ 20 nm in diameter), crystals fuse into larger and thicker plates in which their periodic deposition (≈ 50–70 nm) and parallel nature are still maintained. At this stage, interfibrillar plates may be developing. (d) Crystal plates grow larger in all dimensions at the level of collagen fibers (≈ 80 nm and greater in diameter). (e) Fibers next associate to create a series of parallel plate aggregates that may vary in length, width, and thickness. Some of the aggregates may represent the interfibrillar plates formed earlier. The typical thickness of the aggregates is ≈ 80 nm and a frequent size along their length is ≈ 500 nm. Individual plate aggregates are initially separated by ≈ 50 nm (e), but this space gradually disappears as mineral deposition proceeds in the tissue and aggregates would grow to thicknesses of ≈ 130 nm. (f) Edges of plate aggregates still maintain ≈ 50- to 70-nm periodicity, indicative of the basic collagen structure underlying mineral formation. (g) Ultimately the plate aggregates become lamellar in shape and constitute a portion of bone or

mineralized tendon. Independent of the mineralization associated with the hole and overlap zones, there is surface mineralization of the collagen structures in b–f. This aspect of mineral formation is not depicted in b–d.

2.1. Cancellous Bone

Cancellous bone generally exists only within the confines of the cortical bone coverings. Cancellous bone is also called trabecular bone because it is composed of short struts of bone material called trabeculae (from the Latin for "little beam"). The connected trabeculae give cancellous bone a spongy appearance and it is often called spongy bone (Figure 5). There are seldom blood vessels within the trabeculae, but there are vessels immediately adjacent to the tissue and they weave in and out of the large spaces between the individual trabeculae. Cancellous bone has a vast surface area as would be suggested by its spongy appearance. This is illustrated by the human pelvis, which has an average volume of 40 cm^3 and an average periosteal surface area of 80 cm^2, but the average surface area of its trabecular bone is 1600 cm^2.

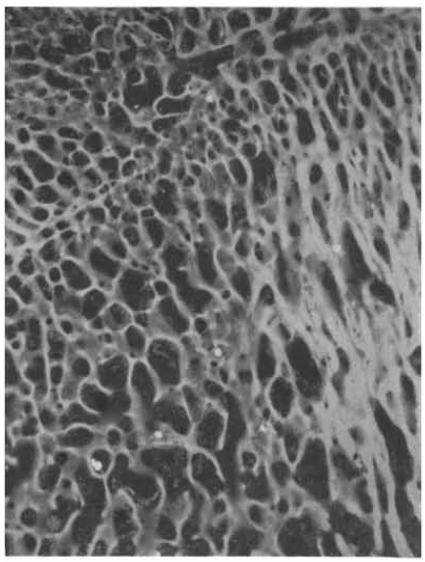

Figure 5. Porous structure of cancellous bone tissue

2.2. Lamellar Bone

Lamellar bone consists of a number of concentrically arranged laminae when it occurs in the midshaft of a long bone, as illustrated in Figure 2. The thickness of the laminae is about 200 μm. Between each lamina and the next there is a net-like system of blood vessels that is essentially two-dimensional, with an occasional large radial vessel through a lamina connecting two of the tangential two-dimensional nets. Each lamina is divided into the three zones shown in Figure 2. The first zone, which extends from the surface of the blood network to about one-third of the way across the lamina, is of highly organized bone that is dense. The second zone, which also extends for about one-third of the distance, is a poorly organized tissue. This zone is interrupted in the middle by a line that, in ordinary light, appears to be bright. This line, called the bright line, is the boundary between the two blood supply networks bounding the lamina. The lamina

is symmetric about the bright line and there is another half-layer of poorly organized bone, followed by a full layer of highly organized bone before the next blood network is reached.

2.3. Osteonal Bone

Osteonal bone is illustrated in Figures 2 and 3. It consists of quasi-cylindrical-shaped elements called *osteons* or Haversian systems. These bone microstructures were originally named after Clopton Havers (1650-1702), an English physician and anatomist. However, they were first identified by Antoni van Leeuwenhoek (1632-1723), a Dutch maker of microscopes who made pioneering discoveries at the microscopic scale. Contemporary preference is to avoid eponyms and call the structures osteons rather than Haversian systems. There are two kinds of osteons, primary and secondary. Primary osteons are the structures around blood vessels that are formed when the bone is initially formed. Secondary osteons are osteons formed after the tissue is mineralized by a process in which bone cells first excavate a tubular path through the hard tissue, and then deposit the osteon layer by layer. Secondary osteons are the osteons of primary interest because important human adult bones (e.g., the leg and arm bones) consist mainly of secondary osteons. Because the secondary osteons are the osteons of primary interest, the prefix secondary is usually dropped when referring to them. The prefix primary is not dropped when referring to primary osteons. This is one of the rare cases when the secondary is more important than the primary.

