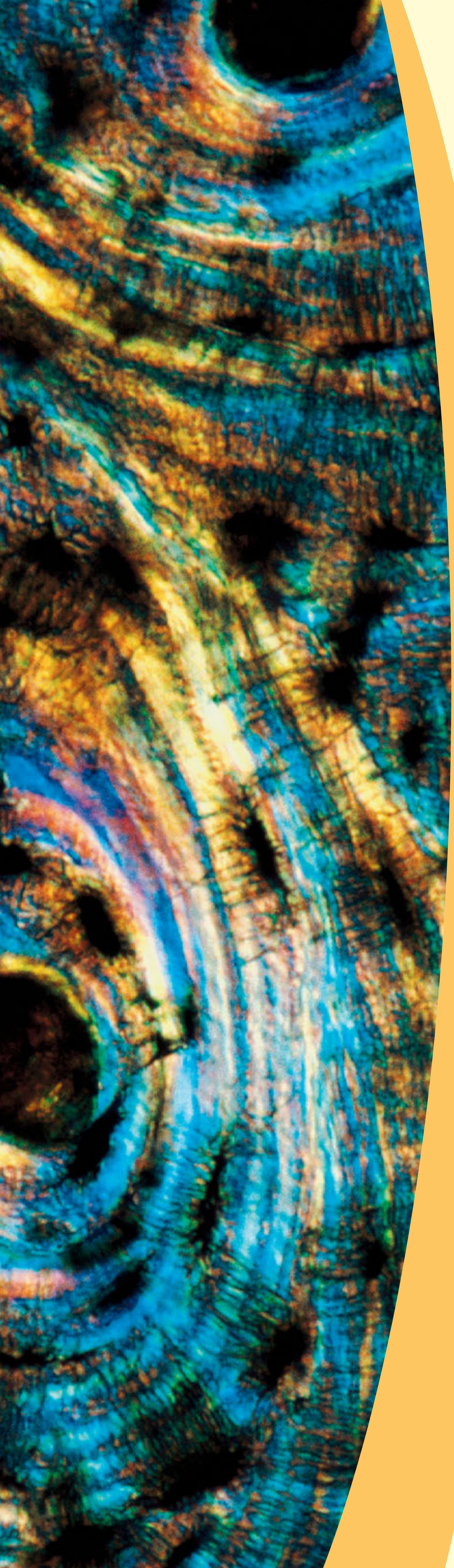


6 Bones and Skeletal Tissues

Osteons in human compact bone (color-enhanced image).

The skeletal system is composed of the bones, cartilages, and joints that form the internal framework. Bones provide support and shape to the body, attachment sites for muscle, and a storage depot for essential minerals. Cartilage, a component of many joints, aids in support and movement as it cushions abutting bone surfaces. Cartilage and bone are also linked developmentally; most bones are first formed in cartilage tissue, which is then replaced by bone tissue during prenatal and childhood growth.

The skeletal system also contains clues to our personal story. The bones within you are not like the dead, dried bones you are examining in the laboratory; rather, they are living, dynamic organs that reflect many aspects of your life: age, gender, ethnicity, height, and health and nutrition status. Clues to these details can be understood only by using knowledge of the structure and growth of bone tissue.

This chapter focuses on the structure, function, and growth of cartilage and bone. The individual bones of the skeleton are described in Chapters 7 and 8. The details of joint structure and function are covered in Chapter 9.

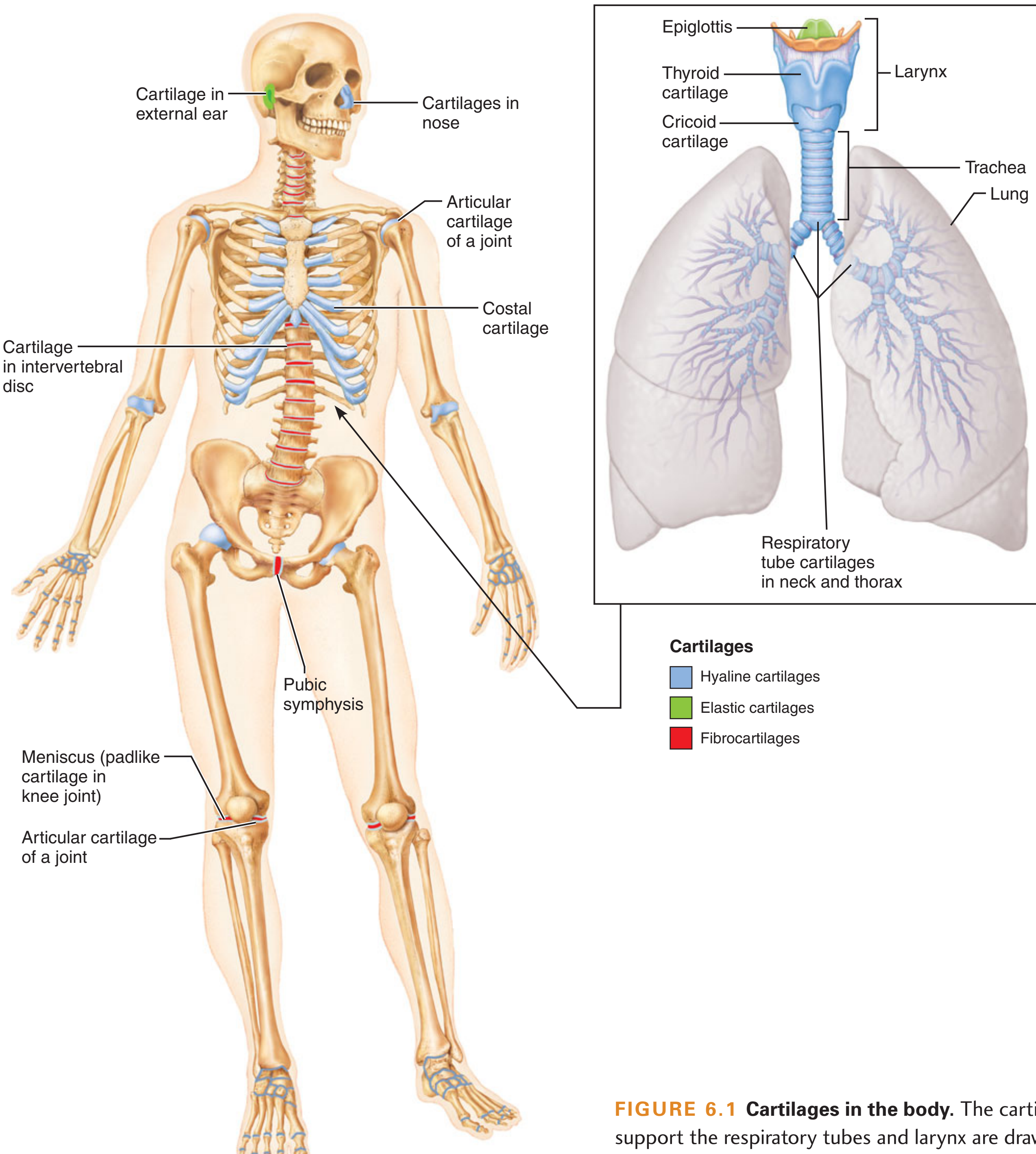


FIGURE 6.1 Cartilages in the body. The cartilages that support the respiratory tubes and larynx are drawn separately at right.

CARTILAGES

- Locate the major cartilaginous structures of the adult human body, and explain the functional properties of cartilage tissue.
- Compare the structure, functions, and locations of the three kinds of cartilage tissue.
- Explain how cartilage grows.

Location and Basic Structure

Cartilaginous structures are found throughout the adult human body. These cartilages, shown in **Figure 6.1**, include (1) cartilage in the external ear; (2) cartilages in the nose; (3) **articular cartilages,** which cover the ends of most bones at movable joints; (4) **costal cartilages,** which connect the ribs to the sternum (breastbone); (5) cartilages in the larynx (voice box), including the *epiglottis,* a flap that keeps food from entering the larynx and the lungs; (6) cartilages that hold open the air tubes of the respiratory system; (7) cartilage in the discs between the vertebrae; (8) cartilage in the pubic symphysis; and (9) cartilages that form the *articular discs* within certain movable joints, the *meniscus* in the knee for example.

Cartilage is far more abundant in the embryo than in the adult: Most of the skeleton is initially formed by fast-growing cartilage, which is subsequently replaced by bone tissue in the fetal and childhood periods. This process is described later in the chapter, pp. 135–136.

A typical cartilaginous structure in the skeleton is composed of the connective tissue cartilage, which contains no nerves or blood vessels. The structure is surrounded by a layer of dense irregular connective tissue, the **perichondrium** (per″ĭ-kon′dre-um; "around the cartilage"), which acts like a girdle to resist outward expansion when the cartilage is subjected to pressure. The perichondrium also functions in the growth and repair of cartilage (see Figure 6.2a).

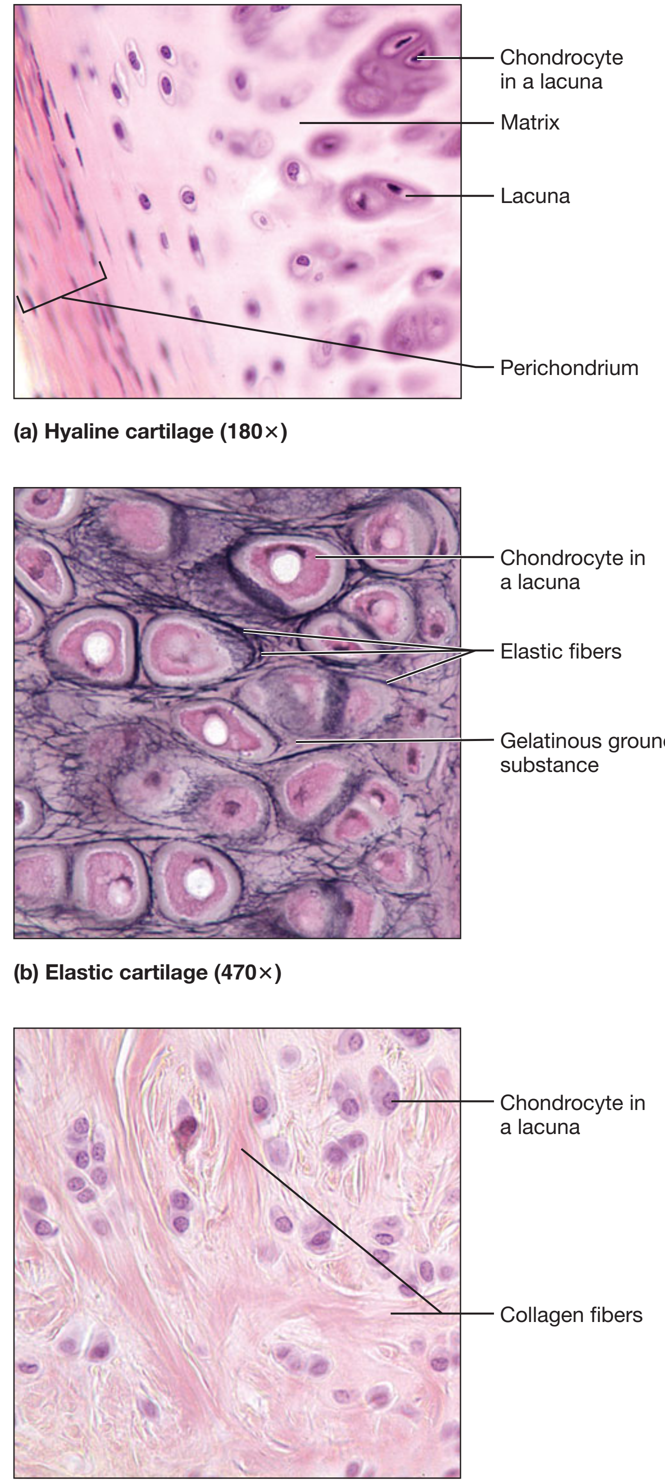
Cartilage tissue consists primarily of water (60% to 80%) and is very resilient; that is, it has the ability to spring back to its original shape after being compressed. For more information on the unique properties of cartilage tissue, see **A Closer Look** on p. 124.

Types of Cartilage

Three types of cartilage tissue occur in the body: *hyaline cartilage, elastic cartilage,* and *fibrocartilage* **(Figure 6.2)**. While reading about these, keep in mind that cartilage is a connective tissue that consists of cells called **chondrocytes** and an abundant extracellular matrix. In contrast to connective tissue proper, in cartilage tissue each chondrocyte is located in a space in the matrix called a **lacuna** (lah-koo′nah), literally a "lake" or "cavity." The matrix contains fibers and a jellylike ground substance of complex sugar molecules that attract and hold water (see Chapter 4, p. 80).

Hyaline Cartilage

Hyaline cartilage (hi′ah-līn; "glass"), which looks like frosted glass when viewed by the unaided eye, is the most abundant kind of cartilage (see Figure 6.1). When viewed under the light microscope, its chondrocytes appear spherical (Figure 6.2a). The only type of fiber in the matrix is a collagen unit fibril, which forms networks that are too thin to be seen with a light microscope. The gelatinous ground substance



(a) Hyaline cartilage (180×)

(b) Elastic cartilage (470×)

(c) Fibrocartilage (285×)

FIGURE 6.2 Types of cartilage tissue.

a closer look

The Marvelous Properties of Cartilage

Without healthy cartilage to cushion the movable joints, people would find vigorous activities such as playing tennis next to impossible. Cartilage is resilient: If you push on it and then ease the pressure, it bounces back. Such resilience allows the articular cartilages at the ends of the bones to cushion the impact of various activities, including lifting heavy objects, sprinting, and jumping. After an action is complete, the cartilage tissue springs back to await the next movement.

Another important feature of cartilage tissue is its capability for rapid growth, which enables it to keep pace with the rapid growth of the embryo. Indeed, most of the embryo's "bones" originate as cartilage models that are gradually replaced by bone tissue. Throughout childhood and adolescence, growth plates of cartilage remain in most bones and bring about most growth of the skeleton. Once adult size is reached, growth plates fuse, and cartilage growth slows. One would expect cartilage to require a rich blood supply for rapid growth, yet cartilage contains no blood vessels. Instead, the cells (chondrocytes) in cartilage are specially adapted to live under low-oxygen conditions and can survive on the little oxygen that diffuses to them from distant vessels in the surrounding perichondrium. In fact, cartilage and blood vessels are strictly incompatible: Cartilage secretes chemicals that prevent blood vessels from growing into it, and it cannot develop in parts of the embryo that are well supplied with blood vessels or oxygen.

The cartilage of tennis players and other athletes should be well nourished and well hydrated because of the great physical demands vigorous sports place on the joints.

The reason for the resilience of cartilage is its ability to hold tremendous amounts of water. In fact, cartilage is 60% to 80% water, largely because the complex sugars in its ground substance have so many water-attracting negative charges. When the cartilage is compressed, the water molecules are forced away from the negative charges. As the pressure increases, the negative charges are pushed closer together until they repel each other, resisting further compression. Then, when the pressure is released, the water molecules rush back to their original sites, causing the cartilage to spring back forcefully to its original shape. These dynamics also play a vital role in the nourishment of cartilage: The flow of fluid during and after compression carries nutrients to the chondrocytes. For this reason, long periods of inactivity can weaken the cartilages of the joints.

The rapid growth of cartilage is another result of its capacity to hold fluid. Because cartilage matrix is mostly water, nutrients from distant capillaries can diffuse through it quickly enough to supply the metabolic needs of the rapidly dividing cartilage-forming cells (chondroblasts). There is no need for a slow, time-consuming process of growing new capillary beds within the cartilage tissue itself. Furthermore, the ground substance secreted by the chondroblasts attracts so much water that the cartilage expands (grows) quickly with little expenditure of materials.

