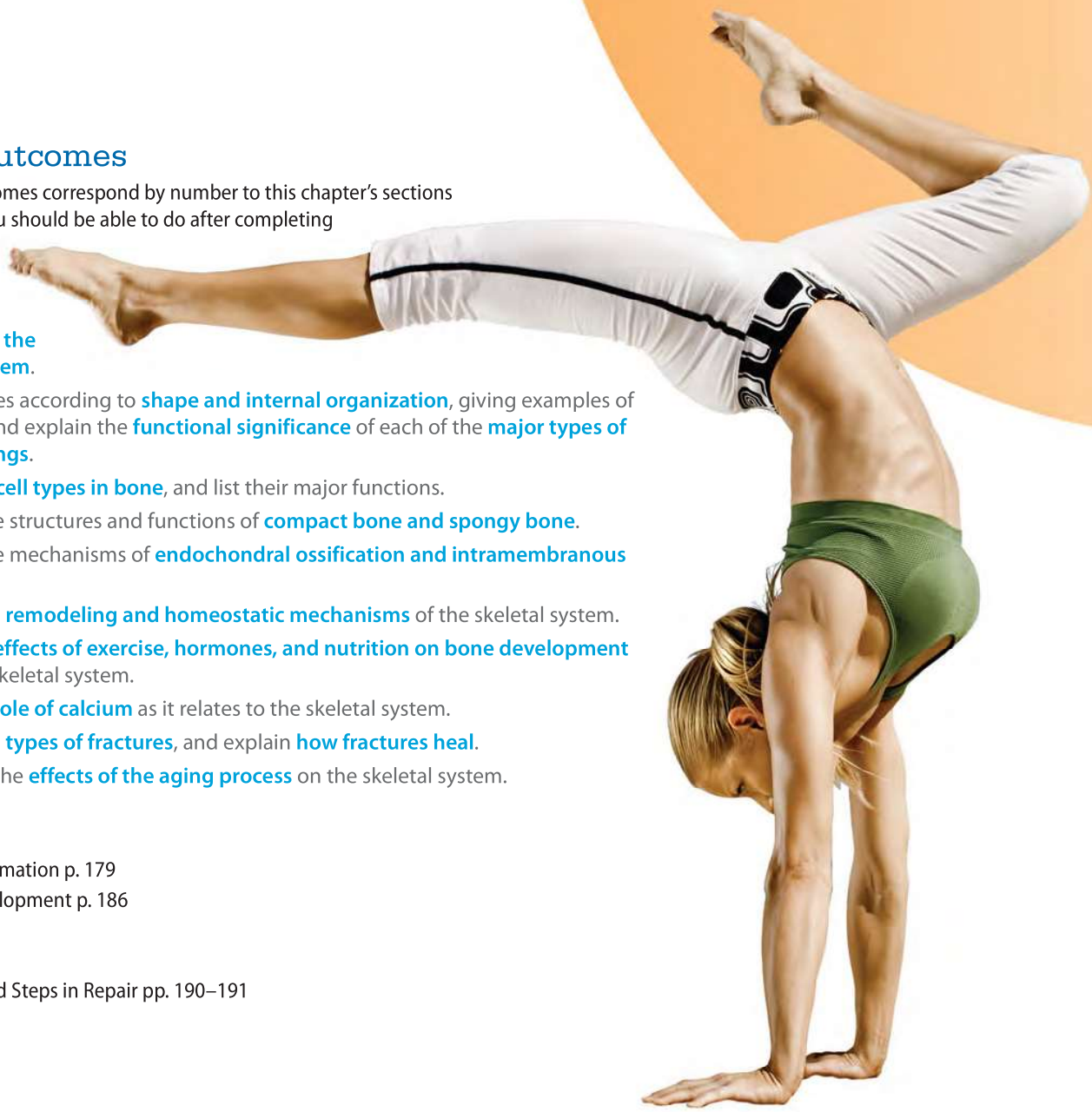
6

Osseous Tissue and Bone Structure



Learning Outcomes

These Learning Outcomes correspond by number to this chapter's sections and indicate what you should be able to do after completing the chapter.

- 6-1 Describe the **primary functions of the skeletal system**.
- 6-2 Classify bones according to **shape and internal organization**, giving examples of each type, and explain the **functional significance** of each of the **major types of bone markings**.
- 6-3 Identify the **cell types in bone**, and list their major functions.
- 6-4 Compare the structures and functions of **compact bone and spongy bone**.
- 6-5 Compare the mechanisms of **endochondral ossification and intramembranous ossification**.
- 6-6 Describe the **remodeling and homeostatic mechanisms** of the skeletal system.
- 6-7 Discuss the **effects of exercise, hormones, and nutrition on bone development** and on the skeletal system.
- 6-8 Explain the **role of calcium** as it relates to the skeletal system.
- 6-9 Describe the **types of fractures**, and explain **how fractures heal**.
- 6-10 Summarize the **effects of the aging process** on the skeletal system.

Clinical Notes

Spotlight

An Introduction to the Skeletal System

This chapter expands upon the introduction to bone, presented in Chapter 4, by examining the mechanisms involved with the growth, remodeling, and repair of the skeleton. Skeletal elements are more than just racks from which muscles hang; they have a variety of vital functions. In addition to supporting the weight of the body, bones work together with muscles to maintain body position and to produce controlled, precise movements. Without the skeleton to pull against, contracting muscle fibers could not make us sit, stand, walk, or run.

6

6-1 The skeletal system has five primary functions

The skeletal system includes the bones of the skeleton and the cartilages, ligaments, and other connective tissues that stabilize or interconnect the bones. This system has five primary functions:

1. *Support.* The skeletal system provides structural support for the entire body. Individual bones or groups of bones provide a framework for the attachment of soft tissues and organs.
2. *Storage of Minerals and Lipids.* As we will learn in Chapter 25, minerals are inorganic ions that contribute to the osmotic concentration of body fluids. Minerals also participate in various physiological processes, and several are important as enzyme cofactors. Calcium is the most abundant mineral in the human body. The calcium salts of bone are a valuable mineral reserve that maintains normal concentrations of calcium and phosphate ions in body fluids. In addition to acting as a mineral reserve, the bones of the skeleton store energy reserves as lipids in areas filled with *yellow bone marrow*.
3. *Blood Cell Production.* Red blood cells, white blood cells, and other blood elements are produced in *red bone marrow*, which fills the internal cavities of many bones. We will describe blood cell formation when we examine the cardiovascular and lymphatic systems (Chapters 19 and 22).
4. *Protection.* Many soft tissues and organs are surrounded by skeletal structures. The ribs protect the heart and lungs, the skull encloses the brain, the vertebrae shield the spinal cord, and the pelvis cradles digestive and reproductive organs.
5. *Leverage.* Many bones function as levers that can change the magnitude and direction of the forces generated by skeletal muscles. The movements produced range from the precise motion of a fingertip to changes in the position of the entire body.

Chapters 6–9 describe the structure and function of the skeletal system. We begin by describing bone, or osseous tissue, a supporting connective tissue introduced in Chapter 4. p. 130 All of the features and properties of the skeletal system ultimately depend on the unique and dynamic properties of bone. The bone specimens that you study in lab or that you are familiar with from skeletons of dead animals are only the dry remains of this living tissue. They have the same relationship to the bone in a living organism as a kiln-dried 2-by-4 does to a living oak tree.

Checkpoint

1. **Name the five primary functions of the skeletal system.**

See the blue Answers tab at the back of the book.

6-2 Bones are classified according to shape and structure, and feature surface markings

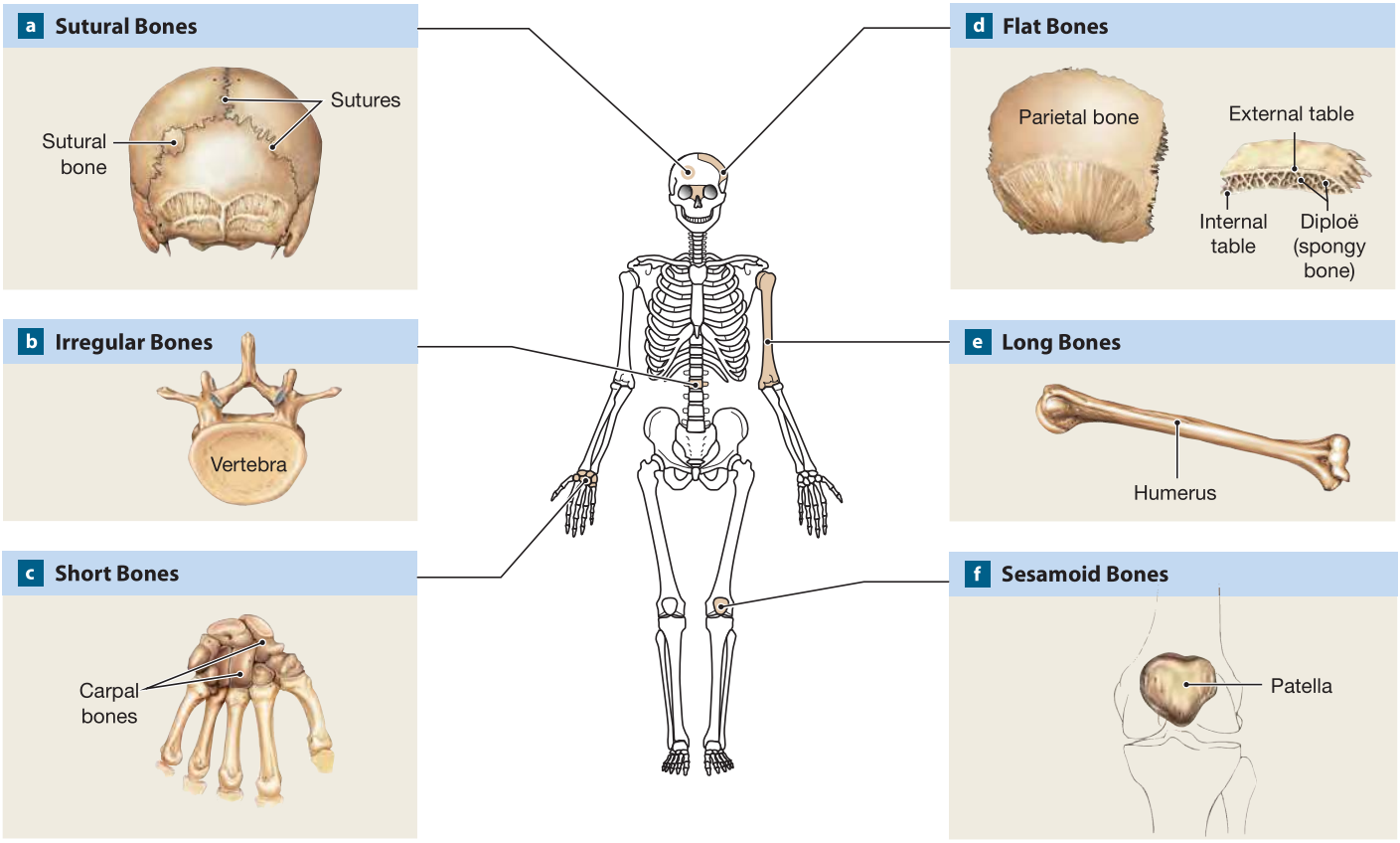
A bone may be classified by its general shape or by its internal tissue organization. Before considering specific bones of the skeleton, you must be familiar with both classification schemes.

Bone Shapes

The typical adult skeleton contains 206 major bones, which we can divide into six broad categories according to their individual shapes (**Figure 6–1**):

1. **Sutural bones,** or *Wormian bones*, are small, flat, irregularly shaped bones between the flat bones of the skull (**Figure 6–1a**). There are individual variations in the number, shape, and position of the sutural bones. Their borders are like pieces of a jigsaw puzzle, and they range in size from a grain of sand to as wide as a quarter.
2. **Irregular bones** have complex shapes with short, flat, notched, or ridged surfaces (**Figure 6–1b**). The spinal vertebrae, the bones of the pelvis, and several skull bones are irregular bones.
3. **Short bones** are small and boxy (**Figure 6–1c**). Examples of short bones include the carpal bones (wrists) and tarsal bones (ankles).
4. **Flat bones** have thin, parallel surfaces. Flat bones form the roof of the skull (**Figure 6–1d**), the sternum, the ribs, and the scapulae. They provide protection for underlying soft tissues and offer an extensive surface area for the attachment of skeletal muscles.
5. **Long bones** are fairly long and slender (**Figure 6–1e**). Long bones are located in the arm and forearm, thigh and leg, palms, soles, fingers, and toes. The femur, the long bone of the thigh, is the largest and heaviest bone in the body.