Osteons are typically about 200 μm in diameter, the same thickness as the laminae in lamellar bone, and about one to two centimeters long. The thickness is the same because the blood supply for the osteon is a central lumen containing a blood vessel and thus every point in the osteon is no more than about 100 μm from the blood supply, as was the case with lamellar bone. Osteonal bone is organized to accommodate small arteries, arterioles, capillaries, and venules of the microcirculation. While the blood vessels in the osteonal canal transport blood generally along the long axis of a long bone, it is the Volkmann canals that contain the blood vessels that transport blood generally perpendicular to the long axis of a long bone. These canals were named after the German physiologist Alfred Wilhelm Volkmann (1800-1877) who discovered them. A Volkmann canal connects different osteonal canals, generally intersecting the osteonal canals at right angles.

2.4. Woven Bone

Woven bone is found typically in both cortical and cancellous bone of young growing animals and in adults after a bone injury. During normal maturation woven bone is gradually replaced by lamellar bone so that, in man for example, there is normally no woven bone present after the age of 14 to 16 years. An additional distinguishing feature of woven bone is the relationship of mineral to collagen. In lamellar and osteonal bone these elements are present in fixed ratios and it seems virtually impossible for lamellar bone to become hypermineralized. The ratio of mineral to collagen in woven bone varies enormously, and hyper-mineralization is often observed. Woven bone appears to bear the same relationship to lamellar bone as a temporary scaffolding bears to a completed structure.

2.5. Similarities and Conversions of Bone Types

The osteons of osteonal bone and the laminae of lamellar bone appear to be just different geometric configurations of the same material. It was indicated above that in both geometric configurations no point in the tissue is more than about 100 μm away from the blood supply. Both osteonal and lamellar bone occur simultaneously in the long bones of mature animals. In very young animals the long bones are composed of woven bone with a few primary osteons. With maturation the woven bone is converted to lamellar bone and, at maturity, there is a partial conversion to osteonal bone. The conversion from lamellar to osteonal bone is somewhat of a biological enigma. Osteonal bone is known to have a less efficient local circulation system and to have less mechanical strength compared to lamellar bone, yet the percentage of osteonal bone generally increases with age.

3. Bone Interfaces, Porosities and Fluids or Gels

There are three levels of bone porosity within cortical bone and within the trabeculae of cancellous bone, all containing a fluid or gel; these are, from the one with the largest pores to the one with smallest pores, the vascular porosity, the lacunar-canalicular porosity and the collagen-apatite porosity. In addition there is a porosity of the “spongy” bone that consists of the pores external to the trabeculae in trabecular bone. There are two interfaces between the three levels of bone porosity within cortical bone and within the trabeculae of cancellous bone. There is an additional interface, called the cement line, which forms the outside boundary of an osteon. The purpose of this section is to describe these interfaces, porosities and the fluids or gels within them. A sketch of a partial cross-section of an osteon (Figure 6) shows some of the small-scale features of bone. It was noted above that osteons are cylindrical structures about 100 mm in radius. They make an angle of about 5˚ to 15˚ with the long axis of a bone and trace a generally helical path. They contain at their center an osteonal canal (Haversian canal). This canal contains blood vessel(s), a nerve and some space occupied by bone fluid. The walls of the osteonal canals are covered with cells and behind the cells are the entrances to the canaliculi. The canaliculi are passageways that run inside an array of roughly disk shaped cavities called lacunae, which contain bone cells (osteocytes), or from the lacunae to the osteonal canal (Figure 6). The three-dimensional region between adjacent osteons is called the cement line. The bone interfaces are described below - the periosteum, the cellular interface (IC) (which includes the endosteum), the interface consisting of the walls of the lacunae and the canaliculi (ILC), and the cement lines. The porosities, also described in greater detail below, include the vascular porosity (PV), the lacunar-canalicular porosity (PLC), the collagen-apatite porosity (PCA), and the porosity of the inter-trabecular space (PIT). These acronyms have been selected so that the first letter indicates the structure, interface (I) or porosity (P), and the subsequent letters in the acronym indicate which interface or which porosity. The fluids or gels are bone marrow, fat, blood and bone fluid. The interfaces are structures of varying thickness and permeability between the relevant fluid compartments and structures in bone.