Because of the water-attracting nature of its ground substance, cartilage has a natural tendency to swell with water. To prevent excessive swelling, its matrix contains a network of thin, unstretchable collagen fibrils. This collagen also gives cartilage its ability to resist tension when pulled by external forces. Even though cartilage is strong in resisting tension and compression, it is weak in resisting shear forces (twisting and bending). Because of this weakness, torn cartilages are a common sports injury.

holds large amounts of water; thus, this tissue resists compression well. Hyaline cartilage provides support through flexibility and resilience. It makes up the articular cartilage that covers the ends of adjoining bones in movable joints. It also forms the cartilaginous attachments of the ribs to the sternum, accounts for most of the cartilage found in the respiratory structures, and forms the embryonic skeleton.

Elastic Cartilage

Elastic cartilage is similar to hyaline cartilage, but its matrix contains many elastic fibers along with the delicate collagen fibrils (Figure 6.2b). This cartilage is more elastic than hyaline cartilage and better able to tolerate repeated bending. The epiglottis, which bends down to cover the glottis (opening) of the larynx each time we swallow, is made of elastic cartilage, as is the highly bendable cartilage in the outer ear (Figure 6.1).

Fibrocartilage

Fibrocartilage is an unusual tissue that resists both strong compression and strong tension (pulling) forces. It occurs in certain ligaments and certain cartilages that experience both of these forces. It is a perfect structural intermediate between hyaline cartilage and dense regular connective tissue. Microscopically, it consists of thick collagen fibers (as in dense regular connective tissue) surrounding the chondrocytes within lacunae (Figure 6.2c). Two specific locations of fibrocartilage are in the *anulus fibrosus* portion of the discs between the vertebrae and in the articular discs of some joints, for example the menisci of the knee.

Growth of Cartilage

A piece of cartilage grows in two ways. In **appositional** (ap″o-zish′un-al) **growth,** "growth from outside," cartilage-forming cells (chondroblasts) in the surrounding perichondrium produce the new cartilage tissue by actively secreting matrix. In **interstitial** (in″ter-stish′al) **growth,** "growth from within," the chondrocytes within the cartilage divide and secrete new matrix. Cartilage stops growing in the late teens when the skeleton itself stops growing, and chondrocytes do not divide again. As a result, cartilage regenerates poorly in adults. The limited healing that occurs within cartilage in adults reflects the ability of the surviving chondrocytes to secrete more extracellular matrix, and typically cartilage is repaired with fibrocartilage.

Under certain conditions, crystals of calcium phosphate precipitate in the matrix of cartilage. Such calcification is a sign of aging in an adult, but in a child it is a normal stage in the growth of most bones (see p. 135). Note, however, that **calcified cartilage** is not bone: Bone and cartilage are always distinct tissues.

check your understanding

1. How does the matrix differ in each of the three types of cartilage?
2. Which type of cartilage is most abundant? List three locations where this type of cartilage is found.
3. Where are the chondroblasts located that produce new cartilage by appositional growth?

For answers, see Appendix B.

BONES

- Describe the functions of the bony skeleton and of bone tissue.
- Describe the structural components of bone tissue and the functions of its organic and inorganic parts.
- Differentiate the cells found in bone tissue and their functions.

The bones of the skeleton are *organs* because they contain several different tissues. Although bone tissue predominates, bones also contain nervous tissue in nerves, blood tissue in blood vessels, cartilage in articular cartilages, and epithelial tissue lining the blood vessels.

In our discussion of bone, we describe the functions of bone and then examine the composition of bone tissue. We then look at bone as an organ, examining the macroscopic and microscopic structure of bones, bone development and growth, and bone repair.

Functions of Bones

The functions of the skeletal system were briefly mentioned in the introductory paragraph of this chapter. More specifically, bone carries out the following functions:

1. **Support.** Bones provide a hard framework that supports the weight of the body. For example, the bones of the legs are pillars that support the trunk of the body in the standing person.
2. **Movement.** Skeletal muscles attach to the bones by tendons and use the bones as levers to move the body and its parts. As a result, humans can walk, grasp objects, and move the rib cage to breathe. The arrangement of the bones and the structure of the joints determine the types of movement that are possible. Support and movement are mutually dependent functions: The supportive framework is necessary for movement, and the skeletal muscles contribute significantly to the support of body weight.
3. **Protection.** The bones of the skull form a protective case for the brain. The vertebrae surround the spinal cord, and the rib cage helps protect the organs of the thorax.
4. **Mineral storage.** Bone serves as a reservoir for minerals, the most important of which are calcium and phosphate. The stored minerals are released into the bloodstream as ions for distribution to all parts of the body as needed.
5. **Blood cell formation and energy storage.** Bones contain red and yellow *bone marrow.* Red marrow makes the blood cells, and yellow marrow is a site of fat storage, with little or no role in blood cell formation. Red bone

marrow and the production of blood cells are described in detail in Chapter 18.

6. **Energy metabolism.** The role of bone cells in regulating energy metabolism has just recently been identified. Bone-producing cells, *osteoblasts* (described in the next section), secrete a hormone that influences blood sugar regulation. This hormone, *osteocalcin,* stimulates pancreatic secretions that reduce blood sugar levels (insulin). Osteocalcin also influences fat cells, causing them to store less fat and to secrete a hormone that increases the insulin sensitivity of cells. These results have clinical implications for the treatment of metabolic disorders related to blood sugar regulation, such as type 2 diabetes.

Bone Tissue

Like other connective tissues, bone tissue consists of cells separated by an extracellular matrix. Unlike other connective tissues, bone has both organic and inorganic components. The organic components are the cells, fibers, and ground substance. The inorganic components are the mineral salts that invade the bony matrix, making bone tissue hard. Bone does contains a small amount of tissue fluid, although bone contains less water than other connective tissues.

Extracellular Matrix

As with other connective tissues, it is the unique composition of the matrix that gives bone its exceptional physical properties. The organic components of bone tissue account for 35% of the tissue mass. These organic substances, particularly collagen, contribute the flexibility and tensile strength that allow bone to resist stretching and twisting. Collagen is remarkably abundant in bone tissue.

The balance of bone tissue, 65% by mass, consists of inorganic hydroxyapatites (hi-drok″se-ap′ah-tītz), or mineral salts, primarily calcium phosphate. These mineral salts are present as tiny crystals that lie in and around the collagen fibrils in the extracellular matrix. The crystals pack tightly, providing bone with its exceptional hardness, which enables it to resist compression. These mineral salts also explain how bones can endure for hundreds of millions of years, providing information on the sizes, shapes, lifestyles, and even some of the diseases (for example, arthritis) of ancient vertebrates.

Soaking a long bone in a weak acid for several weeks dissolves away the bone's mineral salts, leaving only the organic component, mainly collagen. The demineralized bone can be tied in a knot, demonstrating the great flexibility provided by the collagen in bone. It also confirms that without its mineral content, bone bends too easily to support weight. Baking a bone at high temperature destroys the organic portion of bone. What remains is the mineral component, stiff but extremely brittle. The proper combination of organic and inorganic elements allows bones to be exceedingly durable, strong, and resilient without being brittle.

The composite nature of bone can be compared to reinforced concrete: The collagen fibers, like the steel rods, provide tensile strength; the mineral salts, like the sand and rock in the concrete, provide compressional strength. In fact, bone is stronger than reinforced concrete in resisting compression and almost equal in tensile strength. Neither bone nor reinforced concrete resist torsional forces well. Indeed, most fractures to limb bones are caused by torsional forces.

Cells

Three types of cells in bone tissue produce or maintain the tissue: osteogenic cells, osteoblasts, and osteocytes. **Osteogenic cells** (os′tē-ō-jen′ik; *osteo* = bone, *genic* = producing) are stem cells that differentiate into bone-forming osteoblasts. **Osteoblasts** (os′tē-ō-blasts; *blast* = bud, sprout) are cells that actively produce and secrete the organic components of the bone matrix: the ground substance and the collagen fibers. This bone matrix secreted by osteoblasts is called **osteoid** (os′te-oid, "bonelike"). Within a week, inorganic calcium salts crystallize within the osteoid. Once osteoblasts are completely surrounded by bone matrix and are no longer producing new osteoid, they are called osteocytes. **Osteocytes** (*cyte* = cell) function to keep the bone matrix healthy. In fact, if osteocytes die or are destroyed, the bone matrix is resorbed.

The cells responsible for the resorption of bone are the fourth type of cell found within bone tissue, osteoclasts. **Osteoclasts** (*clast* = break; see Figure 6.14) are derived from a lineage of white blood cells. These multinucleated cells break down bone by secreting hydrochloric acid, which dissolves the mineral component of the matrix, and lysosomal enzymes, which digest the organic components.

Creating and destroying bone tissue is an ongoing process in normal, healthy bones. Destroying old bone tissue and replacing it with new tissue helps to keep our bones strong and enables them to respond to changing stresses. When we are physically active, new bone is formed, strengthening our skeletal support; when we are incapacitated, as with a broken limb or bedridden with illness, bone is resorbed because it is not needed to support the body. We will return to this process, called bone remodeling, later in the chapter.

check your understanding

4. Which component of bone tissue contributes to the strength and flexibility of bone? Which contributes to the hardness of bone?
5. What minerals are stored in bone, and which cells in bone tissue function to remove these minerals from the bone tissue?
6. What is the difference between an osteoblast and an osteocyte?

For answers, see Appendix B.

Classification of Bones

- Describe the gross anatomy of a typical long bone and a typical flat bone.
- Explain how bones withstand tension and compression.
- Describe the types of markings found on bones.

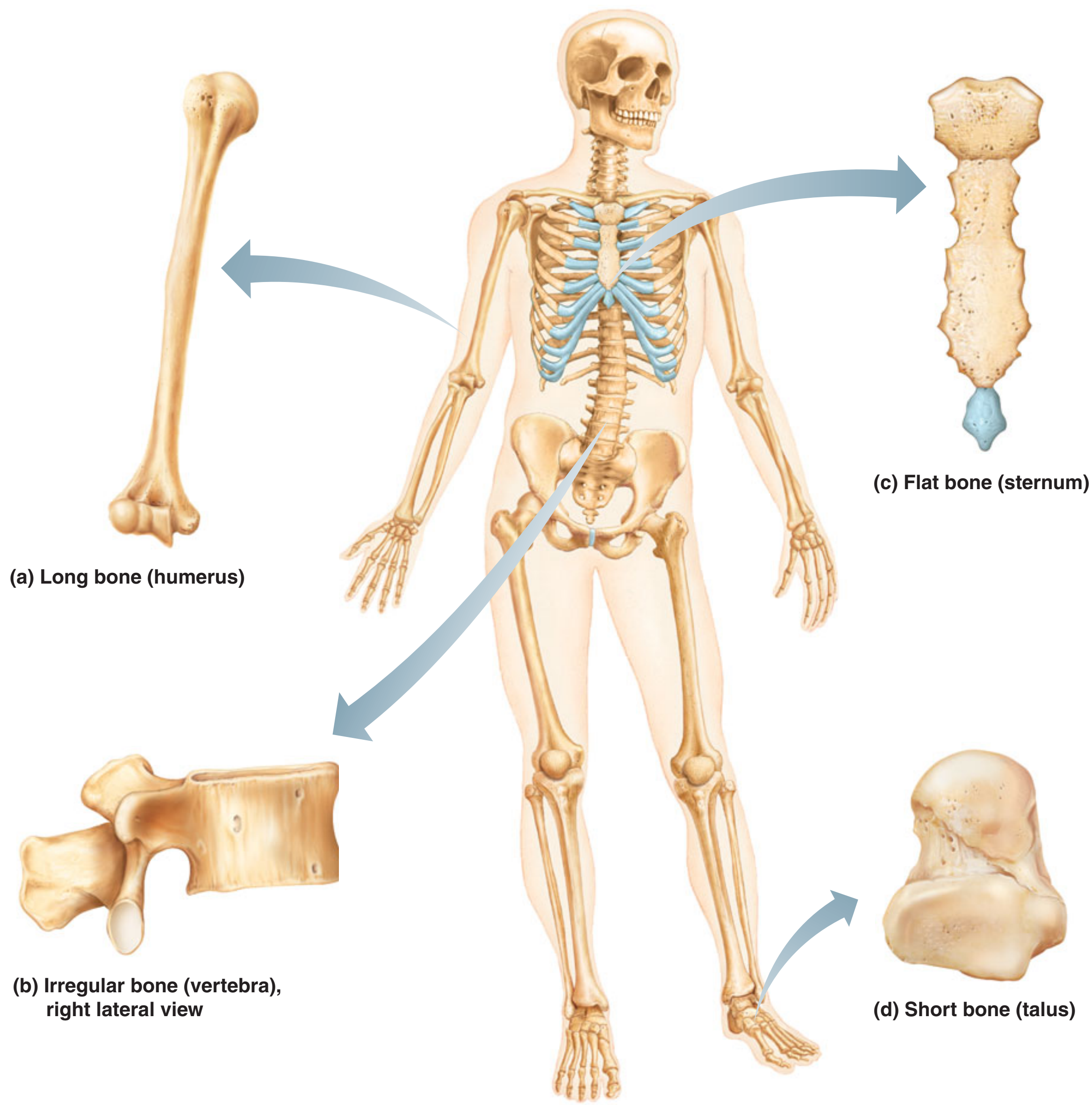


FIGURE 6.3 Classification of bones.

Bones come in many sizes and shapes. For example, the tiny pisiform bone of the wrist is the size and shape of a pea, whereas the femur (thigh bone) is large and elongated. The shape of each bone reflects its function and formation. The femur, for example, must withstand great weight and pressure, and its hollow cylindrical design provides maximum strength with minimum weight.

Bones are classified by their shape as long, short, flat, or irregular **(Figure 6.3)**.

1. **Long bones.** As their name suggests, long bones are considerably longer than they are wide (Figure 6.3a). A long bone has a shaft plus two distinct ends. Most bones in the limbs are long bones. These bones are named for their elongated shape, not their overall size: The bones of the fingers and toes are long bones, even though they are small.
2. **Short bones.** Short bones are roughly cube-shaped. They occur in the wrist and the ankle (Figure 6.3d).

   Sesamoid bones (ses′ah-moid; "shaped like a sesame seed") are a special type of short bone that forms within a tendon. A good example is the kneecap, or patella. Sesamoid bones vary in size and number in different people. Some clearly act to alter the direction of pull of a tendon. Others reduce friction and modify pressure in tendons, thus reducing abrasion or tearing.
3. **Flat bones.** Flat bones are thin, flattened, and usually somewhat curved (Figure 6.3c). Most cranial bones of the skull are flat, as are the ribs, sternum (breastbone), and scapula (shoulder blade).
4. **Irregular bones.** Irregular bones have various shapes that do not fit into the previous categories. Examples are the vertebrae and hip bones (Figure 6.3b).