Figure 6–1 A Classification of Bones by Shape.



6. **Sesamoid bones** are small, flat, and shaped somewhat like a sesame seed (**Figure 6–1f**). They develop inside tendons and are most commonly located near joints at the knees, the hands, and the feet. Everyone has sesamoid *patellae* (pa-TEL-ē; singular, *patella*, a small shallow dish), or kneecaps, but individuals vary in the location and abundance of other sesamoid bones. This variation, among others, accounts for disparities in the total number of bones in the skeleton. (Sesamoid bones may form in at least 26 locations.)

Bone Markings

Each bone in the body has characteristic external and internal features. Elevations or projections form where tendons and ligaments attach, and where adjacent bones articulate (that is, at joints). Depressions, grooves, and tunnels in bone indicate sites where blood vessels or nerves lie alongside or penetrate the bone. Detailed examination of these **bone markings,** or *surface features*, can yield an abundance of anatomical information. For example, anthropologists, criminologists, and pathologists can often determine the size, age, sex, and general appearance of an individual on the basis of incomplete skeletal remains.

Table 6–1 presents an introduction to the prominent bone markings, using specific anatomical terms to describe the various projections, depressions, and openings. These markings provide fixed landmarks that can help us determine the position of the soft-tissue components of other organ systems.

Bone Structure

Figure 6–2a introduces the anatomy of the femur, a representative long bone with an extended tubular shaft, or **diaphysis** (dī-AF-i-sis). At each end is an expanded area known as the **epiphysis** (ē-PIF-i-sis). The diaphysis is connected to each epiphysis at a narrow zone known as the **metaphysis** (me-TAF-i-sis; *meta*, between). The wall of the diaphysis consists of a layer of compact bone, or *dense bone*. **Compact bone,** which is relatively solid, forms a sturdy protective layer that surrounds a central space called the **medullary cavity** (*medulla*, innermost part), or *marrow cavity*. The epiphyses consist largely of spongy bone, also called *cancellous* (KAN-se-lus) or *trabecular bone*. **Spongy bone** consists of an open network of struts and plates that resembles latticework with a thin covering, or **cortex,** of compact bone. This superficial layer covering spongy bone is also known as *cortical bone*.

Table 6–1 An Introduction to Bone Markings

General Description	Anatomical Term	Definition
Elevations and projections	**Process**	Any projection or bump
	Ramus	An extension of a bone making an angle with the rest of the structure
Processes formed where tendons or ligaments attach	**Trochanter**	A large, rough projection
	Tuberosity	A smaller, rough projection
	Tubercle	A small, rounded projection
	Crest	A prominent ridge
	Line	A low ridge
	Spine	A pointed or narrow process
Processes formed for articulation with adjacent bones	**Head**	The expanded articular end of an epiphysis, separated from the shaft by a neck
	Neck	A narrow connection between the epiphysis and the diaphysis
	Condyle	A smooth, rounded articular process
	Trochlea	A smooth, grooved articular process shaped like a pulley
	Facet	A small, flat articular surface
Depressions	**Fossa**	A shallow depression
	Sulcus	A narrow groove
Openings	**Foramen**	A rounded passageway for blood vessels or nerves
	Canal	A duct or channel
	Meatus	A passageway through a bone
	Fissure	An elongated cleft or slit
	Sinus	A chamber within a bone, normally filled with air

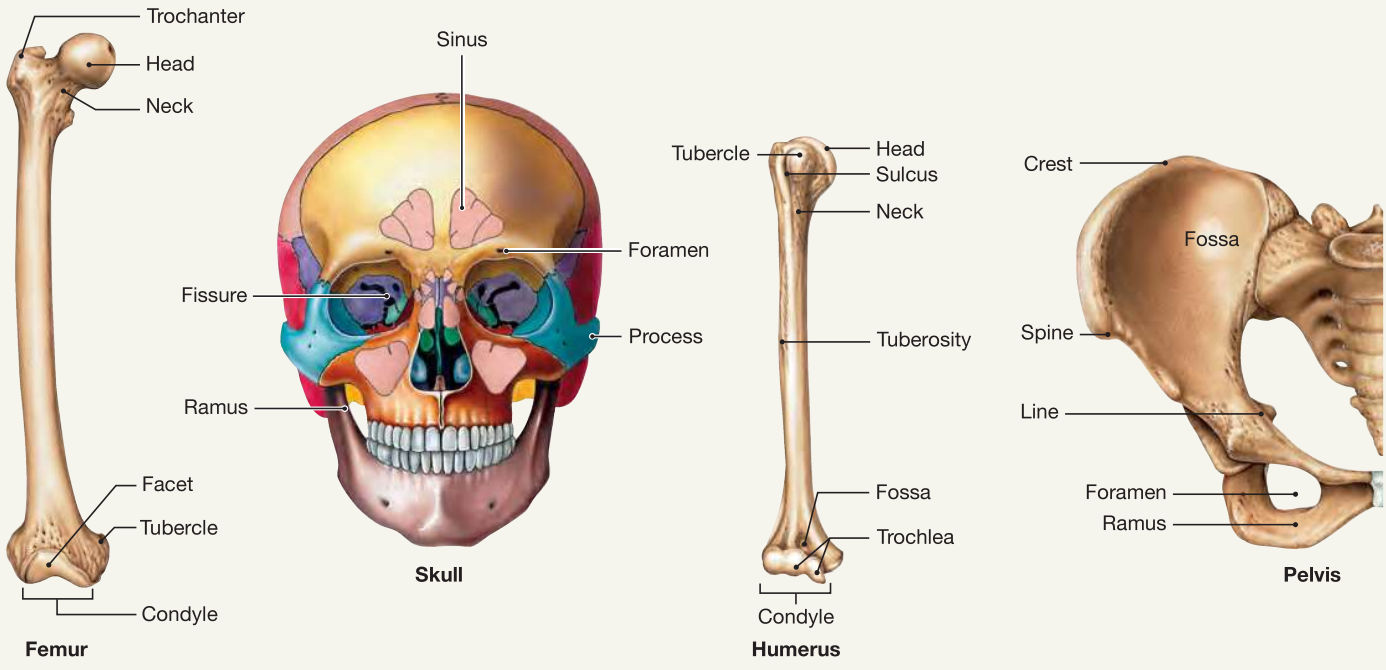


Figure 6–2b details the structure of a flat bone from the skull, such as one of the *parietal bones*. A flat bone resembles a spongy bone sandwich, with layers of compact bone covering a core of spongy bone. Within the cranium, the layer of spongy bone between the layers of compact bone is called the *diploë* (DIP-lō-ē; *diplous*, twofold). Although red bone marrow is present within the spongy bone, there is no large medullary cavity as in the diaphysis of a long bone.

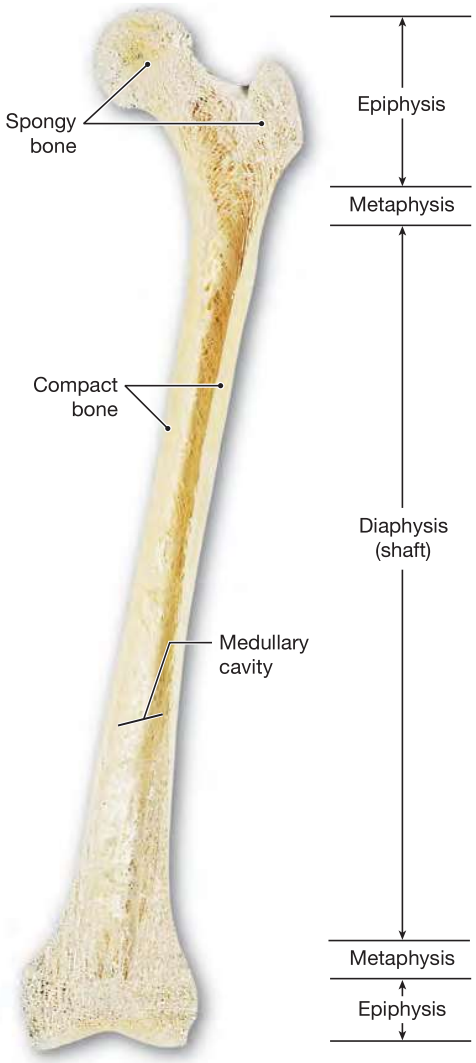
Many people imagine the skeleton to be rather dull and boring. This is far from the truth. Our bones are complex, dynamic organs that constantly change to adapt to the demands we place on them. We will now consider the histological organization of a typical bone.

Checkpoint

2. **Identify the six broad categories for classifying a bone according to shape.**
3. **Define bone marking.**

See the blue Answers tab at the back of the book.

Figure 6–2 Bone Structure.



a The structure of a representative long bone (the femur) in longitudinal section

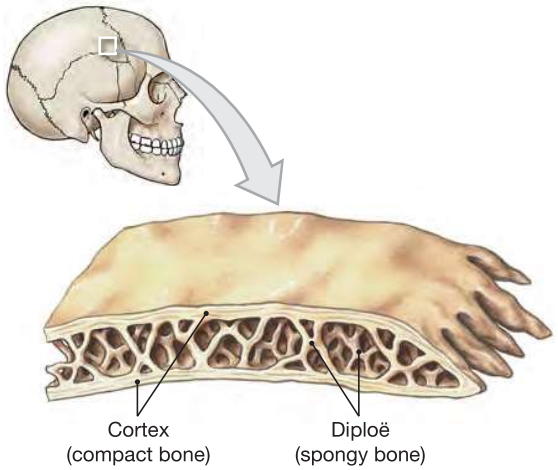
6-3 Bone is composed of matrix and several types of cells: osteocytes, osteoblasts, osteoprogenitor cells, and osteoclasts

Osseous tissue is a supporting connective tissue. (You may wish to review the sections on dense connective tissues, cartilage, and bone in Chapter 4.) pp. 125–131 Like other connective tissues, osseous tissue contains specialized cells and a matrix consisting of extracellular protein fibers and a ground substance. The matrix of bone tissue is solid and sturdy, due to the deposition of calcium salts around the protein fibers.

In Chapter 4, we discussed the following characteristics of bone:

- The matrix of bone is very dense and contains deposits of calcium salts.
- The matrix contains bone cells, or *osteocytes*, within pockets called *lacunae*. (The spaces that chondrocytes occupy in cartilage are also called lacunae. p. 127) The lacunae of bone are typically organized around blood vessels that branch through the bony matrix.
- *Canaliculi*, narrow passageways through the matrix, extend between the lacunae and nearby blood vessels, forming a branching network for the exchange of nutrients, waste products, and gases.
- Except at joints, a periosteum, which consists of an outer fibrous and an inner cellular layer, covers the outer surfaces of bones.

We now take a closer look at the organization of the matrix and cells of bone.



b The structure of a flat bone (the parietal bone)

Bone Matrix

Calcium phosphate, $Ca_3(PO_4)_2$, accounts for almost two-thirds of the weight of bone. Calcium phosphate interacts with calcium hydroxide, $Ca(OH)_2$, to form crystals of **hydroxyapatite,** $Ca_{10}(PO_4)_6(OH)_2$. As they form, these crystals incorporate other calcium salts, such as calcium carbonate ($CaCO_3$), and ions such as sodium, magnesium, and fluoride. Approximately one-third of the weight of bone is collagen fibers. Cells account for only 2 percent of the mass of a typical bone.

Calcium phosphate crystals are very hard, but relatively inflexible and quite brittle. They can withstand compression, but are likely to shatter when exposed to bending, twisting, or sudden impacts. Collagen fibers, by contrast, are remarkably strong; when subjected to tension (pull), they are stronger than steel. Flexible as well as tough, they can easily tolerate twisting and bending, but offer little resistance to compression. When compressed, they simply bend out of the way.

The composition of the matrix in compact bone is the same as that in spongy bone. The collagen fibers provide an organic framework on which hydroxyapatite crystals can form. These crystals form small plates and rods that are locked into the collagen fibers at regular angles. The result is a protein–crystal combination that possesses the flexibility of collagen and the compressive strength of hydroxyapatite crystals. The protein–crystal interactions allow bone to be strong, somewhat flexible, and highly resistant to shattering. In its overall properties, bone is on a par with the best steel-reinforced concrete. In fact, bone is far superior to concrete, because it can undergo remodeling (cycles of bone formation and resorption) as needed and can repair itself after injury.