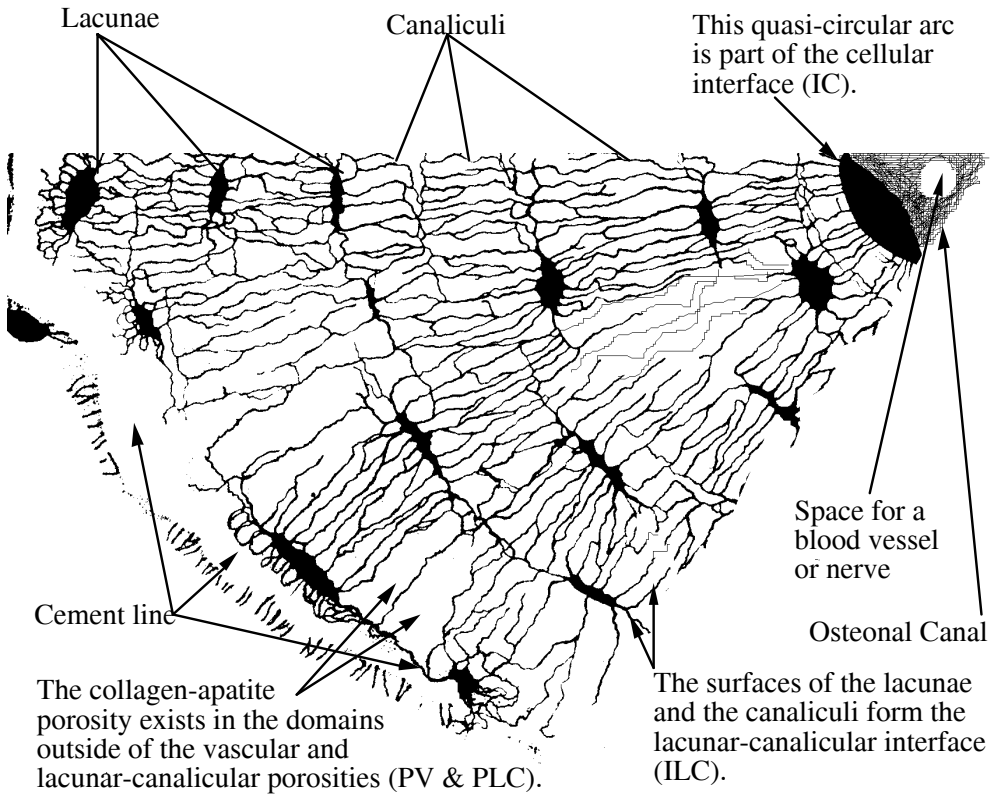

Figure 6. A pie-shaped section of an osteon; the osteonal canal is on the upper right, the cement line to the left. The osteonal canal is part of the vascular porosity (PV), the lacunae and the canaliculi are part of the lacunar-canalicular porosity (PLC) and the material in the space that is neither PV nor PLC contains the collagen-apatite porosity (PCA). The three interfaces, the cement line, the cellular interface (IC) and the lacunar-canalicular interface are each indicated. The radius of an osteon is usually about 100 μm, and the long axis of a lacuna is about 15 μm. Using this information it should be possible to establish the approximate scale of the printed version of this illustration

3.1. IC-The Cellular Interface, Including the Endosteum

All the surfaces of the tubular cavities of bone that contain the vasculature, the osteonal canals and the Volkmann canals, as well as the endosteum and the inner layer of the periosteum, form a single cellular interface. This interface, a small part of which is illustrated in Figure 6, is a continuous confluent layer of bone lining cells, one side of which faces the vascular space and the other side of which faces the mineralized matrix. The region interior to this interface was called the "milieu intérieur" by the French physiologist Claude Bernard (1813 - 1878). There is transport of bone fluids through the interface. During each cycle of bone loading due to the animal’s activity, the fluid on the vascular side of the interface will mix briefly with the fluid on the mineralized matrix side of the interface. As a first approximation it appears reasonable to assume that the hydraulic resistance of this interface is much less than the hydraulic resistance of the lacunar-canalicular porosity, which is on the bone side of the interface.

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Biography Sketch

Stephen Corteen Cowin received his BES and MS in Civil Engineering from Johns Hopkins University and his Ph.D. in Engineering Mechanics from the Pennsylvania State University. He has been a City University of New York Distinguished Professor in the Departments of Biomedical and Mechanical Engineering at City College since 1988. Before taking up his position at City College he was the Alden J. Laborde Professor of Engineering in the Department of Biomedical Engineering at Tulane University. His principal research interest is the mechanics of materials, particularly in determining the influence of microstructure on the gross mechanical behavior of granular, composite, and biological materials. He was the recipient of the Best Paper Award from the Bioengineering Division of the American Society of Mechanical Engineers in 1992; a recipient of the Melville Medal from the American Society of Mechanical Engineers in 1993, and a recipient of the European Society of Biomechanics Research Award in 1994. In 1999 he received the H. R. Lissner medal of the American Society of Mechanical Engineers for contributions to biomedical engineering. In 2004 he was elected to the United States National

Academy of Engineering. In 2004 he also received the Maurice A. Biot medal of the American Society of Civil Engineers. He is the author of over 250 research papers and editor or co-editor of seven books and he presently serves, or has served, in an editorial capacity on 11 technical journals.