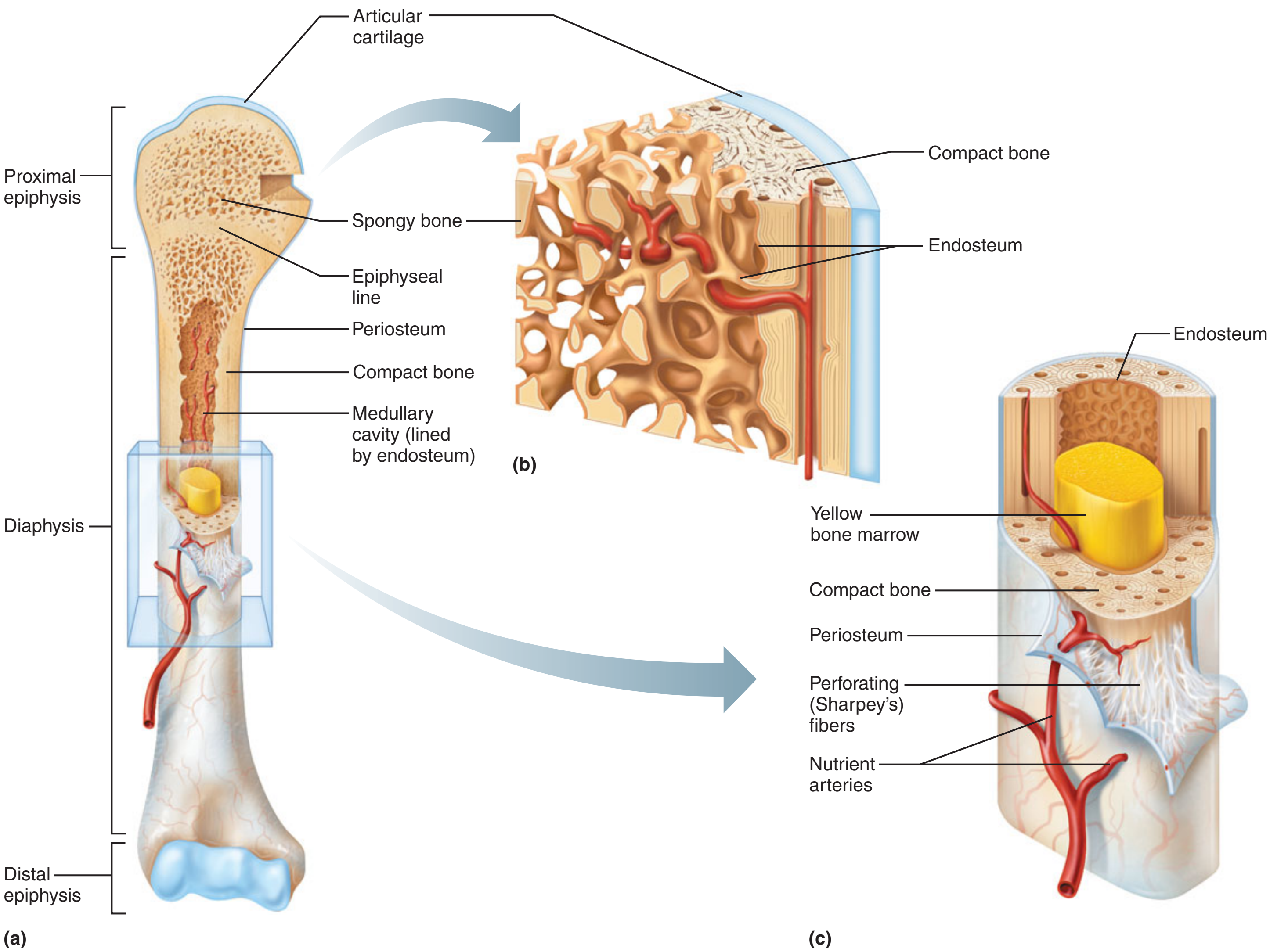


FIGURE 6.4 The structure of a long bone (humerus). (a) Anterior view, with the bone sectioned frontally to show the interior at the proximal end. **(b)** Enlargement of (a), showing the spongy bone and compact bone of the epiphysis. **(c)** Enlargement of the diaphysis from (a). Note that the external surface of the diaphysis is covered with periosteum but that the articular surface of the epiphysis is covered with hyaline cartilage.

Gross Anatomy of Bones

Compact and Spongy Bone

Almost every bone of the skeleton has a dense outer layer that looks smooth and solid to the naked eye. This external layer is **compact bone** (Figure 6.4 and Figure 6.5). Internal to this is **spongy bone,** also called *trabecular bone,* a honeycomb of small needle-like or flat pieces called **trabeculae** (trah-bek′u-le; "little beams"). In this network, the open spaces between the trabeculae are filled with red or yellow bone marrow.

Structure of a Typical Long Bone

With few exceptions, all the long bones in the body have the same general structure (Figure 6.4).

Diaphysis and Epiphyses The tubular **diaphysis** (di-af′ĭ-sis), or shaft, forms the long axis of a long bone; the **epiphyses** (e-pif′ĭ-sez) are the bone ends (Figure 6.4a). The joint surface of each epiphysis is covered with a thin layer of hyaline cartilage called the **articular cartilage.** Between the diaphysis and each epiphysis of an adult long bone is an **epiphyseal line.** This line is a remnant of the epiphyseal plate, a disc of hyaline cartilage that grows during childhood to lengthen the bone.

Blood Vessels Unlike cartilage, bones are well vascularized. In fact, at any given time between 3% and 11% of the blood in the body is in the skeleton. The main vessels serving the diaphysis are a *nutrient artery* (Figure 6.4c) and a *nutrient vein.* Together these run through a hole in the wall of the diaphysis, the *nutrient foramen* (fo-ra′men; "opening"). The nutrient artery runs inward to supply the bone marrow and the spongy bone. Branches then extend outward to supply the compact bone. Several *epiphyseal arteries* and *veins* serve each epiphysis in the same way.

The Medullary Cavity The interior of all bones consists largely of spongy bone. However, the very center of the diaphysis of long bones contains no bone tissue at all and is called the **medullary cavity** (med′u-lar-e; "middle") or *marrow cavity* (Figure 6.4a). As its name implies, this cavity is filled with yellow bone marrow. Recall that the spaces between the trabeculae of spongy bone are also filled with marrow.

Membranes A connective tissue membrane called the **periosteum** (per″e-os′te-um; "around the bone") covers the entire outer surface of each bone except on the ends of the epiphyses, where articular cartilage occurs (Figure 6.5a and 6.5b). This periosteal membrane has two sublayers: a superficial layer of dense irregular connective tissue, which resists tension placed on a bone during bending, and a deep layer that abuts the compact bone. This deep layer is osteogenic, containing bone-depositing cells (osteoblasts) and bone-destroying cells (osteoclasts). These cells remodel bone surfaces throughout our lives (see p. 137 for details). The osteogenic cells of the deep layer of the periosteum are indistinguishable from the fibroblasts within this layer. During periods of bone growth or deposition, the osteogenic cells differentiate into osteoblasts. These osteoblasts produce the layers of bone tissue that encircle the perimeter of the bone, the circumferential lamellae (see Figure 6.8a).

The periosteum is richly supplied with nerves and blood vessels, which is why broken bones are painful and bleed profusely. The vessels that supply the periosteum are branches from the nutrient and epiphyseal vessels. The periosteum is secured to the underlying bone by **perforating fibers** *(Sharpey's fibers),* thick bundles of collagen that run from the periosteum into the bone matrix (Figure 6.4c). The periosteum also provides insertion points for the tendons and ligaments that attach to a bone. At these points, the perforating fibers are exceptionally dense.

Whereas periosteum covers the external surface of bones, *internal* bone surfaces are covered by a much thinner connective tissue membrane called **endosteum** (en-dos′te-um; "within the bone"). Specifically, endosteum covers the trabeculae of spongy bone (Figure 6.4b); it also lines the central canals of osteons (see Figure 6.7a). Like periosteum, endosteum is osteogenic, containing both osteoblasts and osteoclasts.

Structure of Short, Irregular, and Flat Bones

Short, irregular, and flat bones have much the same composition as long bones: periosteum-covered compact bone externally and endosteum-covered spongy bone internally. However, because these bones are not cylindrical, they have no diaphysis. They contain bone marrow (between the trabeculae of their spongy bone), but no marrow cavity is present. **Figure 6.5** shows a typical flat bone of the skull. In flat bones, the internal spongy bone is called **diploë** (dip′lo-e; "double"). A flat bone might be likened to a reinforced sandwich in structure.

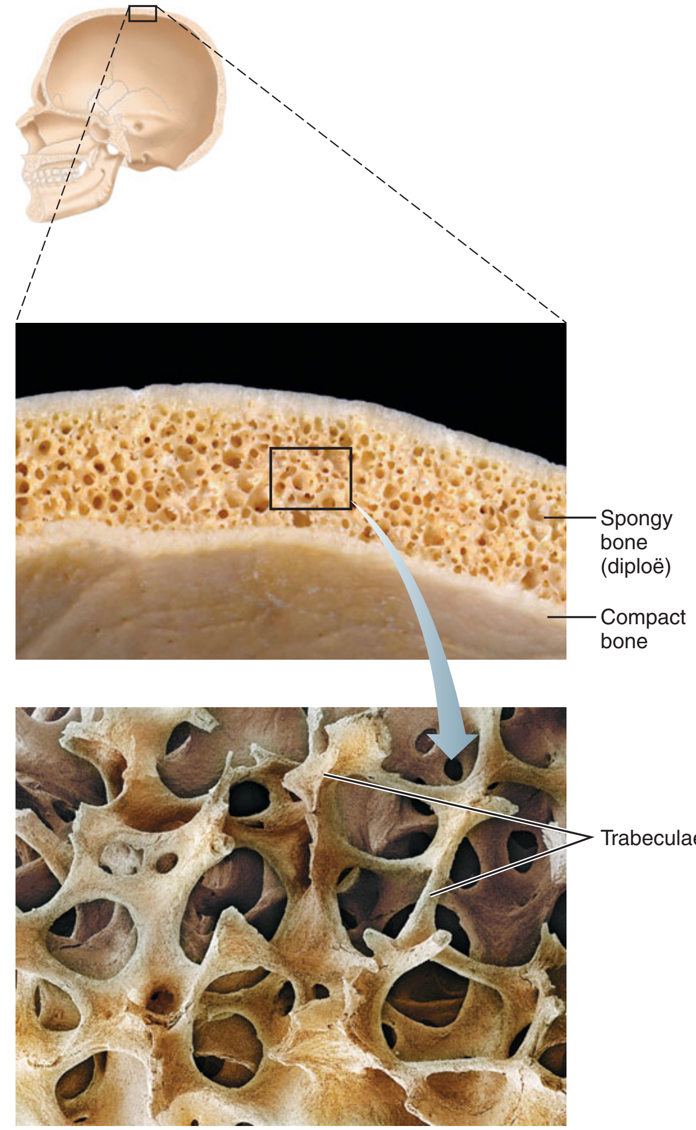
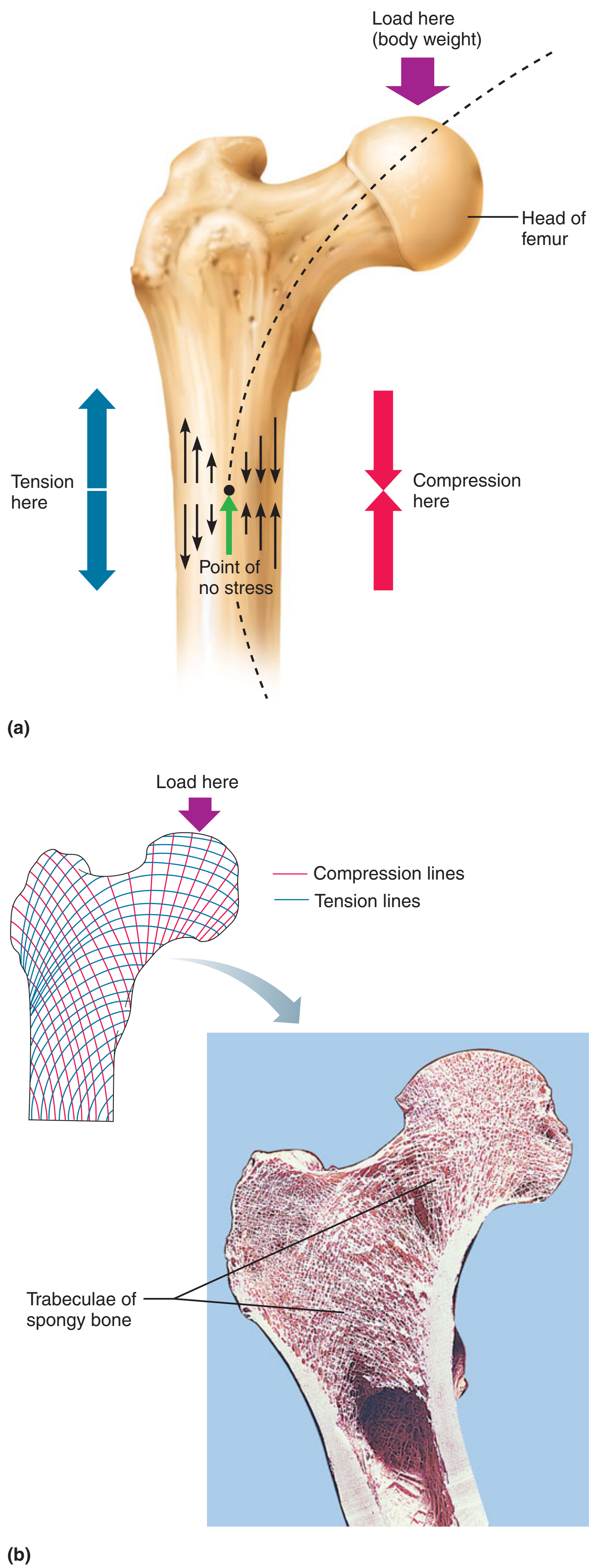


FIGURE 6.5 Structure of a flat bone. Flat bones consist of a layer of spongy bone (the diploë) sandwiched between two thin layers of compact bone. (Photomicrograph at bottom, 25×.)

Bone Design and Stress

The anatomy of each bone reflects the stresses most commonly placed on it. Bones are subjected to compression as weight bears down on them or as muscles pull on them. The loading usually is applied off center, however, and threatens to *bend* the bone **(Figure 6.6a)**. Bending compresses the bone on one side and stretches it (subjects it to tension) on the other. Both compression and tension are greatest at the external bone surfaces. To resist these maximal stresses, the strong, compact bone tissue occurs in the external portion of the bone. Internal to this region, however, tension and compression forces tend to cancel each other out, resulting in less overall stress. Thus, compact bone is not found in the bone interiors; spongy bone is sufficient. Because no stress occurs at the bone's center, the lack of bone tissue in the central medullary cavity does not impair the strength of long bones. In fact, a hollow cylinder is stronger than a solid rod of equal weight, thus this design is efficient from a biological as well as a mechanical perspective. The spongy bone and marrow cavities lighten the heavy skeleton and provide room for the bone marrow.



Spongy bone is not a random network of bone fragments. Instead, the trabeculae of spongy bone seem to align along stress lines in an organized pattern of tiny struts as crucially positioned as the flying buttresses that support the walls of a Gothic cathedral (Figure 6.6b).

The surfaces of bones also reflect the stresses that are applied to the bone. The superficial surfaces have distinct **bone markings** **(Table 6.1)** that fit into three categories: (1) projections that are the attachment sites for muscles and ligaments; (2) surfaces that form joints; and (3) depressions and openings. These bone markings provide a wealth of information about the functions of bone and muscles, and on the relationship of bones to their associated soft structures. You will identify these markings on individual bones when you study the detailed structure of bones presented in Chapters 7 and 8.

check your understanding

7. What are the two osteogenic membranes found in a bone, where is each located, and what types are cells are found in these membranes?
8. In a flat bone, where is compact bone located? Where is spongy bone located?
9. What is the function of each of the following bone markings—condyle, tubercle, foramen?

For answers, see Appendix B.

Microscopic Structure of Bone

➤ Describe the histology of compact and spongy bone.