Bone Cells

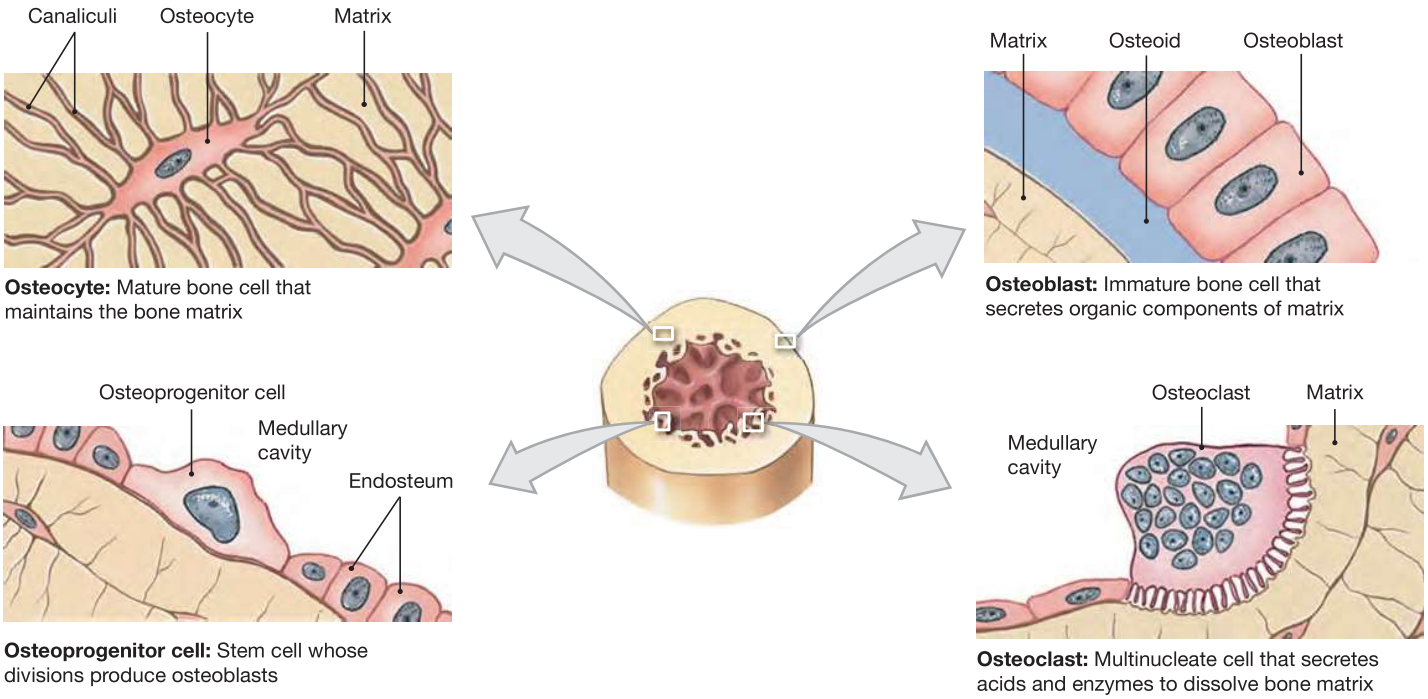
Although osteocytes are most abundant, bone contains four types of cells: osteocytes, osteoblasts, osteoprogenitor cells, and osteoclasts (**Figure 6–3**).

Osteocytes (OS-tē-ō-sīts) (*osteo-*, bone + *-cyte*, cell) are mature bone cells that make up most of the cell population. Each osteocyte occupies a lacuna, a pocket sandwiched between layers of matrix. The layers are called **lamellae** (lah-MEL-lē; singular, *lamella*, a thin plate). Osteocytes cannot divide, and a lacuna never contains more than one osteocyte. Narrow passageways called **canaliculi** penetrate the lamellae, radiating through the matrix and connecting lacunae with one another and with sources of nutrients, such as blood vessels in the central canal.

Canaliculi contain cytoplasmic extensions of osteocytes. Neighboring osteocytes are linked by gap junctions, which permit the exchange of ions and small molecules, including nutrients and hormones, between the cells. The interstitial fluid that surrounds the osteocytes and their extensions provides an additional route for the diffusion of nutrients and waste products. Osteocytes have two major functions:

1. *Osteocytes maintain the protein and mineral content of the surrounding matrix.* This is not a static process, as there is continual turnover of matrix components. Osteocytes secrete chemicals that dissolve the adjacent matrix, and the min-

Figure 6–3 Types of Bone Cells.



erals released enter the circulation. Osteocytes then rebuild the matrix, stimulating the deposition of new hydroxyapatite crystals. The turnover rate varies from bone to bone; we will consider this process further in a later section.

2. *Osteocytes participate in the repair of damaged bone.* If released from their lacunae, osteocytes can convert to a less specialized type of cell, such as an osteoblast or an osteoprogenitor cell.

Osteoblasts (OS-tē-ō-blasts; *blast*, precursor) produce new bone matrix in a process called **ossification,** or **osteogenesis** (os-tē-ō-JEN-e-sis; *gennan*, to produce). Osteoblasts make and release the proteins and other organic components of the matrix. Before calcium salts are deposited, this organic matrix is called **osteoid** (OS-tē-oyd). Osteoblasts also assist in elevating local concentrations of calcium phosphate above its solubility limit, thereby triggering the deposition of calcium salts in the organic matrix. This process converts osteoid to bone. Osteocytes develop from osteoblasts that have become completely surrounded by bone matrix.

Bone contains small numbers of mesenchymal cells called **osteoprogenitor** (os-tē-ō-prō-JEN-i-tor) **cells** (*progenitor*, ancestor). These squamous stem cells divide to produce daughter cells that differentiate into osteoblasts. Osteoprogenitor cells maintain populations of osteoblasts and are important in the repair of a *fracture* (a break or a crack in a bone). Osteoprogenitor cells are located in the inner, cellular layer of the periosteum; in an inner layer, or *endosteum*, that lines medullary cavities; and in the lining of passageways, containing blood vessels, that penetrate the matrix of compact bone.

Osteoclasts (OS-tē-ō-clasts; *clast*, to break) are cells that remove and recycle bone matrix. These are giant cells with 50 or more nuclei. Osteoclasts are not related to osteoprogenitor cells or their descendants. Instead, they are derived from the same stem cells that produce monocytes and macrophages. Acids and proteolytic (protein-digesting) enzymes secreted by osteoclasts dissolve the matrix and release the stored minerals. This erosion process, called **osteolysis** (os-tē-OL-i-sis; *osteo-*, bone + *lysis*, a loosening) or *resorption*, is important in the regulation of calcium and phosphate concentrations in body fluids.

In living bone, osteoclasts are constantly removing matrix, and osteoblasts are always adding to it. The balance between the opposing activities of osteoblasts and osteoclasts is very important. When osteoclasts remove calcium salts faster than osteoblasts deposit them, bones weaken. When osteoblast activity predominates, bones become stronger and more massive. This opposition causes some interesting differences in skeletal components among individuals. Those who subject their bones to muscular stress through weight training or strenuous exercise develop not only stronger muscles, but also stronger bones. Alternatively, declining muscular activity due to immobility leads to a reduction in bone mass at sites of muscle attachment. We will investigate this phenomenon further in a later section of the chapter.

Checkpoint

4. Mature bone cells are known as _____, bone-building cells are called _____, and _____ are bone-resorbing cells.
5. How would the compressive strength of a bone be affected if the ratio of collagen to hydroxyapatite increased?
6. If the activity of osteoclasts exceeds the activity of osteoblasts in a bone, how will the mass of the bone be affected?

See the blue Answers tab at the back of the book.

6-4 Compact bone contains parallel osteons, and spongy bone contains trabeculae

In this section, we examine the structures of compact and spongy bone in detail. Additionally, two bone layers, the periosteum and endosteum, will be discussed.

Compact Bone Structure

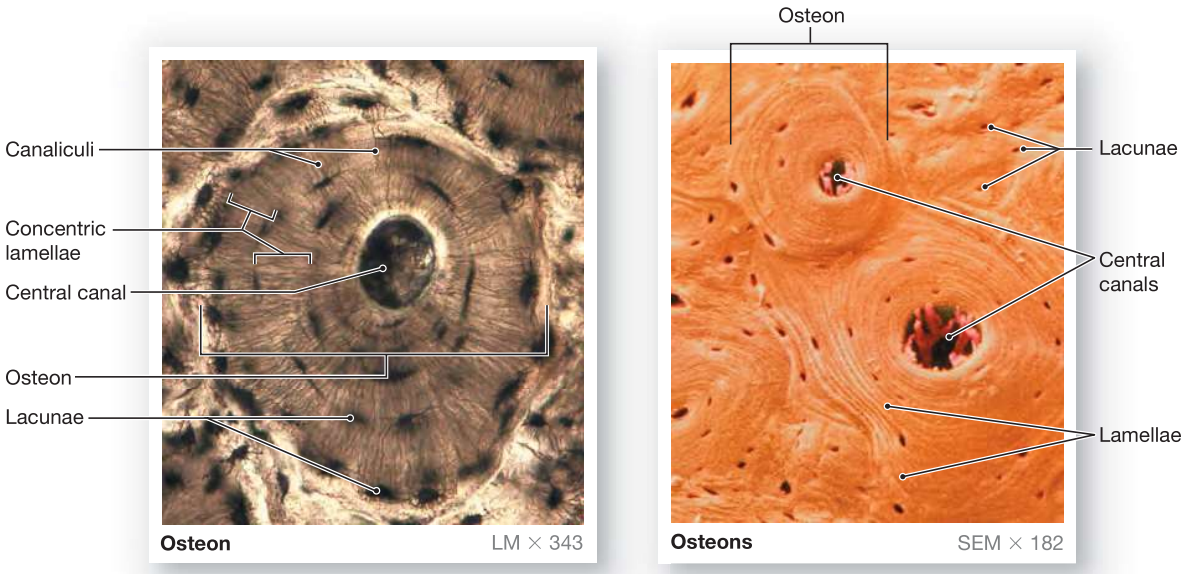
The basic functional unit of mature compact bone is the **osteon** (OS-tē-on), or *Haversian system* (**Figures 6–4** and **6–5a**). In an osteon, the osteocytes are arranged in concentric layers around a **central canal,** or *Haversian canal*. This canal contains one or more blood vessels (normally a capillary and a *venule*, a very small vein) that carry blood to and from the osteon. Central canals generally run parallel to the surface of the bone. Other passageways, known as **perforating canals** or *Volkmann's canals*, extend perpendicular to the surface. Blood vessels in these canals supply blood to osteons deeper in the bone and to tissues of the medullary cavity.

The lamellae of each osteon form a series of nested cylinders around the central canal. In transverse section, these *concentric lamellae* create a targetlike pattern, with the central canal as the bull's-eye. Collagen fibers within each lamella form a spiral that adds strength and resiliency. Canaliculi radiating through the lamellae interconnect the lacunae of the osteons with one another and with the central canal. *Interstitial lamellae* fill in the spaces between the osteons in compact bone. These lamellae are remnants of osteons whose matrix components have been almost completely recycled by osteoclasts. *Circumferential lamellae* (*circum-*, around + *ferre*, to bear) are found at the outer and inner surfaces of the bone, where they are covered by the periosteum and endosteum, respectively (**Figure 6–5a,b**). These lamellae are produced during the growth of the bone, and this process will be described in a later section.

Tips & Tricks

To understand the relationship of collagen fibers to bone matrix, envision the placement of reinforcing steel rods (rebar) in concrete. Like the rebar in concrete, collagen adds strength to bone.