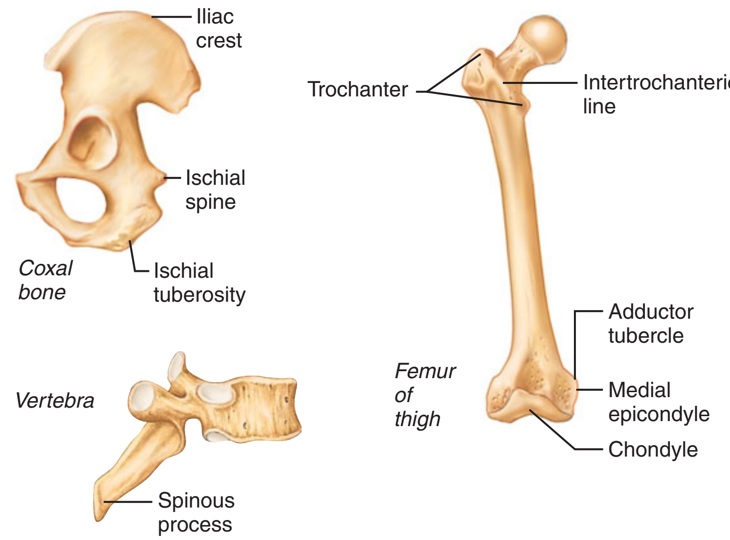
Compact Bone

Viewed by the unaided eye, compact bone looks solid. However, microscopic examination reveals that it is riddled with passageways for blood vessels and nerves **(Figure 6.7a)**. An important structural component of compact bone is the **osteon** (os′te-on; "bone"), or **Haversian** (ha-ver′shan) **system.** Osteons are long, cylindrical structures oriented parallel to the long axis of the bone and to the main compression stresses. Functionally, osteons can be viewed as miniature weight-bearing pillars. Structurally, an osteon is a group of concentric tubes resembling the rings of a tree trunk in cross section (Figure 6.7c). Each of the tubes is a **lamella** (lah-mel′ah; "little plate"), a layer of bone matrix in which

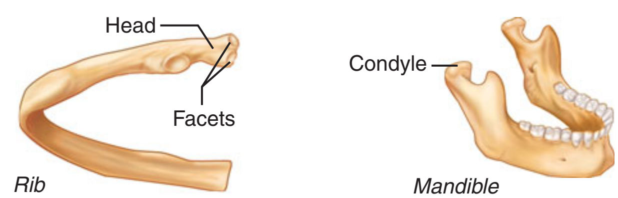
FIGURE 6.6 Bone anatomy and bending stress. (a) Body weight transmitted through the head of the femur (thigh bone) threatens to bend the bone along the indicated arc. The strongest forces occur at the periphery of the long bone—compression on the loaded side, tension on the opposite surface—where they are resisted by compact bone. Tension and compression cancel each other out internally at the point of no stress; much less bone material is needed internally. **(b)** Diagram of the stress trajectories through the proximal femur during loading and photograph of the alignment of trabeculae within the proximal femur.

TABLE 6.1 Bone Markings

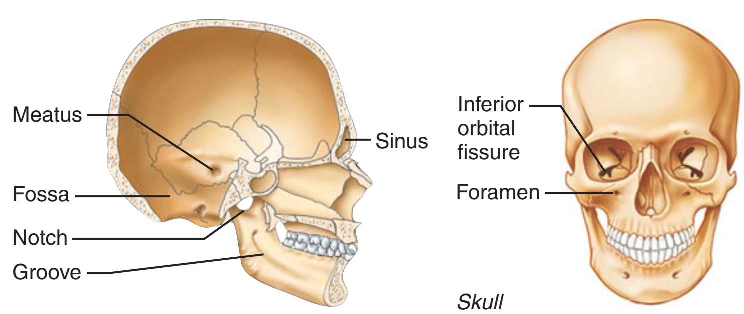
Name of Bone Marking	Description	Illustration
PROJECTIONS THAT ARE SITES OF MUSCLE AND LIGAMENT ATTACHMENT		
Tuberosity (too″be-ros′ĭ-te)	Large rounded projection; may be roughened	
Crest	Narrow ridge of bone; usually prominent	
Trochanter (tro-kan′ter)	Very large, blunt, irregularly shaped process (the only examples are on the femur)	
Line	Narrow ridge of bone; less prominent than a crest	
Tubercle (too′ber-kl)	Small rounded projection or process	
Epicondyle (ep″ĭ-kon′dīl)	Raised area on or above a condyle	
Spine	Sharp, slender, often pointed projection	
Process	Any bony prominence	



Name of Bone Marking	Description	Illustration
SURFACES THAT FORM JOINTS		
Head	Bony expansion carried on a narrow neck	
Facet	Smooth, nearly flat articular surface	
Condyle (kon′dīl)	Rounded articular projection, often articulates with a corresponding fossa	



Name of Bone Marking	Description	Illustration
DEPRESSIONS AND OPENINGS		
For passage of vessels and nerves:		
Foramen (fo-ra′men)	Round or oval opening through a bone	
Groove	Furrow	
Fissure	Narrow, slitlike opening	
Notch	Indentation at the edge of a structure	
Others:		
Fossa (fos′ah)	Shallow basinlike depression in a bone, often serving as an articular surface	
Meatus (me-a′tus)	Canal-like passageway	
Sinus	Cavity within a bone, filled with air and lined with mucous membrane	



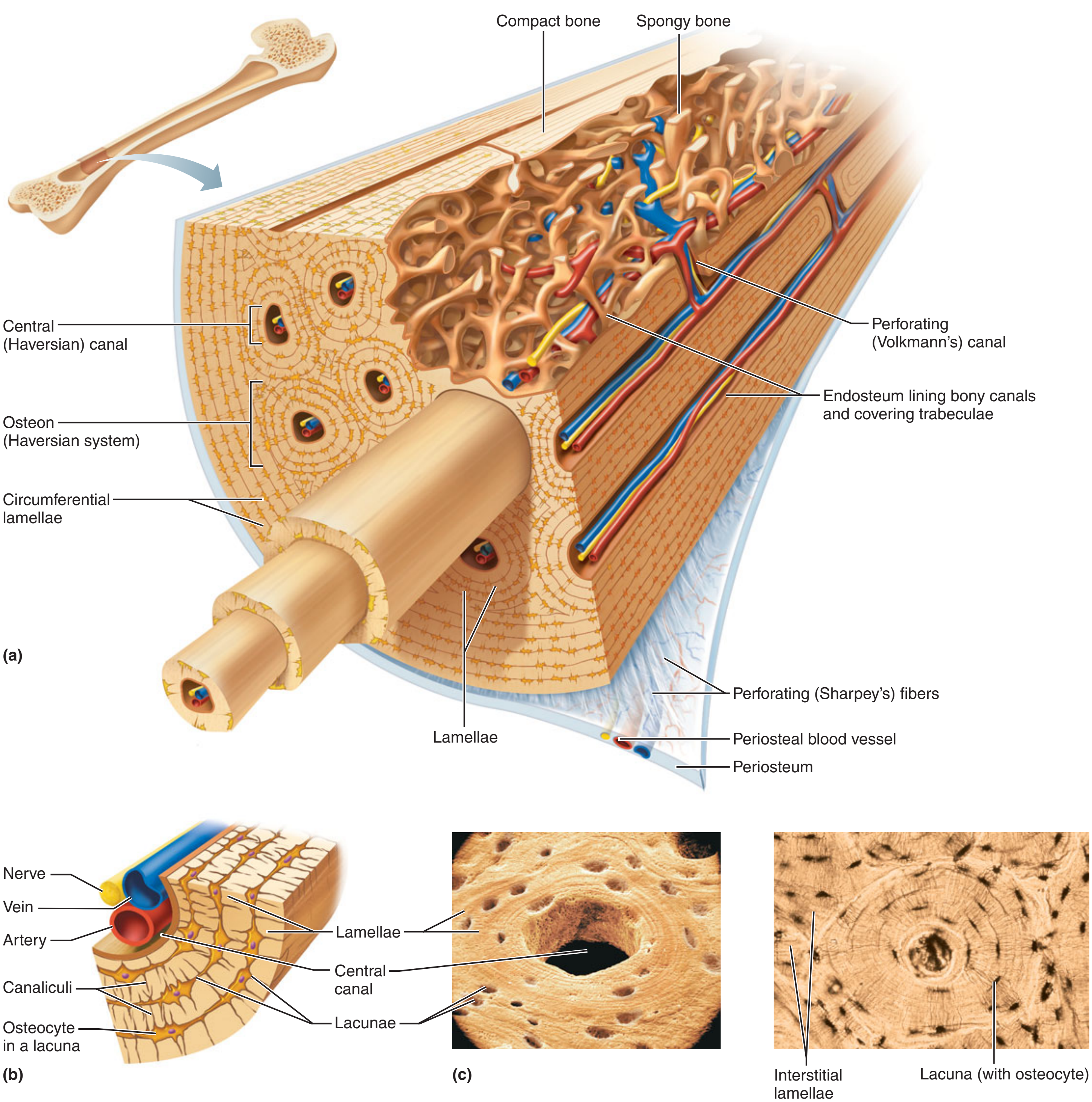


FIGURE 6.7 Microscopic structure of compact bone. (a) Illustration of a section from the diaphysis of a long bone. **(b)** Close-up of a portion of one osteon. **(c)** SEM (left) and light photomicrograph (right) of a cross section of one osteon (215× and 200×, respectively). (See *A Brief Atlas of the Human Body,* Second Edition, Plate 20.)
Source: Kessel and Kardon/Visuals Unlimited.

the collagen fibers and mineral crystals align and run in a single direction. However, the fibers and crystals of adjacent lamellae always run in roughly opposite directions. This alternating pattern is optimal for withstanding torsion, or twisting, stresses **(Figure 6.8)**. The lamellae of bone also inhibit crack propagation. When a crack reaches the edge of a lamella, the forces causing the crack are dispersed around the lamellar boundaries, thus preventing the crack from progressing into deeper parts of the bone and causing fracture.

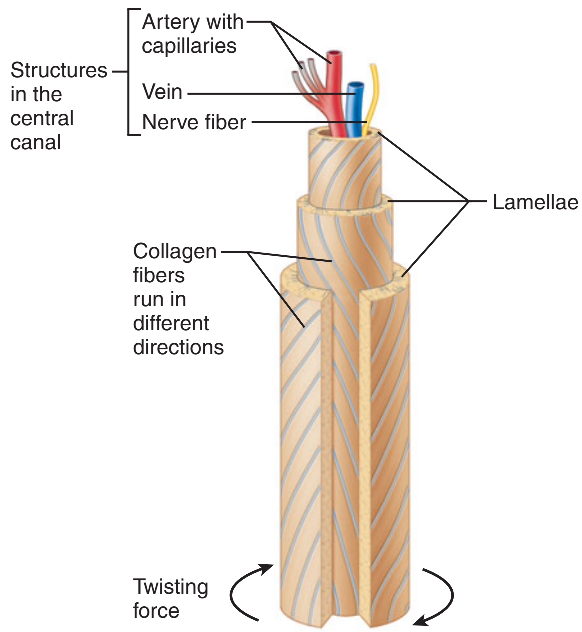


FIGURE 6.8 A single osteon. The osteon is drawn as though it were pulled out like a telescope to illustrate the individual lamellae.

Through the core of each osteon runs a canal called the **central canal,** or **Haversian canal** (see Figure 6.7a). Like all internal bone cavities, it is lined by endosteum. The central canal contains its own blood vessels, which supply nutrients to the bone cells of the osteon, and its own nerve fibers. The endosteum that lines the central canal is an osteogenic layer. Unlike the growth rings in trees, lamellae of bone tissue are added to the inner surface of the osteon, thus decreasing the diameter of the central canal. **Perforating canals,** also called **Volkmann's** (fōlk′mahnz) **canals,** lie at right angles to the central canals and connect the blood and nerve supply of the periosteum to that of the central canals and the marrow cavity.

The mature bone cells, the osteocytes, are spider-shaped (Figure 6.7b). Their bodies occupy small cavities in the solid matrix called lacunae ("little lakes"), and their "spider legs" occupy thin tubes called **canaliculi** (kan″ah-lik′u-li). These "little canals" run through the matrix, connecting neighboring lacunae to one another and to the nearest capillaries, such as those in the central canals. Within the canaliculi, the extensions of neighboring osteocytes touch each other and form gap junctions (see p. 75). Nutrients diffusing from capillaries in the central canal pass across these gap junctions, from one osteocyte to the next, throughout the entire osteon. This direct transfer from cell to cell is the only way to supply the osteocytes with the nutrients they need, because the intervening bone matrix is too solid and impermeable to act as a diffusion medium.

Not all lamellae in compact bone occur within osteons. Lying between the osteons are groups of incomplete lamellae called **interstitial** (in″ter-stish′al) **lamellae** (Figure 6.7c). These are simply the remains of old osteons that have been cut through by bone remodeling. Additionally, **circumferential lamellae** occur in the external and internal surfaces of the layer of compact bone; each of these lamellae extends around the entire circumference of the diaphysis (Figure 6.7a). Functioning like an osteon but on a much larger scale, the circumferential lamellae effectively resist twisting of the entire long bone.

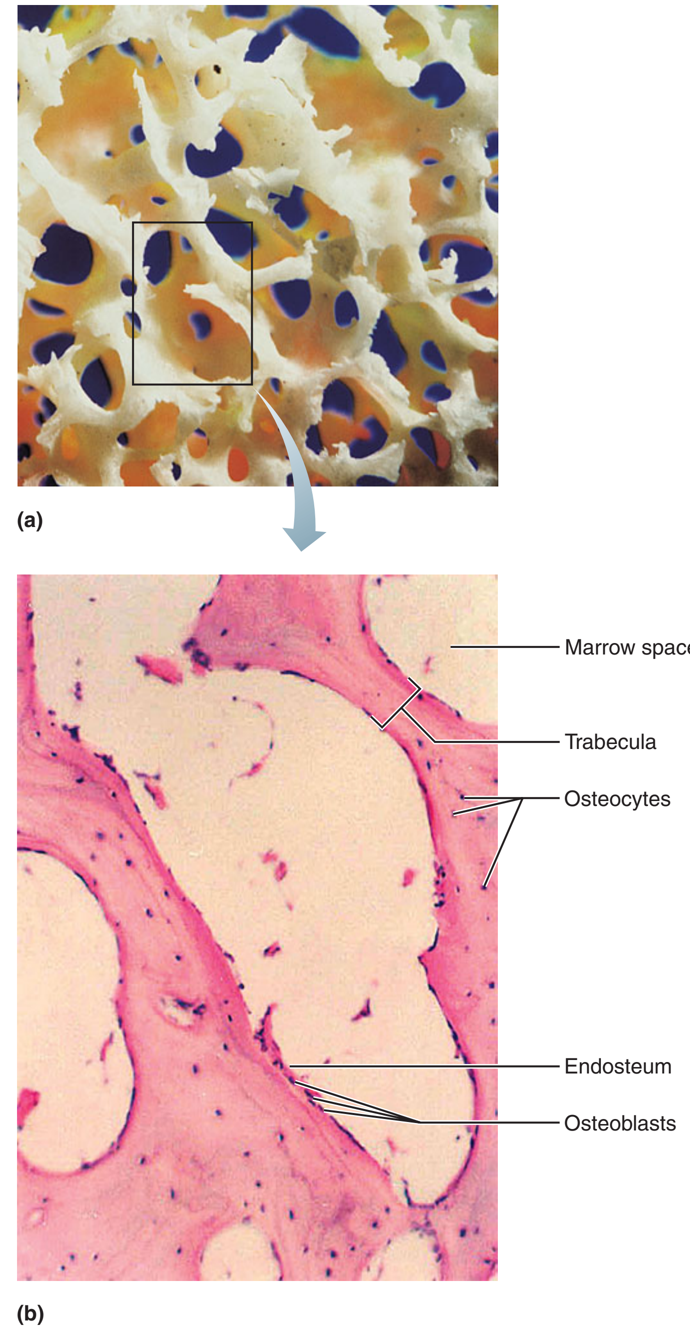
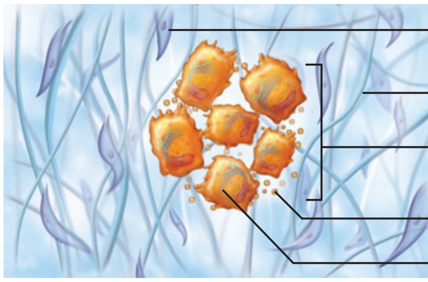


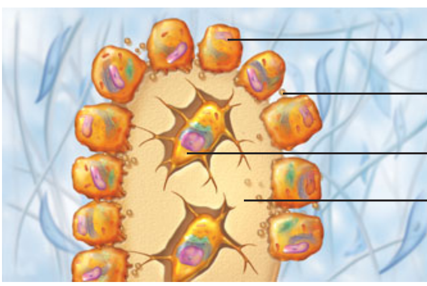
FIGURE 6.9 Spongy bone. (a) Micrograph of spongy bone, showing a network of bone trabeculae (20×). **(b)** Photomicrograph of trabeculae (85×). (See *A Brief Atlas of the Human Body,* Second Edition, Plate 21.)

Spongy Bone

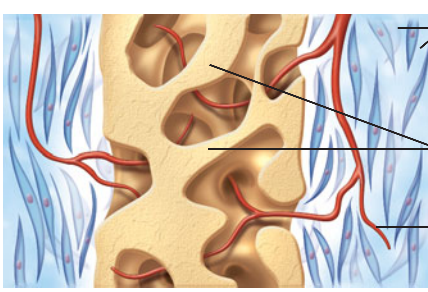
The microscopic anatomy of spongy bone **(Figure 6.9)** is less complex than that of compact bone. Each trabecula contains several layers of lamellae and osteocytes but is too small to contain osteons or vessels of its own. The osteocytes receive



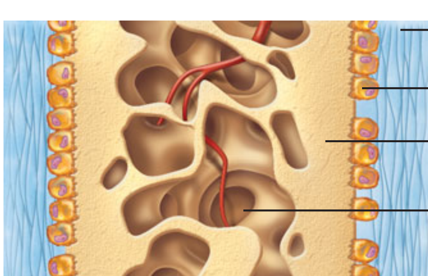
① **Ossification centers appear in the fibrous connective tissue membrane.**
• Selected centrally located mesenchymal cells cluster and differentiate into osteoblasts, forming an ossification center.



② **Bone matrix (osteoid) is secreted within the fibrous membrane and calcifies.**
• Osteoblasts begin to secrete osteoid, which is calcified within a few days.
• Trapped osteoblasts become osteocytes.



③ **Woven bone and periosteum form.**
• Accumulating osteoid is laid down between embryonic blood vessels in a random manner. The result is a network (instead of lamellae) of trabeculae called woven bone.
• Vascularized mesenchyme condenses on the external face of the woven bone and becomes the periosteum.



④ **Lamellar bone replaces woven bone, just deep to the periosteum. Red marrow appears.**
• Trabeculae just deep to the periosteum thicken and are later replaced with mature lamellar bone, forming compact bone plates.
• Spongy bone (diploë), consisting of distinct trabeculae, persists internally, and its vascular tissue becomes red marrow.

their nutrients from capillaries in the endosteum surrounding the trabecula via connections through the canaliculi.

check your understanding

10. Differentiate a central canal, a perforating canal, and the canaliculi.
11. How do the osteocytes in the outer lamella of an osteon receive oxygen and nutrients?
12. What is a trabecula? How is it different from an osteon?

For answers, see Appendix B.

Bone Development and Growth

➤ Compare and contrast the two types of bone formation: intramembranous and endochondral ossification.

➤ Describe how endochondral bones grow at their epiphyseal plates.

Osteogenesis (os″te-o-jen′ĕ-sis) and **ossification** are both names for the process of bone-tissue formation. Osteogenesis begins in the embryo, proceeds through childhood and adolescence as the skeleton grows, and then occurs at a slower rate in the adult as part of a continual remodeling of the full-grown skeleton.

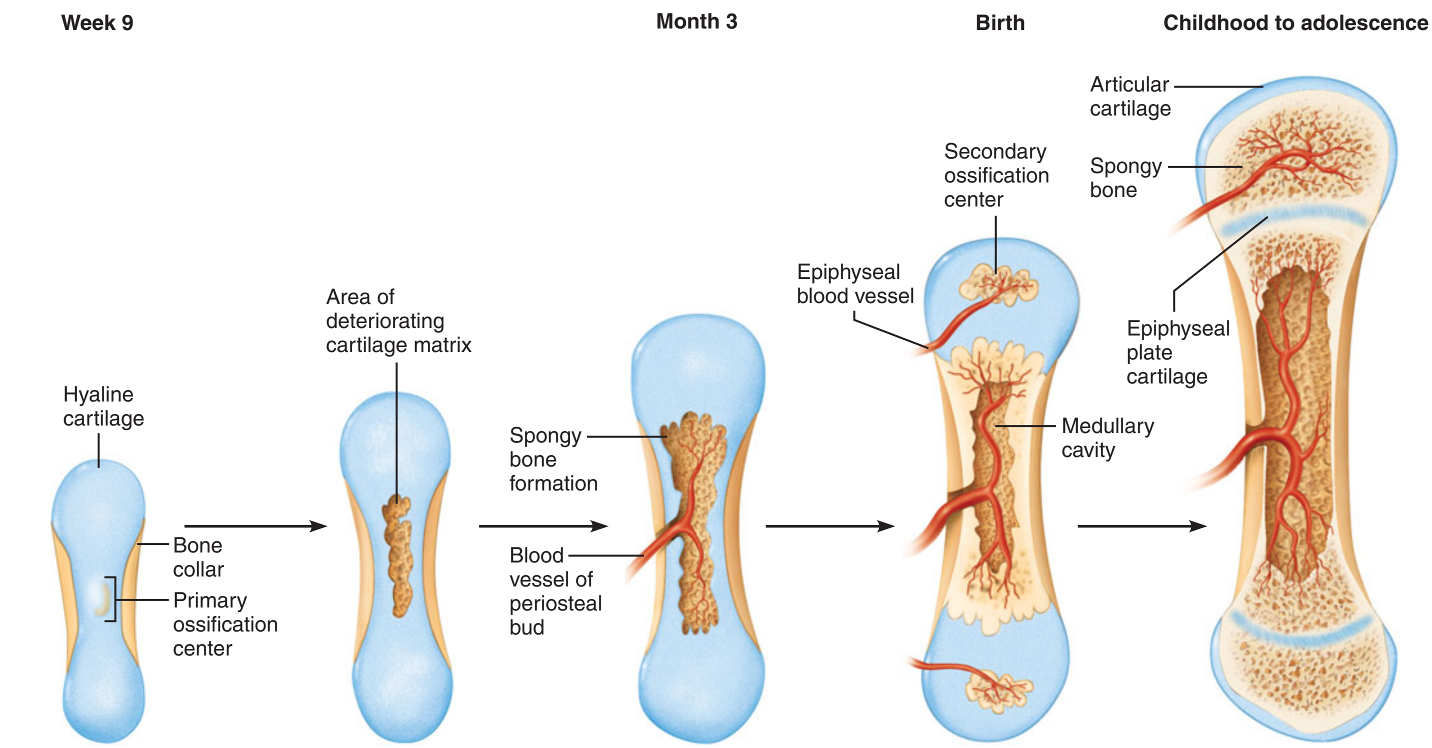
Before week 8, the skeleton of the human embryo consists only of hyaline cartilage and some membranes of mesenchyme, an embryonic connective tissue (Chapter 4, p. 78). Bone tissue first appears in week 8 and eventually replaces most cartilage and mesenchymal membranes in the skeleton. Some bones, called **membrane bones,** develop from a mesenchymal membrane through a process called **intramembranous ossification** (*intra* = inside). Other bones develop as hyaline cartilage, which is replaced through a process called **endochondral ossification** (*endo* = within; *chondro* = cartilage). These bones are called **endochondral bones** or **cartilage replacement bones.**

Intramembranous Ossification

Membrane bones form directly from mesenchyme without first being modeled in cartilage. All bones of the skull, except a few at the base of the skull, are of this category. The clavicles (collarbones) are the only bones formed by intramembranous ossification that are not in the skull.

Intramembranous ossification proceeds in the following way: During week 8 of embryonic development, mesenchymal cells cluster within the connective tissue membrane and become bone-forming osteoblasts (Figure 6.10, ①). These cells begin secreting the organic part of bone matrix, called

FIGURE 6.10 Intramembranous ossification: Development of a flat bone of the skull in the fetus. Diagrams ③ and ④ represent much lower magnification than diagrams ① and ②.



1 Bone collar forms around hyaline cartilage model.

2 Cartilage in the center of the diaphysis calcifies and then develops cavities.

3 The periosteal bud invades the internal cavities, and spongy bone begins to form.

4 The diaphysis elongates and a medullary cavity forms as ossification continues. Secondary ossification centers appear in the epiphyses in preparation for stage 5.

5 The epiphyses ossify. When completed, hyaline cartilage remains only in the epiphyseal plates and articular cartilages.

FIGURE 6.11 Endochondral ossification of a long bone.

osteoid, which then becomes mineralized (Figure 6.10, 2). Once surrounded by their own matrix, the osteoblasts are called osteocytes. The new bone tissue forms between embryonic blood vessels, which are woven in a random network (Figure 6.10, 3). The result is **woven bone tissue,** with trabeculae arranged in networks. This embryonic tissue lacks the lamellae that occur in mature spongy bone. During this same stage, more mesenchyme condenses just external to the developing membrane bone and becomes the periosteum.

To complete the development of a membrane bone, the trabeculae at the periphery grow thicker until plates of compact bone are present on both surfaces (Figure 6.10, 4). In the center of the membrane bone, the trabeculae remain distinct, and spongy bone results. The final pattern is that of the flat bone shown in Figure 6.5.

Endochondral Ossification

All bones from the base of the skull down, except for the clavicles, are endochondral bones. They are first modeled in hyaline cartilage, which then is gradually replaced by bone tissue. Endochondral ossification begins late in the second month of development and is not completed until the skeleton stops growing in early adulthood. Growing endochondral bones increase both in length and in width. The following stages outline only the increase in length, using a large long bone as an example **(Figure 6.11)**.

1. **A bone collar forms around the diaphysis.** In the late embryo (week 8), the endochondral bone begins as a piece of cartilage called a *cartilage model.* Like all cartilages, it is surrounded by a perichondrium. Then, at the end of week 8 of development, the perichondrium surrounding the diaphysis is invaded by blood vessels and becomes a bone-forming periosteum. Osteoblasts in this new periosteum lay down a collar of bone tissue around the diaphysis.
2. **Cartilage calcifies in the center of the diaphysis.** At the same time the bone collar forms, the chondrocytes in the center of the diaphysis enlarge (hypertrophy) and signal the surrounding cartilage matrix to calcify. The matrix of calcified cartilage is impermeable to diffusing nutrients. Cut off from all nutrients, the chondrocytes die and disintegrate, leaving cavities in the cartilage. No longer maintained by chondrocytes, the cartilage matrix starts to deteriorate. This does not seriously weaken the diaphysis, which is well stabilized by the bone collar around it. These changes affect only the center of the diaphysis. Elsewhere, the cartilage remains healthy and continues to grow, causing the entire endochondral bone to elongate.
3. **The periosteal bud invades the diaphysis, and the first bone trabeculae form.** In the third month of development, the cavities within the diaphysis are invaded by a collection of elements called the **periosteal bud.** This bud consists of a nutrient artery and vein, along with the cells that will

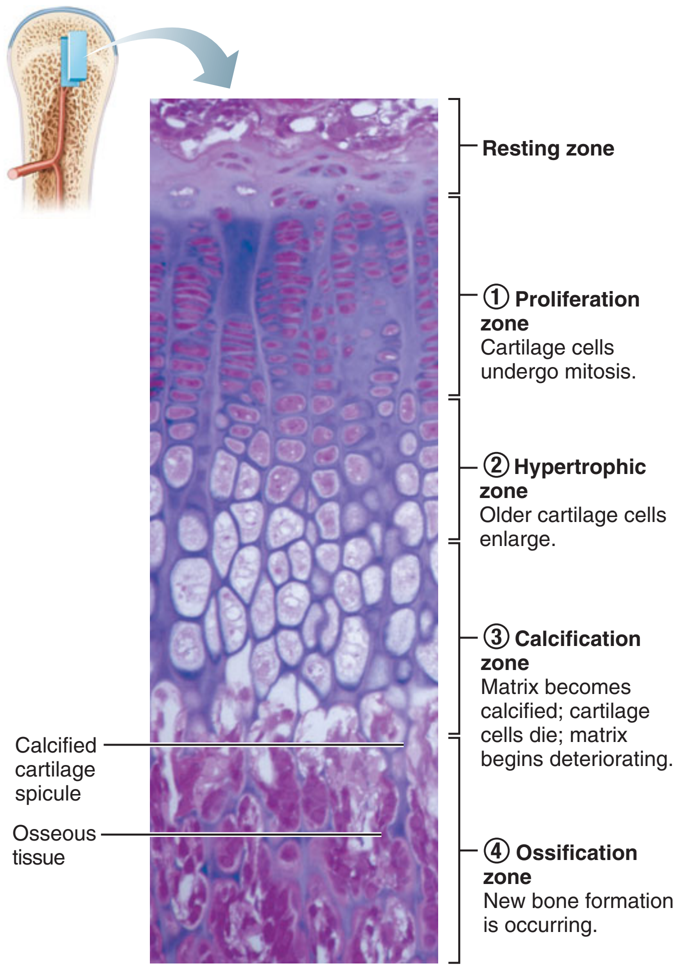


FIGURE 6.12 Organization of the cartilage within the epiphyseal plate of a growing long bone (110×). The chondrocytes adjacent to the epiphysis are inactive. This region is the resting zone. The other cartilage cells within the epiphyseal plate are organized into four distinct zones: growth, hypertrophic, calcification, and ossification.

form the bone marrow. Most important, the bud contains bone-forming and bone-destroying cells (osteogenic stem cells and osteoclasts). The entering osteoclasts partly erode the matrix of calcified cartilage, and the osteogenic cells differentiate into osteoblasts, which secrete osteoid around the remaining fragments of this matrix, forming bone-covered trabeculae. In this way, the earliest version of spongy bone appears within the diaphysis.

By the third month of development, bone tissue continues to form around the diaphysis from the periosteum and has begun to appear in the center of the diaphysis. This bone tissue of the diaphysis makes up the **primary ossification center.**

④ **Diaphysis elongates, and the medullary cavity forms.** Throughout the rest of the fetal period, the cartilage of the epiphysis continues to grow rapidly, with the part nearest the diaphysis continually calcifying and being replaced by the bone trabeculae, thus elongating the diaphysis. Osteoclasts in turn break down the ends of these bone trabeculae to form a central, boneless medullary cavity.

Shortly before or after birth, the epiphyses gain bone tissue: First, the cartilage in the center of each epiphysis calcifies and degenerates. Then, a bud containing the epiphyseal vessels invades each epiphysis. Bone trabeculae appear, just as they appeared earlier in the primary ossification center. The areas of bone formation in the epiphyses are called **secondary ossification centers.** The larger long bones of the body can have several ossification centers in each epiphysis.