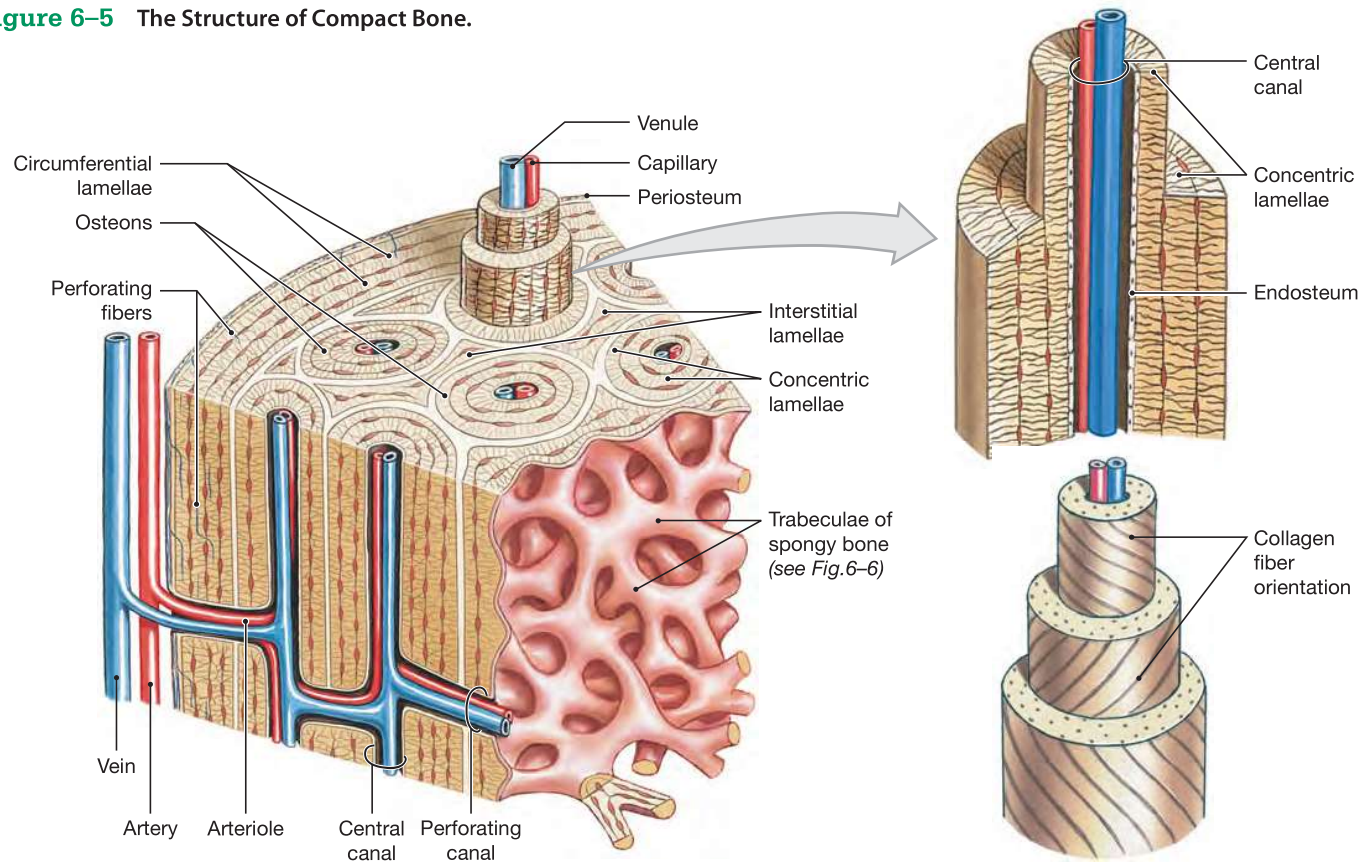
Figure 6–4 The Histology of Compact Bone.



a A thin section through compact bone. By this procedure the intact matrix making up the lamellae appear white, and the central canal, lacunae, and canaliculi appear black due to the presence of bone dust.

b Several osteons in compact bone.

Figure 6–5 The Structure of Compact Bone.



a The organization of osteons and lamellae in compact bone

b The orientation of collagen fibers in adjacent lamellae

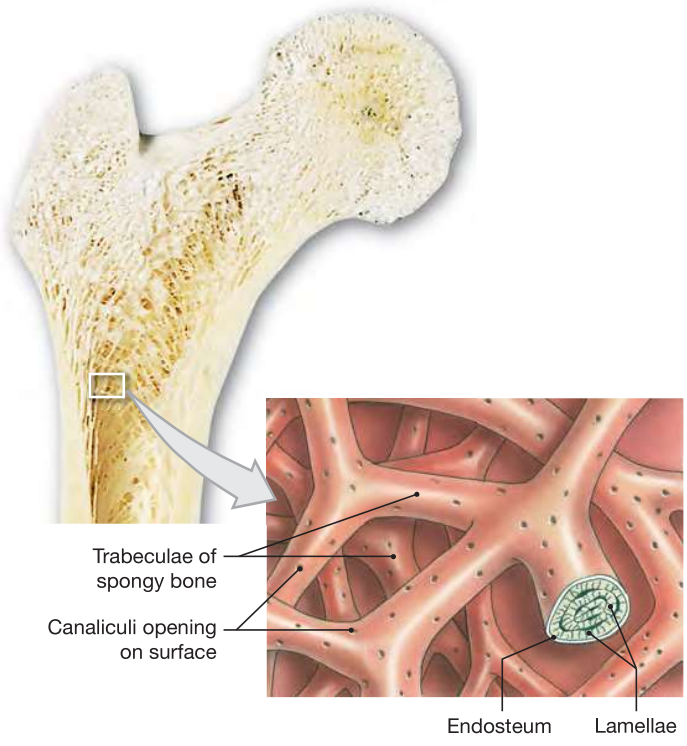
Compact bone is thickest where stresses arrive from a limited range of directions. All osteons in compact bone are aligned the same, making such bones very strong when stressed along the axis of alignment. You might think of a single osteon as a drinking straw with very thick walls: When you attempt to push the ends of the straw together or to pull them apart, the straw is quite strong. But if you hold the ends and push from the side, the straw will bend sharply easily.

The osteons in the diaphysis of a long bone are parallel to the long axis of the shaft. Thus, the shaft does not bend, even when extreme forces are applied to either end. (The femur can withstand 10–15 times the body's weight without breaking.) Yet a much smaller force applied to the side of the shaft can break the femur. A sudden sideways force, such as occurs in a fall or auto accident, causes the majority of breaks in this bone.

Spongy Bone Structure

In spongy bone, lamellae are not arranged in osteons. The matrix in spongy bone forms a meshwork of supporting bundles of fibers called **trabeculae** (tra-BEK-ū-lē) (**Figure 6–6**). These thin trabeculae branch, creating an open network. There are no capillaries or venules in the matrix of spongy bone. Nutrients reach the osteocytes by diffusion along canaliculi that open onto the surfaces of trabeculae. Red bone marrow is found between the trabeculae of spongy bone, and blood vessels within this tissue deliver nutrients to the trabeculae and remove wastes generated by the osteocytes.

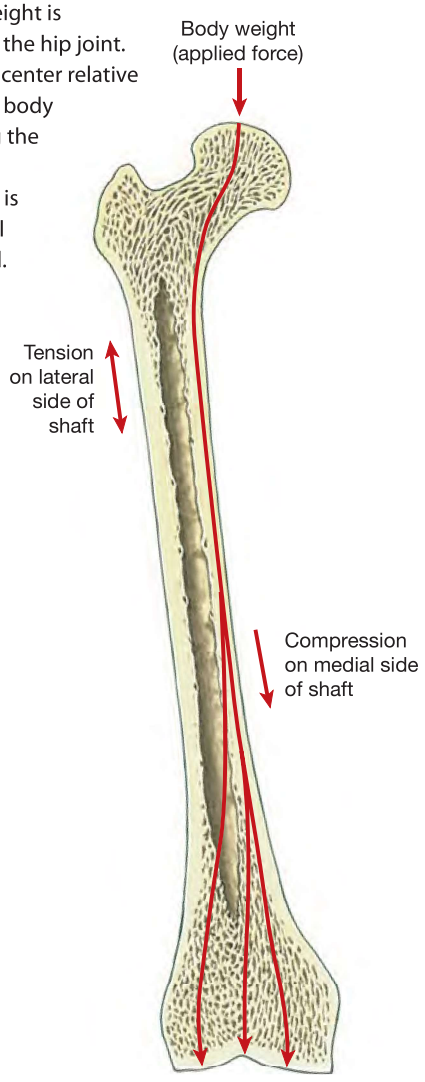
Figure 6–6 The Structure of Spongy Bone.



Spongy bone is located where bones are not heavily stressed or where stresses arrive from many directions. The trabeculae are oriented along stress lines and are cross-braced extensively. In addition to being able to withstand stresses applied from many directions, spongy bone is much lighter than compact bone. Spongy bone reduces the weight of the skeleton and thereby makes it easier for muscles to move the bones. Finally, the framework of trabeculae supports and protects the cells of the bone marrow. Spongy bone within the epiphyses of long bones, such as the femur, and the interior of other large bones such as the sternum and ilium, contains **red bone marrow** responsible for blood cell formation. At other sites, spongy bone may contain **yellow bone marrow**—adipose tissue important as an energy reserve.

Figure 6–7 shows the distribution of forces applied to the femur, and illustrates the functional relationship between compact

Figure 6–7 The Distribution of Forces on a Long Bone.
The femur, or thigh bone, has a diaphysis (shaft) with walls of compact bone and epiphyses filled with spongy bone. The body weight is transferred to the femur at the hip joint. Because the hip joint is off center relative to the axis of the shaft, the body weight is distributed along the bone such that the medial (inner) portion of the shaft is compressed and the lateral (outer) portion is stretched.



bone and spongy bone. The head of the femur articulates with a corresponding socket on the lateral surface of the pelvis. At the proximal epiphysis of the femur, trabeculae transfer forces from the pelvis to the compact bone of the femoral shaft, across the hip joint; at the distal epiphysis, trabeculae transfer weight from the shaft to the leg, across the knee joint. The femoral head projects medially, and the body weight compresses the medial side of the shaft. However, because the force is applied off center, the bone must also resist the tendency to bend into a lateral bow. So while the medial portion of the shaft is under compression, the lateral portion of the shaft, which resists this bending, is placed under a stretching load, or *tension*. Because the center of the bone is not subjected to compression or tension, the presence of the medullary cavity does not reduce the bone's strength.

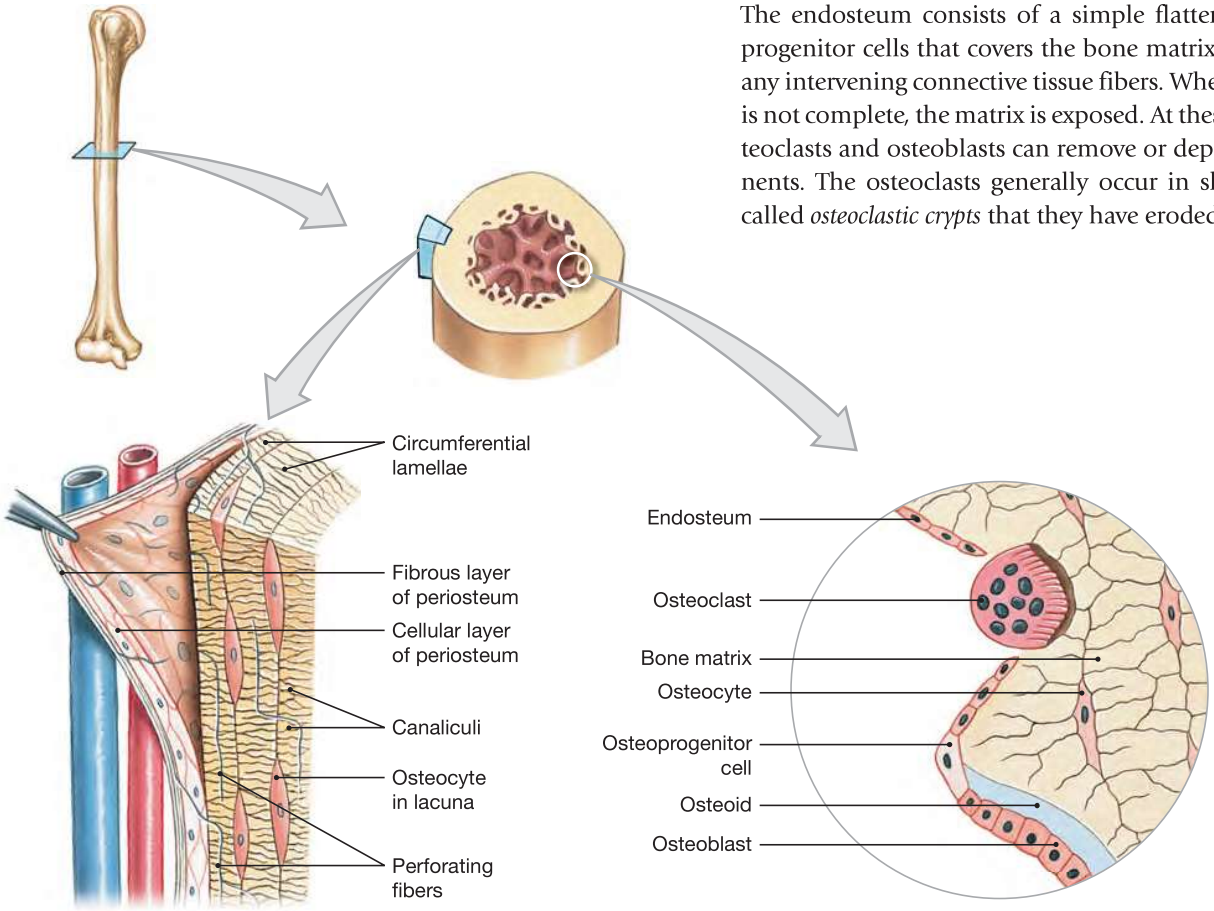
The Periosteum and Endosteum

Except within joint cavities, the superficial layer of compact bone that covers all bones is wrapped by a **periosteum,** a membrane with a fibrous outer layer and a cellular inner layer (**Figure 6–8a**). The periosteum (1) isolates the bone from surrounding tissues, (2) provides a route for the circulatory and nervous supply, and (3) participates in bone growth and repair.