⑤ **Epiphyses ossify, and cartilaginous epiphyseal plates separate diaphysis and epiphyses.** After the secondary ossification centers have appeared and epiphyses have largely ossified, hyaline cartilage remains at only two places: (1) on the epiphyseal surfaces, where it forms the articular cartilages; and (2) between the diaphysis and epiphysis, where it forms the **epiphyseal plates.** The epiphyseal plates, also called growth plates, are responsible for lengthening the bones during the two decades following birth.

Anatomy of the Epiphyseal Plate

In both the epiphyses of the fetus and the epiphyseal plates of the child, the cartilage is organized in a way that allows it to grow exceptionally quickly and efficiently **(Figure 6.12)**. The cartilage cells nearest the epiphysis are relatively small and inactive. This region is called the **resting** *(quiescent)* **zone.** Below the resting zone, the cartilage cells form tall columns, like coins in a stack. The chondroblasts at the "top" of the stack in the **proliferation zone** divide quickly, pushing the epiphysis away from the diaphysis, thereby causing the entire long bone to lengthen. The older chondrocytes deeper in the stack, in the **hypertrophic zone,** enlarge and signal the surrounding matrix to calcify. In the **calcification zone** the cartilage matrix becomes calcified and the chondrocytes die. This process leaves long spicules (trabeculae) of calcified cartilage on the diaphysis side of the epiphysis-diaphysis junction. These spicules are partly eroded by osteoclasts, then covered with bone tissue by osteoblasts, forming spicules of bone. This region is the **ossification zone.** These bony spicules are destroyed from within the diaphysis by the action of osteoclasts at the same rate that they are formed at the epiphysis; thus they stay a constant length and the marrow cavity grows longer as the long bone lengthens.

Postnatal Growth of Endochondral Bones

During childhood and adolescence, the endochondral bones lengthen entirely by growth of the epiphyseal plates. Because its cartilage is replaced with bone tissue on the diaphysis side about as quickly as it grows, the epiphyseal plate maintains a constant thickness while the whole bone lengthens. As adolescence draws to an end, the chondroblasts in the epiphyseal plates divide less often, and the plates become thinner. Eventually, they exhaust their supply of mitotically active cartilage cells, so the cartilage stops growing and is replaced by bone tissue. Long bones stop lengthening when the bone of the epiphyses and diaphysis fuses. This process, called *closure of the epiphyseal plates,* occurs at about 18 years of age in women and 21 years of age in men. After the epiphyseal plates close, a person can grow no taller. The age of a child or adolescent can be estimated by measuring bone length and degree of closure of the epiphyseal plate of a long bone, as shown on an X-ray image. In adults, because no further growth in length occurs after closure of the epiphyseal plates, long bone length can be used to estimate overall height. Both of these techniques are used forensically to help identify unknown individuals.

ACHONDROPLASIA A congenital condition called **achondroplasia** (a-kon″dro-pla′ze-ah) involves defective growth of cartilage and defective endochondral ossification. This condition results from a mutation in a gene on chromosome 4 (fibroblastic growth factor receptor-3 gene or FGFR3). Increased activity of this gene inhibits cartilage proliferation in the epiphyseal plates. As a result, the growth and hypertrophic zones of the epiphyseal plate are narrow and disorganized, and ossification and closure of the epiphyseal plate occurs before normal bone length is reached. Achondroplasia results in typical dwarfism, in which the limbs are short but the trunk and membrane bones are of normal size. Although this condition is genetic, 80% of cases are the result of new mutations. It is also not rare, affecting between 1 in 15,000 and 1 in 40,000 people.

Growing bones must also widen as they lengthen. Osteoblasts in the osteogenic layer of the periosteum add bone tissue to the external face of the diaphysis as osteoclasts in the endosteum remove bone from the internal surface of the diaphysis wall. These two processes occur at about the same rate, so that the circumference of the long bone expands and the bone widens. Growth of a bone by the addition of bone tissue to its surfaces is called **appositional growth.**

This section has focused on the growth and development of large long bones. The other types of endochondral bones grow in slightly different ways. Short bones, such as those in the wrist, arise from only a single ossification center. Most of the irregular bones, such as the hip bone and vertebrae, develop from several distinct ossification centers. Small long bones, such as those in the palm and fingers, form from a primary ossification center (diaphysis) plus a single secondary center; that is, they have just one epiphysis. However, regardless of the number and location of ossification centers, all endochondral bones follow steps similar to those shown in Figure 6.11: calcification and deterioration of cartilage internally, invasion of a periosteal bud containing osteoclasts and osteogenic stem cells, and deposition of bone tissue by osteoblasts.

Bone growth is regulated by several hormones, primarily growth hormone (produced by the pituitary gland), which stimulates the epiphyseal plates to grow. Thyroid hormones modulate the effects of growth hormone, ensuring that the skeleton retains its proper proportions as it grows. The sex hormones (androgens and estrogens) first promote bone growth in the growth spurt at adolescence and later induce the epiphyseal plates to close, ending growth.

check your understanding

13. Which bones of the skeleton are membrane bones?
14. Which portion of the long bones in a 6-month-old fetus is ossified?
15. As a bone grows in length during childhood, does the thickness of the epiphyseal plate change? In which region of the epiphyseal plate is bone tissue added: the epiphyseal end or the diaphyseal end?

For answers, see Appendix B.

Bone Remodeling

- Discuss how bone tissue is remodeled within the skeleton.
- Explain the steps in the healing of bone fractures.

Bones appear to be the most lifeless of body organs when seen in the lab, and once they are formed, they seem set for life. Nothing could be further from the truth. Bone is a dynamic and active tissue. Large amounts of bone matrix and thousands of osteocytes are continuously being removed and replaced within the skeleton, and the small-scale architecture of bones constantly changes. As much as half a gram of calcium may enter or leave the adult skeleton each day.

In the adult skeleton, bone is deposited and removed primarily at the endosteal surface. Together, these two processes constitute **bone remodeling.** The spongy bone in the skeleton, which is covered with endosteum, is entirely replaced every 3 or 4 years. Remodeling in compact bone occurs at the endosteum lining the central canals of the osteons. This process occurs more slowly than in spongy bone; compact bone is completely replaced every 10 years.

Bone remodeling is coordinated by cohorts of adjacent osteoblasts and osteoclasts **(Figure 6.13)**. In healthy young adults, the total mass of bone in the body stays constant, an indication that the rates of deposit and resorption are essentially equal. The remodeling process is not uniform, however. Some bones (or bone parts) are very heavily remodeled; others are not. For example, the distal region of the femur is fully replaced every 5 to 6 months, whereas the diaphysis of the femur changes much more slowly.

Bone resorption is accomplished by osteoclasts (Figure 6.13 and **Figure 6.14**). Each of these giant cells has many nuclei. Osteoclasts crawl along bone surfaces, essentially digging pits as they break down the bone tissue (Figure 6.13). The part of their plasma membrane that touches the bone surface is highly folded, or ruffled. This expanded membrane forms a tight seal against the bone and secretes

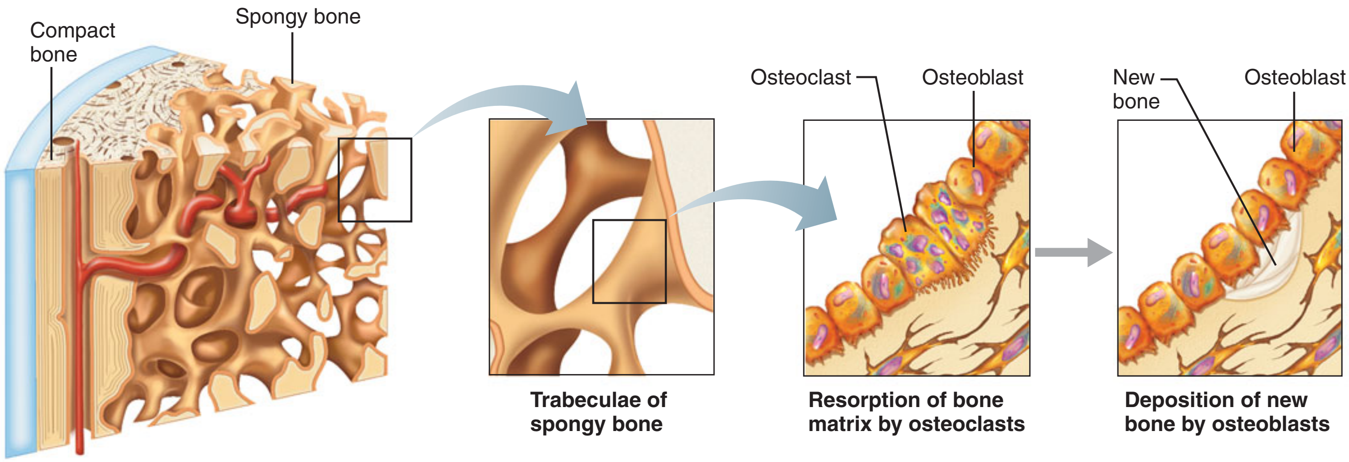


FIGURE 6.13 Remodeling of spongy bone. Resorption of bony matrix by osteoclasts from a cavity at the bone surface. Osteoblasts from the endosteum fill in the cavity forming new bone.

concentrated hydrochloric acid, which dissolves the mineral part of the matrix. The liberated calcium ions (Ca^{2+}) and phosphate ions (PO_4^{3-}) enter the tissue fluid and the bloodstream. Lysosomal enzymes are also released across the ruffled membrane and digest the organic part of the bone matrix. Finally, osteoclasts apparently take up collagen and dead osteocytes by phagocytosis.

Bone deposition is accomplished by osteoblasts, these cells lay down organic osteoid on bone surfaces (Figure 6.13), and calcium salts crystallize within this osteoid. This calcification process takes about a week. As stated earlier, the osteoblasts transform into osteocytes when they are surrounded by bone matrix.

Bone-forming osteoblasts derive from mesenchyme cells. In adults, osteoblasts form from mesenchyme-like stem cells located in the periosteum, the endosteum, and the connective tissues of the nearby bone marrow. Osteoclasts, which also form in the bone marrow, arise from immature blood cells called *hematopoietic stem cells*, and they may be related to macrophages. Many of these stem cells fuse together to form each osteoclast, thus their multinucleate structure.

The bones of the skeleton are continually remodeled for two reasons. First, bone remodeling helps maintain constant concentrations of Ca^{2+} and PO_4^{3-} in body fluids. Ca^{2+} levels are strictly controlled because Ca^{2+} is critical for muscle contraction. When the concentration of Ca^{2+} in body fluids starts to fall, a hormone is released by the parathyroid (par″ah-thi′-roid) glands of the neck. This *parathyroid hormone* stimulates osteoclasts to resorb bone, a process that releases more Ca^{2+} into the blood.

Second, bone is remodeled in response to the mechanical stress it experiences. Accordingly, both the osteons of compact bone and the trabeculae of spongy bone are constantly replaced by new osteons and trabeculae that are more precisely aligned with newly experienced compressive and tensile stresses. Furthermore, bone grows thicker in response to the forces experienced during exercise and gains in weight. Conversely, in the absence of mechanical stress, bone tissue is lost, which is why the bones of bedridden people atrophy. A loss of bone under near-zero-gravity conditions is the main obstacle to long missions in outer space. To slow bone loss, astronauts perform isometric exercises during space missions.

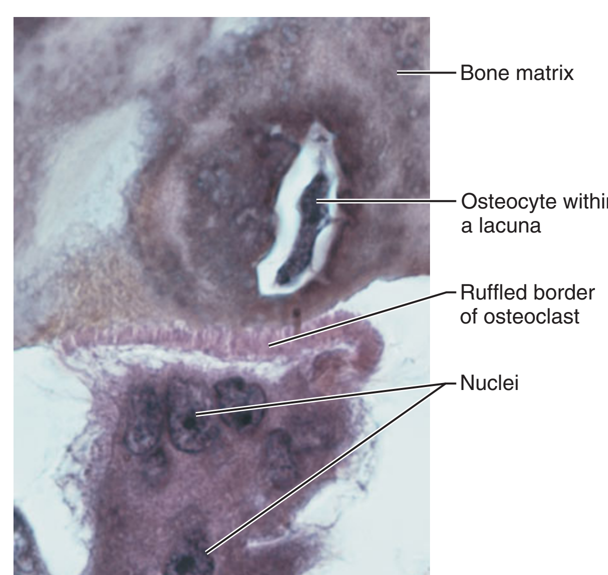


FIGURE 6.14 An osteoclast. Photomicrograph of an osteoclast destroying bone tissue (1070×).

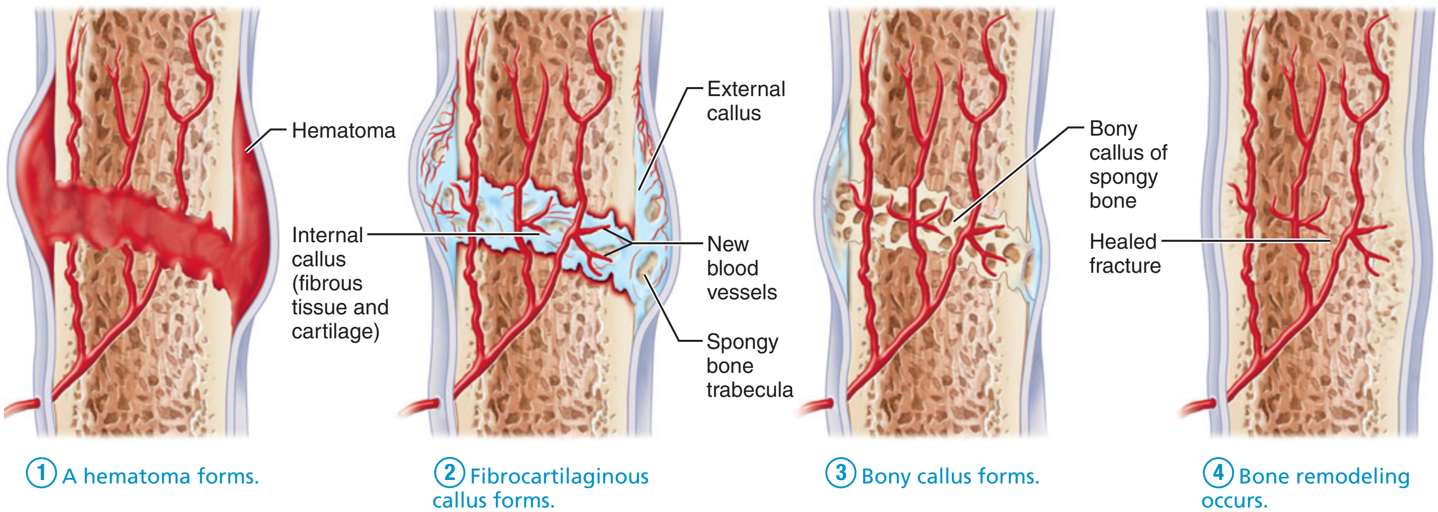


FIGURE 6.15 Stages in the healing of a bone fracture.

Repair of Bone Fractures

Despite their strength, bones are susceptible to **fractures,** or breaks. In young people, most fractures result from trauma (sports injuries, falls, or car accidents, for example) that twists or smashes the bones. In old age, bones thin and weaken, and fractures occur more often. A fracture in which the bone breaks cleanly but does not penetrate the skin is a **simple fracture.** When broken ends of the bone protrude through the skin, the fracture is **compound.** Other common types of fractures are explained in Table 6.2 (p. 140).