Near joints, the periosteum becomes continuous with the connective tissues that lock the bones together. At a synovial joint, the periosteum is continuous with the joint capsule. The fibers of the periosteum are also interwoven with those of the tendons attached to the bone. As the bone grows, these tendon fibers are cemented into the circumferential lamellae by osteoblasts from the cellular layer of the periosteum. Collagen fibers incorporated into bone tissue from tendons and ligaments, as well as from the superficial periosteum, are called *perforating (Sharpey's) fibers*. This method of attachment bonds the tendons and ligaments into the general structure of the bone, providing a much stronger attachment than would otherwise be possible. An extremely powerful pull on a tendon or ligament will usually break a bone rather than snap the collagen fibers at the bone surface.

The **endosteum,** an incomplete cellular layer, lines the medullary cavity (**Figure 6–8b**). This layer, which is active during bone growth, repair, and remodeling, covers the trabeculae of spongy bone and lines the inner surfaces of the central canals. The endosteum consists of a simple flattened layer of osteoprogenitor cells that covers the bone matrix, generally without any intervening connective tissue fibers. Where the cellular layer is not complete, the matrix is exposed. At these exposed sites, osteoclasts and osteoblasts can remove or deposit matrix components. The osteoclasts generally occur in shallow depressions called *osteoclastic crypts* that they have eroded into the matrix.

Figure 6–8 The Periosteum and Endosteum.



a The periosteum contains outer (fibrous) and inner (cellular) layers. Collagen fibers of the periosteum are continuous with those of the bone, adjacent joint capsules, and attached tendons and ligaments.

b The endosteum is an incomplete cellular layer containing osteoblasts, osteoprogenitor cells, and osteoclasts.

Clinical Note — Heterotopic Bone Formation

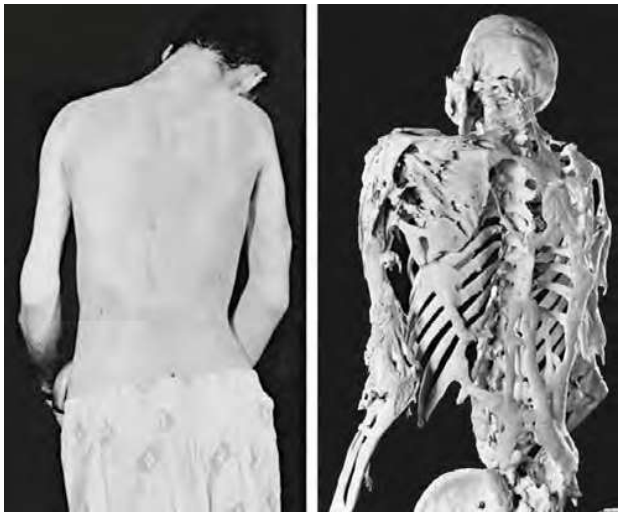
When bone forms outside the skeleton

In response to abnormal stresses, bone may form anywhere in the dermis or within tendons, around joints, in the kidneys, or in skeletal muscles. Dermal bones forming in abnormal locations are called *heterotopic bones* (*hetero-*, different + *topos*, place). These bones can form in very odd places, such as the testes or the whites of the eyes. Physical or chemical events can stimulate the abnormal development of osteoblasts in normal connective tissues, such as sesamoid bones developing within tendons or near points of friction and pressure. Bone can also form within a large blood clot, at an injury site, or within portions of the dermis subjected to chronic abuse.

Persons with the rare genetic disease *Fibrodysplasia Ossificans Progressiva* (FOP) form normal bone in the wrong places after minor injury and provide the most dramatic demonstrations of heterotopic bone formation. The muscles of the back, neck, and upper limbs are gradually replaced by bone. The extent of the conversion can be seen in **Figure 6–9**. **Figure 6–9a** shows an adult male with FOP; **Figure 6–9b** shows the skeleton of an adult male with advanced FOP. Several of the vertebrae have fused into a solid mass, and major muscles of the back, shoulders, and hips have undergone extensive ossification.

Treatment can be problematic, because any surgical excision may trigger more ossification.

Figure 6–9 **Heterotopic Bone Formation.**



a An adult male with FOP, posterior view

b The skeleton of a man with advanced FOP

Checkpoint

7. **Compare the structures and functions of compact bone and spongy bone.**
8. **A sample of bone has lamellae, which are not arranged in osteons. Is the sample most likely taken from the epiphysis or diaphysis?**

See the blue Answers tab at the back of the book.

6-5 Bones form through ossification and they enlarge through appositional growth and remodeling

The growth of the skeleton determines the size and proportions of your body. The bony skeleton begins to form about six weeks after fertilization, when the embryo is approximately 12 mm (0.5 in.) long. (At this stage, the existing skeletal elements are cartilaginous.) During subsequent development, the bones undergo a tremendous increase in size. Bone growth continues through adolescence, and portions of the skeleton generally do not stop growing until about age 25. In this section, we consider the physical process of bone formation, or ossification, and bone growth. Ossification or osteogenesis refer specifically to the formation of bone. The process of **calcification**—the deposition of calcium salts—occurs during ossification, but it can also occur in other tissues. When calcification occurs in tissues other than bone, the result is a calcified tissue (such as calcified cartilage) that does not resemble bone.

Two major forms of ossification exist: endochondral and intramembranous. In *endochondral ossification*, bone replaces existing cartilage. In *intramembranous ossification*, bone develops directly from mesenchyme (loosely organized embryonic tissue) or fibrous connective tissue.

Endochondral Ossification

During development, most bones originate as hyaline cartilages that are miniature models of the corresponding bones of the adult skeleton. These cartilage models are gradually replaced by bone through the process of **endochondral** (en-dō-KON-drul) **ossification** (*endo-*, inside + *chondros*, cartilage). As an example, consider the steps in limb bone development. By the time an embryo is six weeks old, the proximal bone of the limb—either the humerus (arm) or femur (thigh)—is present but composed entirely of hyaline cartilage. This cartilage model continues to grow by expansion of the cartilage matrix *(interstitial growth)* and the production of new cartilage at the outer surface

(appositional growth). ↩ p. 128 Steps in the growth and ossification of a limb bone are diagrammed in **Figure 6–10**:

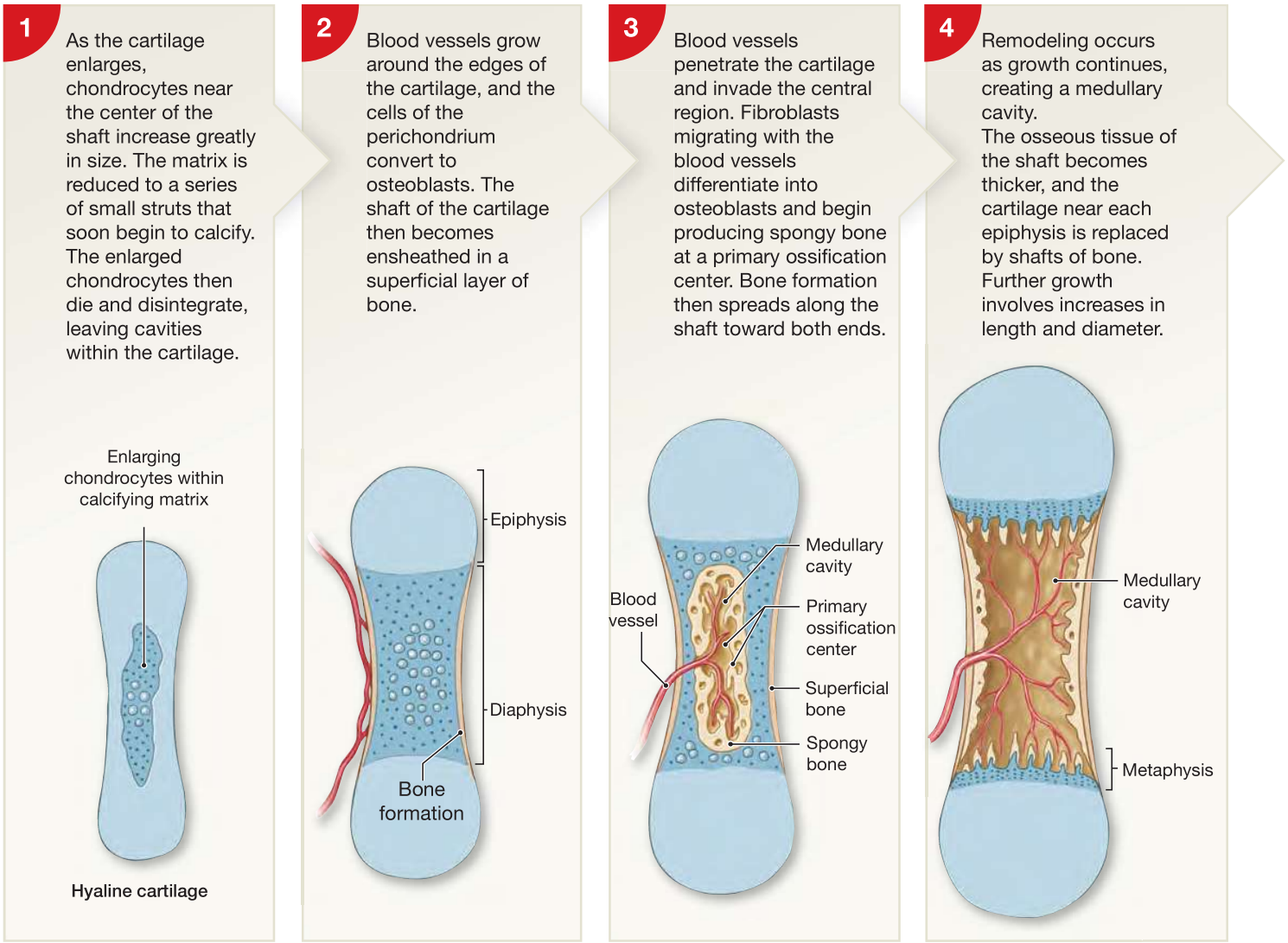
1 As the cartilage enlarges, chondrocytes near the center of the shaft begin to increase greatly in size. As these cells enlarge, their lacunae expand and the matrix is reduced to a series of thin struts that soon begin to calcify. The enlarged chondrocytes are now deprived of nutrients, because diffusion cannot occur through calcified cartilage. These chondrocytes become surrounded by calcified cartilage, die, and disintegrate.

2 Blood vessels grow into the perichondrium surrounding the shaft of the cartilage. (We introduced the structure of the perichondrium and its role in cartilage formation in Chapter 4. ↩ p. 128) The cells of the inner layer of the perichondrium in this region then differentiate into osteoblasts and begin producing a thin layer of bone around the shaft of the cartilage. The perichondrium is now technically a periosteum, because it covers bone rather than cartilage.

3 While these changes are under way, the blood supply to the periosteum increases, and capillaries and fibroblasts migrate into the heart of the cartilage, invading the spaces left by the disintegrating chondrocytes. The calcified cartilaginous matrix breaks down; the fibroblasts differentiate into osteoblasts that replace it with spongy bone. Bone development begins at this site, called the **primary ossification center,** and spreads toward both ends of the cartilaginous model. While the diameter of the diaphysis is small, it is filled with spongy bone and there is no medullary cavity.