A fracture is treated by **reduction,** the realignment of the broken bone ends. In **closed reduction,** the bone ends are coaxed back into position by the physician's hands. In **open reduction,** the bone ends are joined surgically with pins or wires. After the broken bone is reduced, it is immobilized by a cast or traction to allow the healing process to begin. Healing time is about 6 to 8 weeks for a simple fracture, but it is longer for large, weight-bearing bones and for the bones of older people.

The healing of a simple fracture occurs in several phases (Figure 6.15).

1. **Hematoma formation.** The fracture is usually accompanied by hemorrhaging. Blood vessels break in the periosteum and inside the bone, releasing blood that clots to form a hematoma. The stages of inflammation, described in Chapter 4 (p. 93), are evident in and around the clot.
2. **Fibrocartilaginous callus formation.** Within a few days, new blood vessels grow into the clot. The periosteum and endosteum near the fracture site show a proliferation of bone-forming cells, which then invade the clot, filling it with repair tissue called *soft callus* (kal′us; "hard skin"). Initially, the soft callus is a fibrous granulation tissue (p. 93). As more fibers are produced, the soft callus becomes a dense connective tissue containing fibrocartilage and hyaline cartilage. At this point, the soft callus is also called a **fibrocartilaginous callus.**
3. **Bony callus formation.** Within a week, trabeculae of new bone begin to form in the callus, mostly by endochondral ossification. These trabeculae span the width of the callus and unite the two fragments of the broken bone. The callus is now called a bony callus, or *hard callus,* and its trabeculae grow thicker and stronger and become firm about 2 months after the injury.
4. **Bone remodeling.** Over a period of many months, the bony callus is remodeled. The excess bony material is removed from both the exterior of the bone shaft and the interior of the medullary cavity. Compact bone is laid down to reconstruct the shaft walls. The repaired area resembles the original unbroken bone region, because it responds to the same set of mechanical stresses.

check your understanding

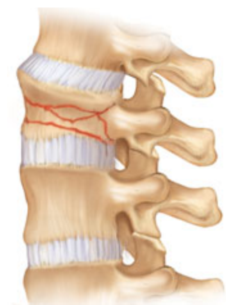
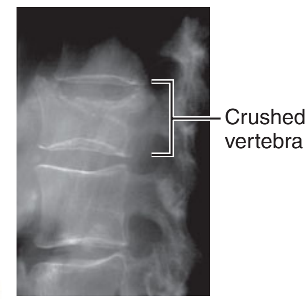
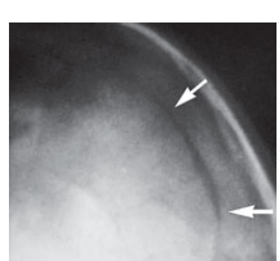
16. How does exercise affect bone? Why?
17. How does bone remodeling help repair a bone after a fracture?
18. Which types of bone fractures are more common in older individuals (see Table 6.2)?

For answers, see Appendix B.

DISORDERS OF BONES

- Relate the disease processes that cause osteoporosis, osteomalacia, rickets, Paget's disease, and osteosarcoma to what you have learned about the structure, composition, and growth of bone tissue.
- Identify the symptoms and treatments for each of these diseases.

TABLE 6.2 Common Types of Fractures

Fracture Type	Description and Comments	Fracture Type	Description and Comments
Comminuted	Bone fragments into three or more pieces. Particularly common in the aged, whose bones are more brittle.  	**Compression**	Bone is crushed. Common in porous bones (i.e., osteoporotic bones) subjected to extreme trauma, as in a fall.  
Spiral	Ragged break occurs when excessive twisting forces are applied to a bone. Common sports fracture.  	**Epiphyseal**	Epiphysis separates from the diaphysis along the epiphyseal plate. Tends to occur where cartilage cells are dying and calcification of the matrix is occurring.  
Depressed	Broken bone portion is pressed inward. Typical of skull fracture.  	**Greenstick**	Bone breaks incompletely, much in the way a green twig breaks. Only one side of the shaft breaks; the other side bends. Common in children, whose bones have relatively more organic matrix and are more flexible than those of adults.  

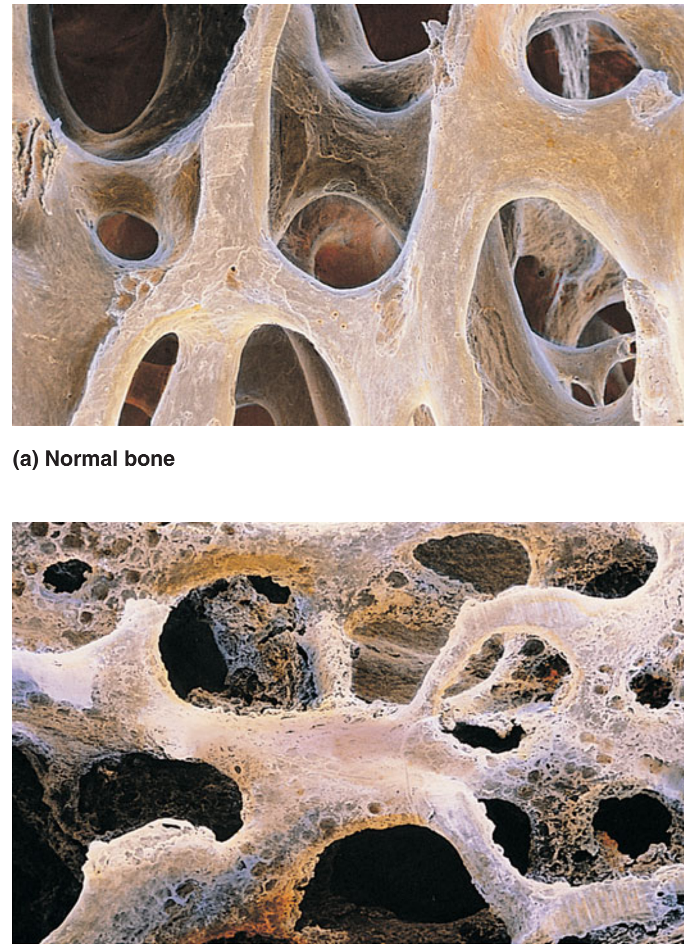
As mentioned in the introduction to this chapter, nutritional deficiencies and disease processes are reflected in our skeleton. Studying the skeletal remains of prehistoric human populations can reveal a wealth of information about their nutrition and lifestyle. For modern humans, understanding the growth and development of bone is essential for treating diseases of the skeletal system.

Osteoporosis

Osteoporosis (os″te-o-po-ro′sis; "bone-porous-condition") is characterized by low bone mass and a deterioration of the microscopic architecture of the bony skeleton **(Figure 6.16)**. Although the chemical composition of the matrix remains normal, bone resorption outpaces bone deposition, in association with elevated numbers of osteoclasts. Osteoporotic bones become porous and light. The compact bone becomes thinner and less dense than normal, and the spongy bone has fewer trabeculae. The loss of bone mass often leads to fractures. Even though osteoporosis affects the whole skeleton, the vertebral column is most vulnerable, and compression fractures of the vertebrae are frequent. The femur (thigh bone), especially its neck near the hip joint, is also very susceptible to fracture. A break there, called a broken hip, is a common problem in people with osteoporosis.

Osteoporosis occurs most often in the aged, particularly in women who have gone through menopause. Although men develop it to a lesser degree, 30% of American women between the ages of 60 and 70 have osteoporosis; 70% have it by age 80. Moreover, 30% of all Caucasian women (the most susceptible group) will experience a bone fracture due to osteoporosis. Estrogen deficiency is strongly implicated in osteoporosis in older women because the secretion of estrogens, which helps maintain bone density, wanes after menopause. Additional factors that contribute to osteoporosis include insufficient exercise to stress the bones and a diet poor in calcium and protein. Because bone deposition rates are high during adolescence and early adulthood, proper diet and exercise during these years is critical to developing and maintaining healthy bone in later life.

Osteoporosis has traditionally been treated by supplemental calcium and vitamin D (remember from Chapter 5 that vitamin D is necessary for the absorption of calcium from the digestive tract), increased exercise, and estrogen replacement. Because of the increased risk of heart attack, stroke, and breast cancer associated with estrogen replacement therapy, this is a controversial treatment. Newer treatments use either bisphosphonate drugs, such as alendronate and risedronate, or hormones (calcitonin, for example) to suppress osteoclast activity and slow bone loss. Selective estrogen receptor modulators (SERMs) such as raloxifene and tamoxifen mimic the beneficial effects of estrogen but target bone alone, without any undesired stimulation of tissues of the breast and uterus. These new treatments do not provide a cure, but they do increase bone mass to a moderate degree and significantly lessen the risk of fractures.



(a) Normal bone

(b) Osteoporotic bone

FIGURE 6.16 Osteoporosis. Scanning electron micrographs, artificially colored (about 80×).

Osteomalacia and Rickets

The term **osteomalacia** (os″te-o-mah-la′she-ah; "soft bones") applies to a number of disorders in adults in which the bones are inadequately mineralized. Even though osteoid matrix is produced, calcification does not occur, and the bones soften and weaken. The main symptom is pain when weight is put on the affected bone.

Rickets, the analogous disease in children, is accompanied by many of the same signs and symptoms. Because young bones are still growing rapidly, however, rickets is more severe than osteomalacia. Along with weakened and bowed leg bones, malformations of the child's head and rib cage are common. Because the epiphyseal plates cannot be replaced with calcified bone, they grow atypically thick, and the epiphyses of the long bones become abnormally long.

Osteomalacia and rickets are caused by inadequate amounts of vitamin D or calcium phosphate in the diet. They are cured by drinking vitamin D–fortified milk and exposing the skin to sunlight.

It is estimated that in the 1800s, upwards of 90% of children in the industrialized cities of North America and Europe suffered from rickets. The change from an agricultural society to an industrial society resulted in large populations living in smog-filled cities and children working long hours in factories with little exposure to sunlight. Vitamin D was added to milk in the United States in 1930 in response to this epidemic triggered by the Industrial Revolution. Child labor laws followed in 1937.

Paget's Disease

Paget's (paj′ets) **disease** is characterized by excessive rates of bone deposition and bone resorption. The newly formed bone, called *Pagetic bone,* has an abnormally high ratio of immature woven bone to mature compact bone. This, along with reduced mineralization, makes the bones soft and weak. Late in the course of the disease, the activity of osteoblasts outpaces that of osteoclasts. Therefore, the bones can thicken, but in an irregular manner, and the medullary cavities may fill with bone. Paget's disease may affect many parts of the skeleton but is usually a localized and intermittent condition. It rarely occurs before age 40 and affects about 3% of all older people in North America. It progresses slowly, often produces no symptoms, and is seldom life-threatening. Its cause is unknown, but it may be initiated by a virus, such as the virus that causes distemper in dogs. A treatment that involves inhibiting osteoclasts with bisphosphonates and other drugs shows considerable success.

Osteosarcoma

A *sarcoma* is any cancer arising from a connective tissue cell or muscle cell, and *osteo* means "bone." Clearly, then, **osteosarcoma** is a form of bone cancer.

Osteosarcoma primarily affects young people between 10 and 25 years of age. It usually originates in a long bone of the upper or lower limb, with 50% of cases arising near the knee. The cancer cells derive from osteoblast-like cells of mesenchymal origin in the parts of the diaphyses nearest the epiphyses. Secreting osteoid and growing quickly, the tumor alters the affected bone by eroding the medullary cavity internally and the compact bone externally. The tumor metastasizes, and most deaths result from secondary tumors in the lungs. Most osteosarcomas are recognized by the pain and the visible swelling they produce in the affected bone, and the diagnosis is confirmed by X-ray studies or other medical imaging techniques. Treatment begins by removing the cancerous region of the bone and replacing it with bone grafts or prostheses (although limb amputation is necessary in severe cases). This is followed by chemotherapy and surgical removal of any metastases in the lung. The survival rate is 60% to 70% if the disease is detected early.

check your understanding

19. Which diseases result from inadequate mineralization of bone?

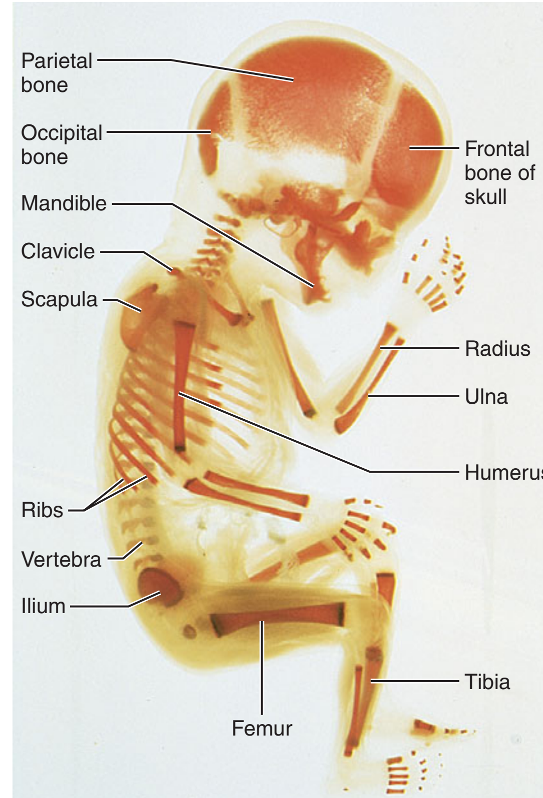


FIGURE 6.17 Primary ossification centers in the skeleton of a 12-week-old fetus.

20. If you wish to slow bone loss, the activity of which cells in bone tissue should be targeted?
21. At what age can you best prevent the development of osteoporosis later in life?

For answers, see Appendix B.

THE SKELETON THROUGHOUT LIFE

➤ Describe how bone architecture and bone mass change from the embryonic period to old age.

As previously noted, cartilage grows quickly during youth and then stops growing during early adulthood. In older adults, it shows fewer chondrocytes and some degradation and calcification of its matrix, resulting in thinning of articular cartilage.

Bones can be said to be on a timetable from the time they form until death. The mesoderm germ layer and neural crest (in the skull) give rise to embryonic mesenchyme cells, which in turn produce the membranes and cartilages that form most of the embryonic skeleton. These structures then ossify according to a predictable schedule. Although each bone of the skeleton has its own developmental schedule, most long bones start ossifying by week 8 and have obvious primary ossification centers by week 12 **(Figure 6.17)**. So precise is the ossification timetable that the age of a fetus in the womb can be determined from X-ray images or sonograms of the fetal skeleton.

At birth, all bones are relatively smooth and featureless. However, as the child increasingly uses its muscles, the bones develop projections and other markings (see Table 6.1). Children's bones are not particularly weak, but the cartilage of their epiphyseal plates is not as strong as bone. Thus, childhood injuries often split the epiphyses off from the diaphysis. To treat such injuries, the bone parts are manipulated back into place, then stabilized with metal pins.

As mentioned earlier, the skeleton keeps growing until the age of 18 to 21 years. In children and adolescents, the rate of bone formation exceeds the rate of bone resorption. In young adults, these two processes are in balance. In old age, resorption predominates. Beginning at about age 40, the mass of both compact and spongy bone declines. Among young adults, skeletal mass is generally greater in men than in women. Age-related bone loss is greater in women than in men.

As bone mass declines with age, other changes occur. An increasing number of osteons remain incompletely formed, and mineralization is less complete. The amount of nonliving compact bone increases, reflecting a diminished blood supply to the bones in old age.

check your understanding

22. At what age do bones begin to ossify? At what age does bone mass begin to decline?
23. Why is age-related bone loss greater in women than in men?

For answers, see Appendix B.

RELATED CLINICAL TERMS

BONE GRAFT Transplantation of a piece of bone from one part of a person's skeleton to another part where bone has been damaged or lost. The graft, often taken from the crest of the iliac bone of the hip, encourages regrowth of lost bone.

BONY SPUR An abnormal projection on a bone due to bone overgrowth; is common in aging bones.

OSTEALGIA (os″te-al′je-ah) (*algia* = pain) Pain in a bone.

OSTEOMYELITIS (os″te-o-mi-ĕ-li′tis; "bone and marrow inflammation"). Bacterial infection of the bone and bone marrow. The pathogen enters bones either from infections in surrounding tissues or through the bloodstream, or follows a compound bone fracture.

PATHOLOGIC FRACTURE Fracture occurring in a diseased bone and involving slight or no physical trauma. An example is a broken hip caused by osteoporosis: The hip breaks first, causing the person to fall.

TRACTION ("pulling") Placing a sustained tension on a region of the body to keep the parts of a fractured bone in the proper alignment. Traction also keeps the bone immobilized as it heals. Without traction of the lower limb, for example, strong spasms of the large muscles of the thigh would separate the fracture in a broken femur. Traction is also used to immobilize fractures of the vertebral column, because any movement there could crush the spinal cord.

CHAPTER SUMMARY

Cartilages (pp. 123–125)

Location and Basic Structure (p. 123)

1. Important cartilages in the adult body are cartilage in the external ear and nose, articular cartilages, costal cartilages, the epiglottis, cartilages of the respiratory tubes, cartilage in intervertebral discs, and cartilage discs in certain movable joints. Cartilage makes up most of the embryonic skeleton.
2. Perichondrium is the girdle of dense connective tissue that surrounds a piece of cartilage.
3. Cartilage is resilient: Water squeezed out of its matrix by compression rushes back in as the compression eases, causing the cartilage to spring back.
4. Growing cartilage enlarges quickly because the small amount of matrix it manufactures attracts a large volume of water. Cartilage is avascular and is weak in resisting shearing stresses.

Types of Cartilage (pp. 123–125)

5. The locations of hyaline, elastic, and fibrocartilage are shown in Figure 6.1.
6. Hyaline cartilage is the most common type. Its matrix contains fine collagen fibrils. Elastic cartilage resembles hyaline cartilage, but its matrix also contains elastic fibers that make it pliable. Fibrocartilage contains thick collagen fibers and can resist both compression and extreme tension.

Growth of Cartilage (p. 125)

7. Cartilages grow from within (interstitial growth) and externally, as chondroblasts in the perichondrium adds cartilage tissue at the periphery (appositional growth). In adults, damaged cartilage regenerates poorly. In the growing and aged skeleton, cartilage calcifies.

Bones (pp. 125–139)

8. Skeletal bones are considered organs because they contain different tissue types.

Functions of Bones (pp. 125–126)

9. Bones support body weight, act as levers for muscles to pull on, protect soft organs, store calcium, and contain bone marrow that makes blood cells. Bone cells also function in energy metabolism by influencing blood sugar regulation.

Bone Tissue (p. 126)

10. Bone consists of cells plus an extracellular matrix. The matrix contains organic substances secreted by osteoblasts, including collagen, which gives bone tensile strength. The organic part of bone matrix is called osteoid. Calcium phosphate salts (hydroxyapatites) crystallize in this matrix, making bone hard and able to resist compression.

11. The cells in bone tissue are osteogenic stem cells; osteoblasts, which secrete osteoid; osteocytes, which maintain the bone matrix; and osteoclasts, which destroy bone tissue.

Classification of Bones (pp. 126–127)

12. Bones are classified on the basis of their shape as long, short, flat, or irregular.

Gross Anatomy of Bones (pp. 128–131)

13. Bones have an external layer of compact bone and are filled internally with spongy bone, in which trabeculae are arranged in networks.

14. A long bone is composed of a diaphysis or shaft, and epiphyses or ends. Epiphyseal vessels serve each epiphysis, and nutrient vessels serve the diaphysis. Bone marrow occurs within the spongy bone and in a central medullary (marrow) cavity. A periosteum covers the outer surface of bones, and an endosteum covers the inner bone surfaces.

15. Flat bones consist of two plates of compact bone separated by a layer of spongy bone.

16. The density of bone material and the magnitude of bending stresses decline from the superficial to the deep regions of the bones. Thus, the strongest forces occur at the periphery, where they are resisted by the strong compact bone. The spaces within bones lighten the skeleton and contain bone marrow.

17. The trabeculae of spongy bone appear to be arranged along the dominant lines of stress experienced by the bone.

18. Bone markings are landmarks that represent sites of muscle attachment, articulation, and passage of blood vessels and nerves (see Table 6.1, p. 131).

Microscopic Structure of Bone (pp. 130–134)

19. An important structural unit in compact bone is the osteon, essentially a pillar consisting of a central canal surrounded by concentric lamellae. Osteocytes, embedded in lacunae, are connected to each other and to the central canal by canaliculi.

20. Bone lamellae are concentric tubes of bone matrix. The collagen fibers in adjacent lamellae run in roughly opposite directions. This arrangement gives bone tissue great strength in resisting torsion (twisting).

21. Spongy bone consists of trabeculae containing several layers of lamellae and osteocytes, but no osteons.

Bone Development and Growth (pp. 134–137)

22. Flat bones of the skull and the clavicle form by intramembranous ossification of embryonic mesenchyme. A network of bone tissue woven around capillaries appears first and is then remodeled into a flat bone.

23. Most bones develop by endochondral ossification of a hyaline cartilage model, starting in the late embryonic period (week 8). The stages of development of a long bone are (1) formation of a bone collar around the diaphysis; (2) calcification and cavitation in the center of the diaphysis; (3) growth of a periosteal bud into the center of the shaft, and formation of the first bone trabeculae; (4) appearance of the medullary cavity and continued rapid growth throughout the fetal period; near birth, secondary ossification centers occur in the epiphyses; (5) ossification of the epiphyses and continued growth in length at the epiphyseal plates through adolescence.

24. The growing cartilage of the fetal epiphyses and the postnatal epiphyseal plates is organized into several zones, which allow rapid growth. These zones are explained in Figure 6.12.

25. Endochondral bones lengthen during youth through the growth of epiphyseal plate cartilages, which close in early adulthood.

26. Bones increase in width through appositional growth.

Bone Remodeling (pp. 137–138)

27. New bone tissue is continuously deposited and resorbed in response to hormonal and mechanical stimuli. Together, these processes are called bone remodeling. Bone remodeling in adults occurs in the endosteum.

28. Osteoclasts break down bone tissue by secreting digestive enzymes and acid onto bone surfaces. This process releases Ca^{2+} and PO_4^{3-} into the blood. Parathyroid hormone stimulates this resorption of bone.

29. Osteoid is secreted by osteoblasts at areas of bone deposit. Calcium salt is then deposited in the osteoid.

30. Compressive forces and gravity acting on the skeleton help maintain bone strength, because bones thicken at sites of stress.

Repair of Bone Fractures (pp. 139, 140)

31. Fractures are treated by open or closed reduction. Healing involves the formation of a hematoma, a fibrocartilaginous callus, and a bony callus, and then a remodeling of the callus into the original bone pattern.

Disorders of Bones (pp. 139–142)

32. Osteoporosis is a condition in which bone breakdown outpaces bone formation, causing bones to weaken. Postmenopausal women are most susceptible.

33. Osteomalacia and rickets occur when bones are inadequately mineralized, making them soft and deformed. The most common cause is inadequate intake or production of vitamin D.

34. Paget's disease is characterized by excessive and abnormal remodeling of bone.

35. Osteosarcoma is the most common form of bone cancer.

The Skeleton Throughout Life (pp. 142–143)

36. Bone formation in the fetus occurs in a predictable and precisely timed manner.

37. The mass of the skeleton increases dramatically during puberty and adolescence, when bone formation exceeds resorption.

38. Bone mass is constant in young adulthood, but beginning at about age 40, bone resorption exceeds formation.

REVIEW QUESTIONS

Multiple Choice/Matching Questions

For answers, see Appendix B.

1. Which is a function of the skeletal system? (a) support, (b) blood cell formation, (c) mineral storage, (d) providing levers for muscle activity, (e) all of these.
2. Articular cartilages are located (a) at the ends of bones, (b) between the ribs and the sternum (breastbone), (c) between the epiphysis and diaphysis, (d) in the nose.
3. The perichondrium of cartilage is similar to the ____ of bone. (a) articular cartilages, (b) spongy bone layer, (c) osteons, (d) marrow, (e) periosteum.
4. Use the key to indicate the type of cartilage that forms each of the structures below.

   Key: (a) hyaline cartilage **(b)** elastic cartilage **(c)** fibrocartilage

   ____ **(1)** articular cartilage covering the surfaces of movable joints

   ____ **(2)** the epiglottis

   ____ **(3)** the thyroid cartilage

   ____ **(4)** the menisci in the knee

   ____ **(5)** the embryonic skeleton
5. Indicate whether each of the following statements is true (T) or false (F).

   ____ **(1)** Cartilage is more resilient than bone.

   ____ **(2)** Cartilage is especially strong in resisting shear (bending and twisting) forces.

   ____ **(3)** Cartilage can grow faster than bone in the growing skeleton.

   ____ **(4)** In the adult skeleton, cartilage heals and regenerates faster than bone when damaged.

   ____ **(5)** Neither bone nor cartilage contains capillaries.

   ____ **(6)** Bone tissue contains very little water compared to other connective tissues, while cartilage tissue contains a large amount of water.

   ____ **(7)** Nutrients diffuse quickly through cartilage matrix but very poorly through the solid bone matrix.
6. A bone that has essentially the same width, length, and height is most likely (a) a long bone, (b) a short bone, (c) a flat bone, (d) an irregular bone.
7. The shaft of a long bone is properly called the (a) epiphysis, (b) periosteum, (c) diaphysis, (d) compact bone.
8. Match the function of bone markings described in column B with the bone markings listed in column A.

Column A	Column B
____ **(1)** trochanter	**(a)** attachment site for muscle or ligament
____ **(2)** condyle	**(b)** forms a joint surface
____ **(3)** foramen	**(c)** passageway for vessels or nerves
____ **(4)** process	
____ **(5)** facet	
____ **(6)** tuberosity	

9. The osteon exhibits (a) a central canal containing blood vessels, (b) concentric lamellae of matrix, (c) osteocytes in lacunae, (d) all of these.
10. The flat bones of the skull develop from (a) areolar tissue, (b) hyaline cartilage, (c) mesenchyme membranes, (d) compact bone.
11. The following events apply to the endochondral ossification process as it occurs in the primary ossification center. Put these events in their proper order by assigning each a number (1–6).

    ____ **(a)** Cartilage in the diaphysis calcifies, and chondrocytes die and disintegrate, leaving cavities.

    ____ **(b)** A collar of bone is laid down around the hyaline cartilage model just deep to the periosteum.

    ____ **(c)** The periosteal bud invades the center of the diaphysis.

    ____ **(d)** The perichondrium of shaft becomes more vascularized and becomes a periosteum.

    ____ **(e)** Osteoblasts first deposit bone tissue around the cartilage spicules within the diaphysis.

    ____ **(f)** Osteoclasts remove the bone from the center of the diaphysis, leaving a medullary cavity that then houses marrow.
12. The remodeling of bone tissue is a function of which cells? (a) chondrocytes and osteocytes, (b) osteoblasts and osteoclasts, (c) chondroblasts and osteoclasts, (d) osteoblasts and osteocytes.
13. Osteogenic cells are located in (a) the lacunae, (b) the fibrous layer of the periosteum, (c) the endosteum, (d) the perichondrium, (e) the growth zone of the epiphysis.
14. A fracture in which the bone penetrates soft tissue and skin is (a) greenstick, (b) compound, (c) simple, (d) comminuted, (e) compression.
15. The disorder in which bones are porous and thin but the chemistry of the bone matrix remains normal is (a) osteomalacia, (b) osteoporosis, (c) osteomyelitis, (d) Paget's disease.
16. Where within an epiphyseal plate is the calcified cartilage located? (a) nearest the diaphysis, (b) in the medullary cavity, (c) farthest from the diaphysis, (d) in the primary ossification center, (e) all of these.
17. Endosteum is in all these places, except: (a) around the exterior of the femur, (b) on the trabeculae of spongy bone, (c) on the lining of the central canal of an osteon, (d) often in direct contact with bone marrow.
18. Match the cells listed in column B with the descriptions in column A. More than one answer may be correct.

Column A	Column B
____ **(1)** located within lacunae	**(a)** osteoblasts
____ **(2)** secrete matrix	**(b)** osteocytes
____ **(3)** maintain bone matrix	**(c)** osteoclasts
____ **(4)** destroy bone tissue	**(d)** chondrocytes
____ **(5)** located in the endosteum	

Short Answer Essay Questions

19. Explain (a) why cartilages are resilient and (b) why cartilage can grow so quickly in the developing skeleton.

20. Some anatomy students are joking between classes, imagining what a bone would look like if it had spongy bone on the outside and compact bone on the inside, instead of the other way around. You tell the students that such an imaginary bone would be of poor mechanical design and would break very easily when bent. Explain why this is so.

21. When and why do the epiphyseal plates close?

22. During what period of life does skeletal mass increase dramatically? Begin to decline? Why are fractures most common in older adults?

23. In a piece of cartilage in the young skeleton, interstitial and appositional growth occur together. Compare and contrast interstitial and appositional growth.

24. Photocopy a picture of a skeleton, and then use a red pencil to color its membrane bones and a blue pencil to color its endochondral bones.

25. Differentiate the following: osteoclast, osteocyte, osteoblast, osteon.

26. List three structural features of cartilage and bone tissue that are similar. List three structural features that are different.

CRITICAL REASONING & CLINICAL APPLICATION QUESTIONS

1. Explain why people confined to wheelchairs because of paralyzed lower limbs have thin, weak bones in their thighs and legs.

2. While walking home from class, 52-year-old Ike fell. He broke a bone and damaged cartilage in his knee. Assuming no special tissue grafts are made, which will probably heal faster, the bone or the cartilage? Why?

3. Carlos went to weight-lifting camp in the summer between seventh and eighth grade. He noticed that the trainer put tremendous pressure on participants to improve their strength. After an especially vigorous workout, Carlos's arm felt extremely sore and weak around the elbow. He went to the camp doctor, who took X-ray photos and then told him that the injury was serious because the "end, or epiphysis, of his upper arm bone was starting to twist off." What had happened? Could the same thing happen to Carlos's 23-year-old sister, Selena, who was also starting a weight-lifting program? Why or why not?

4. Ming posed the following question: "If the epiphyseal growth plates are growing so fast, why do they stay thin? Growing things are supposed to get larger or thicker, but these plates remain the same thickness." How would you answer her?

5. Old Norse stories tell of a famous Viking named Egil, an actual person who lived around A.D. 900. His skull was greatly enlarged and misshapen, and the cranial bones were hardened and thickened (6 cm, or several inches, thick). After he died, his skull was dug up, and it withstood the blow of an ax without damage. In life, he had headaches from the pressure exerted by enlarged vertebrae on his spinal cord. So much blood was diverted to his bones to support their extensive remodeling that his fingers and toes always felt cold, and his heart was damaged through overexertion. What bone disorder did Egil probably have?

6. Bernice, a 75-year-old woman, stumbled slightly while walking, then felt a terrible pain in her left hip. At the hospital, X-ray pictures revealed that the hip was broken. Furthermore, the spongy bone throughout her spine was very thin. What condition does Bernice probably have?

7. Why might repeated pregnancies cause a woman to develop osteomalacia?

8. Traditional treatments for osteoporosis address calcium deficiencies in the diet and the importance of weight-bearing exercise. Describe how weight-bearing exercise improves bone mass.