4 As the bone enlarges, osteoclasts appear and begin eroding the trabeculae in the center of the diaphysis, creating a

Figure 6–10 **Endochondral Ossification.** ATLAS: Plate 90



medullary cavity. Further growth involves two distinct processes: an increase in length, and an enlargement in diameter by appositional growth. (We will consider appositional growth in the next subsection.)

5 The next major change occurs when the centers of the epiphyses begin to calcify. Capillaries and osteoblasts migrate into these areas, creating **secondary ossification centers.** The appearance of secondary ossification centers varies from one bone to another and from individual to individual. Secondary ossification centers may occur at birth in both ends of the humerus (arm), femur (thigh), and tibia (leg), but the ends of some other bones, such as those of the fingers, remain cartilaginous until early adulthood.

6 The epiphyses eventually become filled with spongy bone. A thin cap of the original cartilage model remains exposed to the joint cavity as the **articular cartilage.** This cartilage prevents damaging bone-to-bone contact within the joint. At the metaphysis, a relatively narrow cartilaginous region called the **epiphyseal cartilage,** or *epiphyseal plate,* now separates the epiphysis from the diaphysis.

7 This micrograph shows the interface between the degenerating cartilage and the advancing osteoblasts. As long as the epiphyseal cartilage continues to grow at its epiphyseal surface, the bone will continue to increase in length.

At puberty, the combination of rising levels of sex hormones, growth hormone, and thyroid hormones stimulates bone growth dramatically. Osteoblasts now begin producing bone faster than chondrocytes are producing new epiphyseal cartilage. As a result, the osteoblasts "catch up" and the epiphyseal cartilage gets

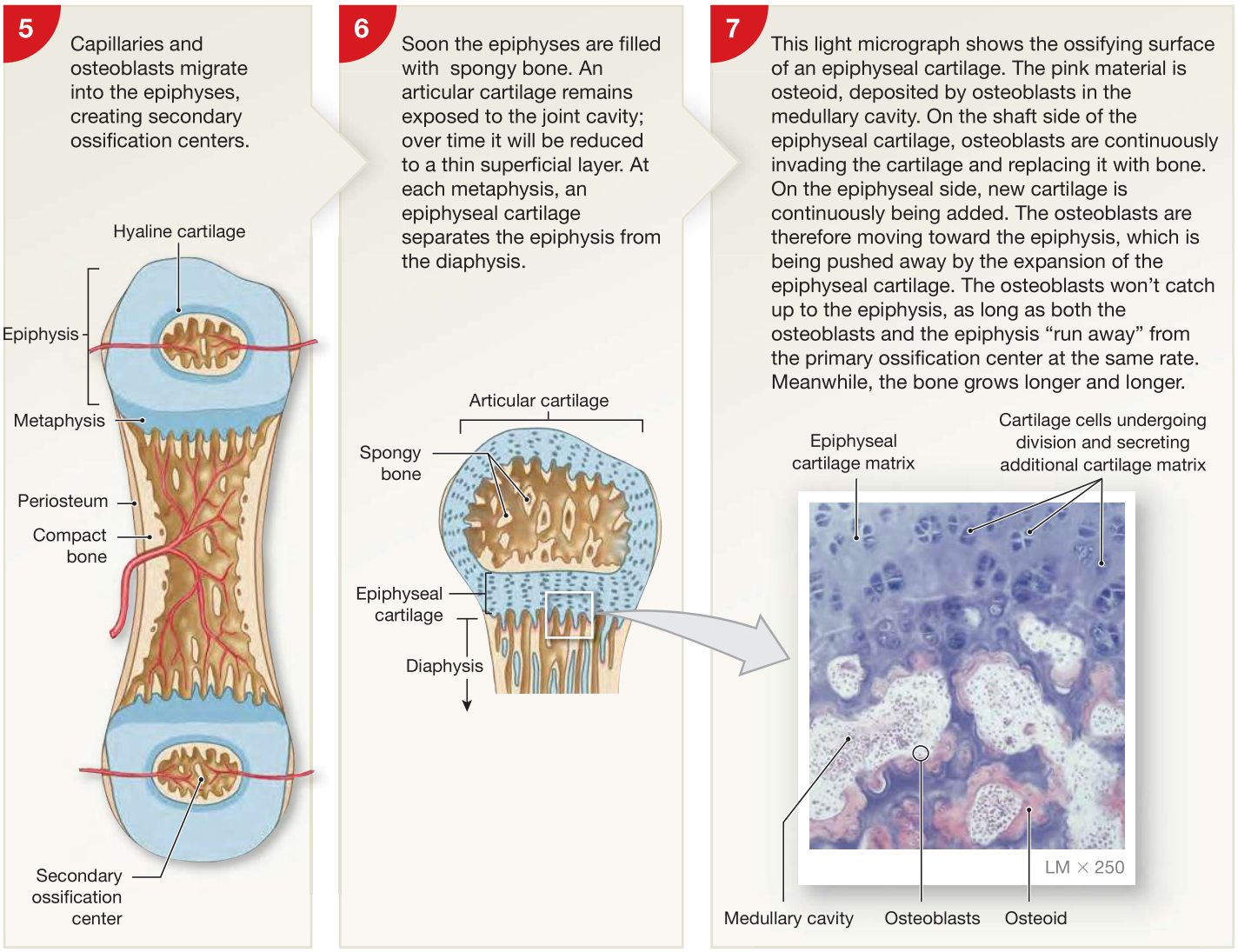
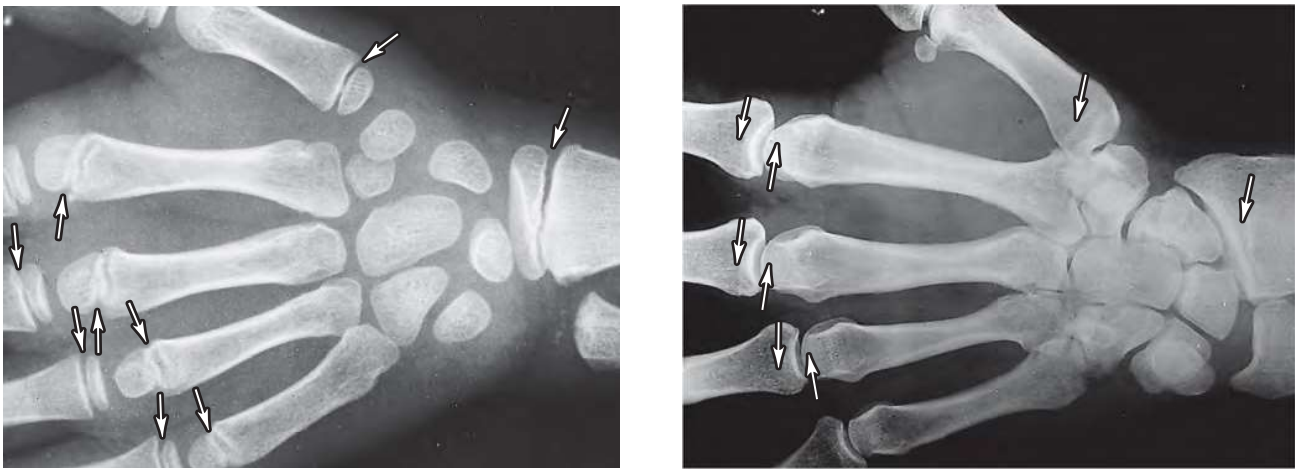


Figure 6–11 Bone Growth at an Epiphyseal Cartilage.



a An x-ray of growing epiphyseal cartilages (arrows)

b Epiphyseal lines in an adult (arrows)

narrower and narrower until it ultimately disappears. The timing of this event can be monitored by comparing the width of the epiphyseal cartilages in successive x-rays. In adults, the former location of this cartilage is often detectable in x-rays as a distinct **epiphyseal line,** which remains after epiphyseal growth has ended (**Figure 6–11**). The completion of epiphyseal growth is called *epiphyseal closure*.

Appositional Growth

A superficial layer of bone forms early in endochondral ossification (**Figure 6–10**, 2). Thereafter, the developing bone increases in diameter through appositional growth at the outer surface. In this process, cells of the inner layer of the periosteum differentiate into osteoblasts and deposit superficial layers of bone matrix. Eventually, these osteoblasts become surrounded by matrix and differentiate into osteocytes. Over much of the surface, appositional growth adds a series of layers that form circumferential lamellae. In time, the deepest circumferential lamellae are recycled and replaced by osteons typical of compact bone. However, blood vessels and collagen fibers of the periosteum can sometimes become enclosed within the matrix produced by osteoblasts. Osteons may then form around the smaller vessels. While bone matrix is being added to the outer surface of the growing bone, osteoclasts are removing bone matrix at the inner surface, albeit at a slower rate. As a result, the medullary cavity gradually enlarges as the bone gets larger in diameter.

Intramembranous Ossification

Intramembranous (in-tra-MEM-bra-nus) **ossification** begins when osteoblasts differentiate within a mesenchymal or fibrous connective tissue. This type of ossification is also called *dermal ossification* because it normally occurs in the deeper layers of the dermis. The bones that result are called **dermal bones.** Examples of dermal bones are the flat bones of the skull, the mandible (lower jaw), and the clavicle (collarbone).

The steps in the process of intramembranous ossification (**Figure 6–12**) can be summarized as follows:

1 Mesenchymal cells first cluster together and start to secrete the organic components of the matrix. The resulting osteoid then becomes mineralized through the crystallization of calcium salts. (The enzyme *alkaline phosphatase* plays a role in this process.) As calcification occurs, the mesenchymal cells differentiate into osteoblasts. The location in a tissue where ossification begins is called an **ossification center.** The developing bone grows outward from the ossification center in small struts called **spicules.** As ossification proceeds, it traps some osteoblasts inside bony pockets; these cells differentiate into osteocytes. Meanwhile, mesenchymal cell divisions continue to produce additional osteoblasts.

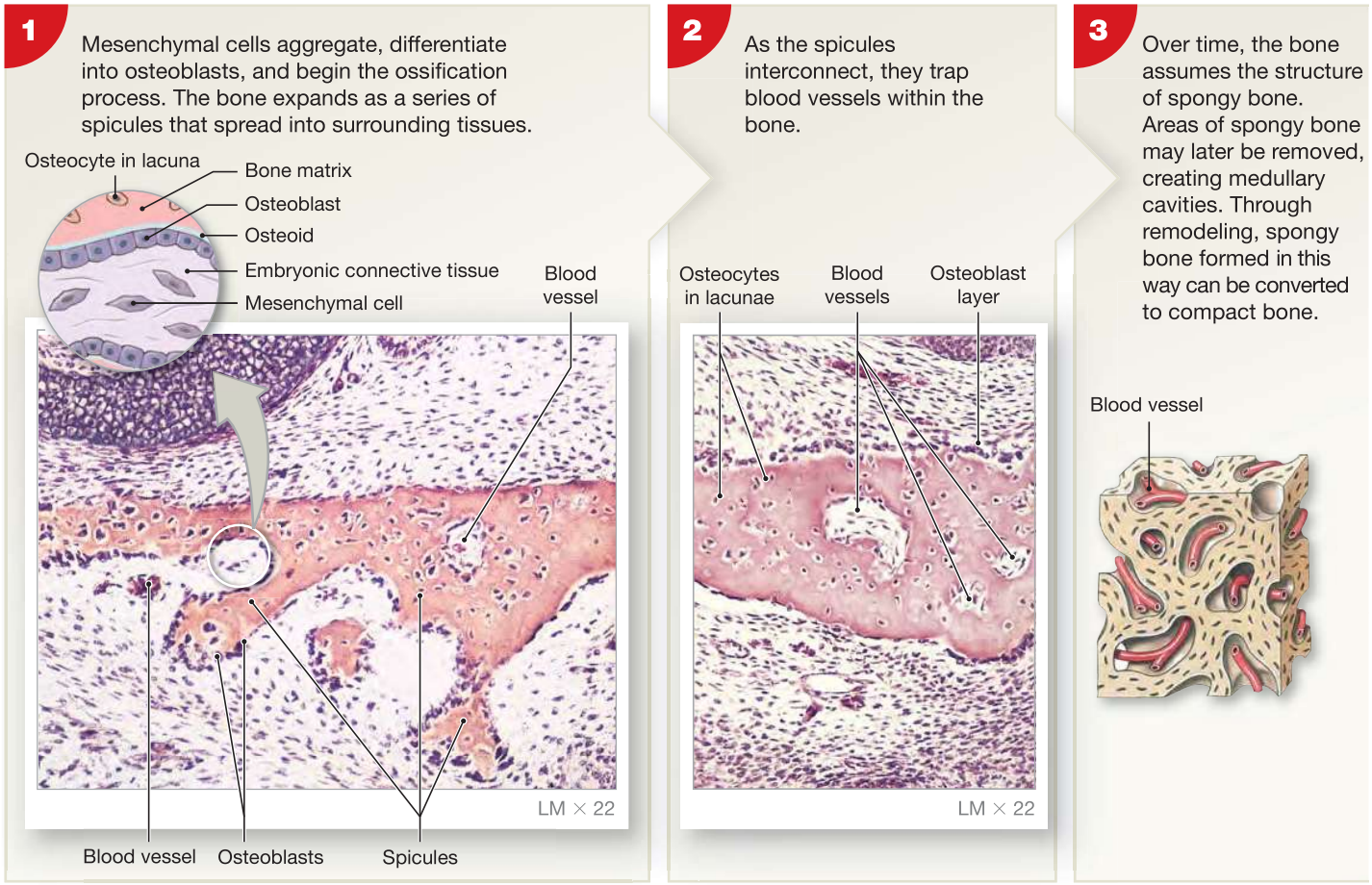
2 Bone growth is an active process, and osteoblasts require oxygen and a reliable supply of nutrients. Blood vessels begin to grow into the area. As spicules meet and fuse together, some of these blood vessels become trapped within the developing bone.

3 Initially, the intramembranous bone consists only of spongy bone. Subsequent remodeling around trapped blood vessels can produce osteons typical of compact bone. As the rate of growth slows, the connective tissue around the bone becomes organized into the fibrous layer of the periosteum. The osteoblasts closest to the bone surface become less active, but remain as the inner, cellular layer of the periosteum.

The Blood and Nerve Supplies to Bone

In order for bones to grow and be maintained, they require an extensive blood supply. Therefore, osseous tissue is highly vas-

Figure 6–12 Intramembranous Ossification.



cular. In a typical bone such as the humerus, three major sets of blood vessels develop (**Figure 6–13**):

1. *The Nutrient Artery and Vein.* The blood vessels that supply the diaphysis form by invading the cartilage model as endochondral ossification begins. Most bones have only one *nutrient artery* and one *nutrient vein*, but a few bones, including the femur, have more than one of each. The vessels enter the bone through one or more round passageways called *nutrient foramina* in the diaphysis. Branches of these large vessels form smaller perforating canals and extend along the length of the shaft into the osteons of the surrounding cortex.
2. *Metaphyseal Vessels.* The *metaphyseal vessels* supply blood to the inner (diaphyseal) surface of each epiphyseal cartilage, where that cartilage is being replaced by bone.
3. *Periosteal Vessels.* Blood vessels from the periosteum provide blood to the superficial osteons of the shaft. During endochondral bone formation, branches of periosteal vessels also enter the epiphyses, providing blood to the secondary ossification centers.

Following the closure of the epiphyses, all three sets of vessels become extensively interconnected.

The periosteum also contains an extensive network of lymphatic vessels and sensory nerves. The lymphatics collect lymph from branches that enter the bone and reach individual osteons via the perforating canals. The sensory nerves penetrate the cortex with the nutrient artery to innervate the endosteum, medullary cavity, and epiphyses. Because of the rich sensory innervation, injuries to bones are usually very painful.

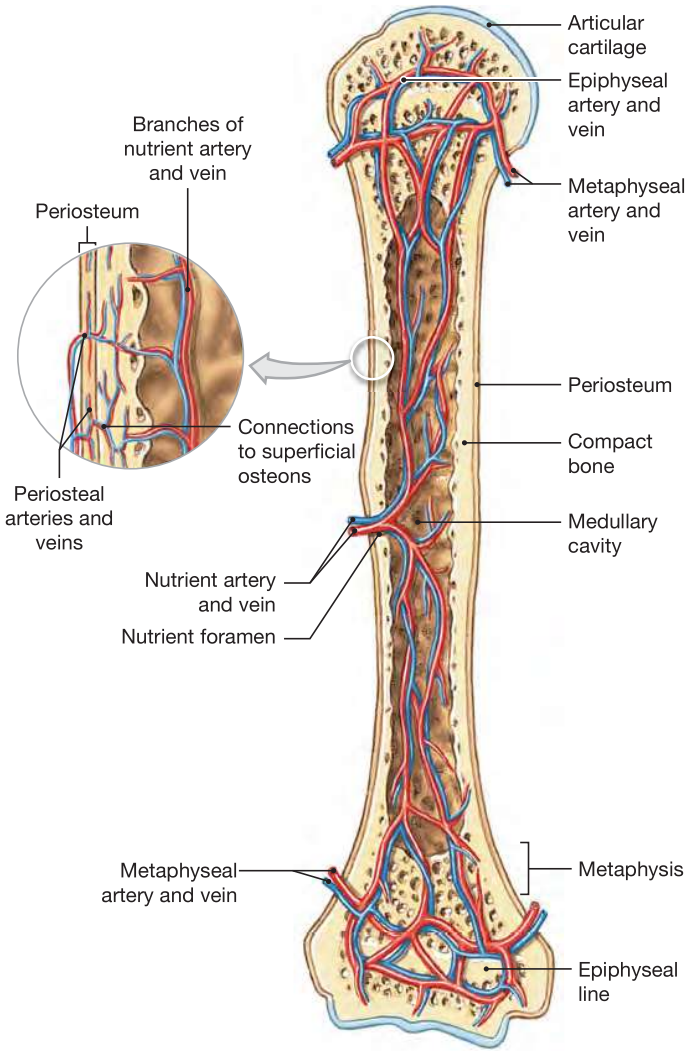
In the next section, we examine the maintenance and replacement of mineral reserves in the adult skeleton.

Checkpoint

9. **During intramembranous ossification, which type of tissue is replaced by bone?**
10. **In endochondral ossification, what is the original source of osteoblasts?**
11. **How could x-rays of the femur be used to determine whether a person has reached full height?**

See the blue Answers tab at the back of the book.

Figure 6–13 The Blood Supply to a Mature Bone.



6-6 Bone growth and development depend on a balance between bone formation and bone resorption

The organic and mineral components of the bone matrix are continuously being recycled and renewed through the process of **remodeling.** Bone remodeling goes on throughout life, as part of normal bone maintenance. Remodeling can replace the matrix but leave the bone as a whole unchanged, or it may change the shape, internal architecture, or mineral content of the bone. Through this remodeling process, older mineral deposits are removed from bone and released into the circulation at the same time that circulating minerals are being absorbed and deposited.

Bone remodeling involves interplay among the activities of osteocytes, osteoblasts, and osteoclasts. In adults, osteocytes are continuously removing and replacing the surrounding calcium salts. Osteoclasts and osteoblasts also remain active, even after the epiphyseal cartilages have closed. Normally, their activities are balanced: As quickly as osteoblasts form one osteon, osteoclasts remove another by osteolysis. The turnover rate of bone is quite high. In young adults, almost one-fifth of the skeleton is recycled and replaced each year. Not every part of every bone is affected equally; the rate of turnover differs regionally and even locally. For example, the spongy bone in the head of the femur may be replaced two or three times each year, whereas the compact bone along the shaft remains largely unchanged.

Because of their biochemical similarity to calcium, heavy-metal ions such as lead, strontium, or cobalt, or radioactive uranium or plutonium, can be incorporated into the matrix of bone. Osteoblasts do not differentiate between these heavy-metal ions and calcium, and any heavy-metal ions present in the bloodstream will be deposited into the bone matrix. Some of these ions are potentially dangerous, and the turnover of bone matrix can have detrimental health effects as ions that are absorbed and accumulated are released into the circulation over a period of years. This was one of the major complications in the aftermath of the Chernobyl nuclear reactor incident in 1986. Radioactive compounds released in the meltdown of the reactor were deposited into the bones of exposed individuals. Over time, the radiation released by their own bones has caused thyroid cancers and may result in cases of leukemia and other potentially fatal cancers.

Checkpoint

12. **Describe bone remodeling.**
13. **Explain how heavy-metal ions could be incorporated into bone matrix.**

See the blue Answers tab at the back of the book.

6-7 Exercise, hormones, and nutrition affect bone development and the skeletal system

In this section we direct our attention to the factors that have the most important effects on the processes of bone remodeling.

The Effects of Exercise on Bone

The turnover and recycling of minerals give each bone the ability to adapt to new stresses. The sensitivity of osteoblasts to electrical events has been theorized as the mechanism that controls the internal organization and structure of bone. Whenever a bone is stressed, the mineral crystals generate minute electrical fields. Osteoblasts are apparently attracted to these electri-

cal fields and, once in the area, begin to produce bone. This finding has led to the successful use of small electric fields in stimulating bone healing.

Because bones are adaptable, their shapes reflect the forces applied to them. For example, bumps and ridges on the surface of a bone mark the sites where tendons are attached. If muscles become more powerful, the corresponding bumps and ridges enlarge to withstand the increased forces. Heavily stressed bones become thicker and stronger, whereas bones that are not subjected to ordinary stresses become thin and brittle. Regular exercise is therefore an important stimulus for maintaining normal bone structure. Champion weight lifters typically have massive bones with thick, prominent ridges. In nonathletes (especially "couch potatoes"), moderate amounts of physical activity and weight-bearing activities are essential for stimulating normal bone maintenance and maintaining adequate bone strength.

Degenerative changes in the skeleton occur after relatively brief periods of inactivity. For example, you may use a crutch to take weight off an injured leg while you wear a cast. After a few weeks, your unstressed bones will lose up to a third of their mass. The bones rebuild just as quickly when you resume normal weight loading. However, the removal of calcium salts can be a serious health hazard both for astronauts remaining in a weightless environment and for bedridden or paralyzed patients who spend months or years without stressing their skeleton.

Hormonal and Nutritional Effects on Bone

Normal bone growth and maintenance depend on a combination of nutritional and hormonal factors.

- Normal bone growth and maintenance cannot occur without a constant dietary source of calcium and phosphate salts. Lesser amounts of other minerals, such as magnesium, fluoride, iron, and manganese, are also required.
- The hormone *calcitriol*, synthesized in the kidneys, is essential for normal calcium and phosphate ion absorption in the digestive tract. Calcitriol is synthesized from a related steroid, *cholecalciferol* (vitamin D_3), which may be produced in the skin or absorbed from the diet. ↩ p. 150
- Adequate levels of vitamin C must be present in the diet. This vitamin, which is required for certain key enzymatic reactions in collagen synthesis, also stimulates osteoblast differentiation. One of the signs of vitamin C deficiency—a condition called *scurvy*—is a loss of bone mass and strength.
- Three other vitamins have significant effects on bone structure. Vitamin A, which stimulates osteoblast activity, is particularly important for normal bone growth in children. Vitamins K and B_{12} are required for the synthesis of proteins in normal bone.
- *Growth hormone*, produced by the pituitary gland, and *thyroxine*, from the thyroid gland, stimulate bone growth. Growth hormone stimulates protein synthesis and cell growth throughout the body. Thyroxine stimulates cell metabolism and increases the rate of osteoblast activity. In proper balance, these hormones maintain normal activity at the epiphyseal cartilages until the time of puberty.
- At puberty, rising levels of sex hormones (*estrogens* in females and *androgens* in males) stimulate osteoblasts to produce bone faster than the rate at which epiphyseal cartilage expands. Over time, the epiphyseal cartilages narrow and eventually close. The timing of epiphyseal closure differs from bone to bone and from individual to individual. The toes may complete ossification by age 11, but parts of the pelvis or the wrist may continue to enlarge until about age 25. Differences in male and female sex hormones account for significant variations in body size and proportions. Because estrogens cause faster epiphyseal closure than do androgens, women are generally shorter than men at maturity.

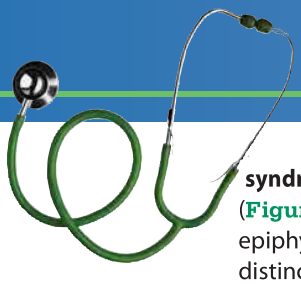
Two other hormones—*calcitonin* (kal-si-TŌ-nin), from the thyroid gland, and *parathyroid hormone*, from the parathyroid gland—are important in the homeostatic control of calcium and phosphate levels in body fluids. We consider the interactions of these hormones in the next section. The major hormones affecting the growth and maintenance of the skeletal system are summarized in **Table 6–2**.

The skeletal system is unique in that it persists after life, providing hints to the sex, lifestyle, and environmental conditions

Table 6–2 Hormones Involved in Bone Growth and Maintenance

Hormone	Primary Source	Effects on Skeletal System
Calcitriol	Kidneys	Promotes calcium and phosphate ion absorption along the digestive tract
Growth hormone	Pituitary gland	Stimulates osteoblast activity and the synthesis of bone matrix
Thyroxine	Thyroid gland (follicle cells)	With growth hormone, stimulates osteoblast activity and the synthesis of bone matrix
Sex hormones	Ovaries (estrogens) Testes (androgens)	Stimulate osteoblast activity and the synthesis of bone matrix; estrogens stimulate epiphyseal closure earlier than androgens
Parathyroid hormone	Parathyroid glands	Stimulates osteoclast (and osteoblast) activity; elevates calcium ion concentrations in body fluids
Calcitonin	Thyroid gland (C cells)	Inhibits osteoclast activity; promotes calcium loss by kidneys; reduces calcium ion concentrations in body fluids

Clinical Note



Abnormal Bone Development

Giants and dwarfs —it all comes down to bones and cartilage

A variety of endocrine or metabolic problems can result in characteristic skeletal changes. In pituitary dwarfism (Figure 6–14a), inadequate production of growth hormone leads to reduced epiphyseal cartilage activity and abnormally short bones. This condition is becoming increasingly rare in the United States, because children can be treated with synthetic human growth hormone.

Gigantism results from an overproduction of growth hormone before puberty. (The world record for height is 272 cm, or 8 ft, 11 in., reached by Robert Wadlow, of Alton, Illinois, who died at age 22 in 1940. Wadlow weighed 216 kg, or 475 lb.) If growth hormone levels rise abnormally after epiphyseal cartilages close, the skeleton does not grow longer, but bones get thicker, especially those in the face, jaw, and hands. Cartilage growth and alterations in soft-tissue structure lead to changes in physical features, such as the contours of the face. These physical changes occur in the disorder called **acromegaly.**

Several inherited metabolic conditions that affect many systems influence the growth and development of the skeletal system. These conditions produce characteristic variations in body proportions. For example, many individuals with **Marfan's syndrome** are very tall and have long, slender limbs (Figure 6–14b), due to excessive cartilage formation at the epiphyseal cartilages. Although this is an obvious physical distinction, the characteristic body proportions are not in themselves dangerous. However, the underlying mutation, which affects the structure of connective tissue throughout the body, commonly causes life-threatening cardiovascular problems.

Figure 6–14 Examples of Abnormal Bone Development.

a Pituitary dwarfism

b Marfan's syndrome

experienced by the individual. Not only do the bones reflect the physical stresses placed on the body, but they also provide clues concerning the person's health and diet. By using the appearance, strength, and composition of bone, forensic scientists and physical anthropologists can detect features characteristic of hormonal deficiencies. Combining the physical clues provided by the skeleton with modern molecular techniques, such as DNA fingerprinting, can provide a wealth of information.

Checkpoint

14. Why would you expect the arm bones of a weight lifter to be thicker and heavier than those of a jogger?
15. A child who enters puberty several years later than the average age is generally taller than average as an adult. Why?
16. A 7-year-old child has a pituitary gland tumor involving the cells that secrete growth hormone (GH), resulting in increased levels of GH. How will this condition affect the child's growth?

See the blue Answers tab at the back of the book.

6-8 Calcium plays a critical role in bone physiology

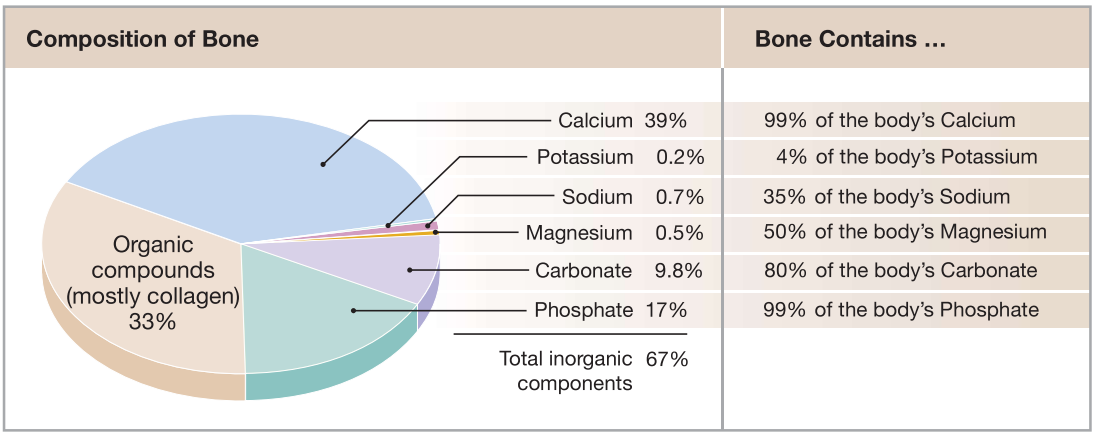
Next we discuss the dynamic relationship between calcium and the skeletal system, and the role of hormones in calcium balance in the body.

The Skeleton as a Calcium Reserve

A chemical analysis of bone reveals its importance as a mineral reservoir (Figure 6–15). For the moment, we will focus on the homeostatic regulation of calcium ion concentration in body fluids; we will consider other minerals in later chapters. Calcium is the most abundant mineral in the human body. A typical human body contains 1–2 kg (2.2–4.4 lb) of calcium, with nearly 99 percent of it deposited in the skeleton.

Calcium ions play a role in a variety of physiological processes, so the body must tightly control calcium ion concentrations in order to prevent damage to essential physiologi-

Figure 6–15 A Chemical Analysis of Bone.



cal systems. Even small variations from the normal concentration affect cellular operations; larger changes can cause a clinical crisis. Calcium ions are particularly important to both the plasma membranes and the intracellular activities of neurons and muscle cells, especially cardiac muscle cells. If the calcium concentration of body fluids increases by 30 percent, neurons and muscle cells become unresponsive. If calcium levels decrease by 35 percent, neurons become so excitable that convulsions can occur. A 50 percent reduction in calcium concentration generally causes death. Calcium ion concentration is so closely regulated, however, that daily fluctuations of more than 10 percent are highly unusual.

Hormones and Calcium Balance

A pair of hormones with opposing effects maintains calcium ion homeostasis. These hormones, parathyroid hormone and calcitonin, coordinate the storage, absorption, and excretion of calcium ions. Three target sites and functions are involved: (1) the bones (storage), (2) the digestive tract (absorption), and (3) the kidneys (excretion). **Figure 6–16a** indicates factors that elevate calcium levels in the blood; **Figure 6–16b** indicates factors that depress blood calcium levels.

When calcium ion concentrations in the blood fall below normal, cells of the **parathyroid glands,** embedded in the thyroid gland in the neck, release **parathyroid hormone (PTH)** into the bloodstream. Parathyroid hormone has three major effects, all of which *increase* blood calcium levels:

1. *Stimulating osteoclast activity and enhancing the recycling of minerals by osteocytes.* (PTH also stimulates osteoblast activity, but to a lesser degree.)
2. *Increasing the rate of intestinal absorption of calcium ions* by enhancing the action of calcitriol. Under normal circumstances, calcitriol is always present, and parathyroid hormone controls its effect on the intestinal epithelium.
3. *Decreasing the rate of excretion of calcium ions by the kidneys.*

Under these conditions, more calcium ions enter body fluids, and losses are restricted. The calcium ion concentration increases to normal levels, and homeostasis is restored.

If the calcium ion concentration of the blood rises above normal, *parafollicular cells (C cells)* in the thyroid gland secrete **calcitonin.** This hormone has two major functions, which together act to *decrease* calcium ion concentrations in body fluids:

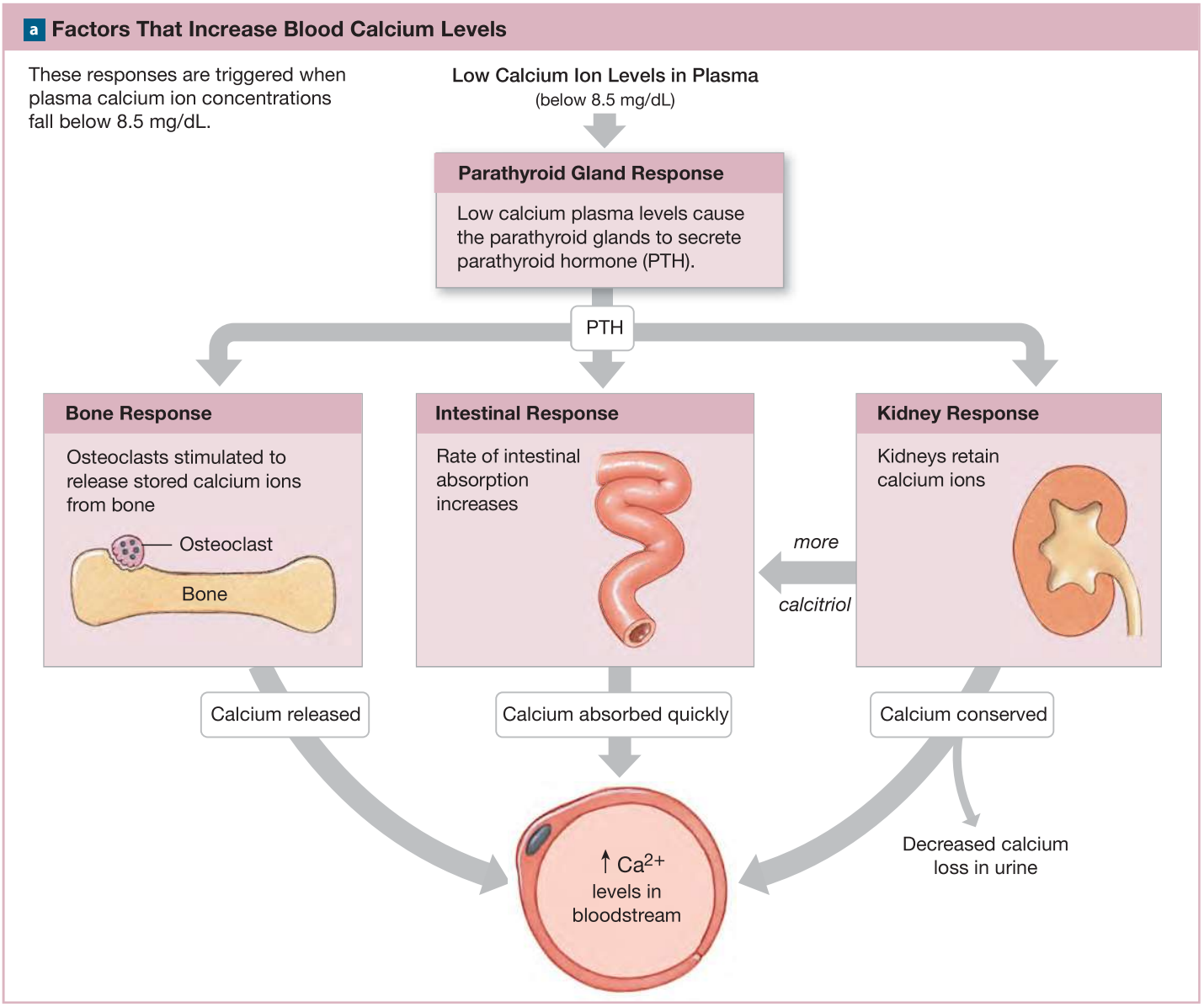
1. *Inhibiting osteoclast activity.*
2. *Increasing the rate of excretion of calcium ions by the kidneys.*

Under these conditions, less calcium *enters* body fluids because osteoclasts leave the mineral matrix alone. More calcium *leaves* body fluids because osteoblasts continue to produce new bone matrix while calcium ion excretion at the kidneys accelerates. Lower levels of PTH (and calcitriol) also reduce the intestinal absorption of calcium. The net result is a decline in the calcium ion concentration of body fluids, restoring homeostasis.

By providing a calcium reserve, the skeleton plays the primary role in the homeostatic maintenance of normal calcium ion concentrations of body fluids. This function can have a direct effect on the shape and strength of the bones in the skeleton. When large numbers of calcium ions are mobilized in body fluids, the bones become weaker; when calcium salts are deposited, the bones become denser and stronger.

Because the bone matrix contains protein fibers as well as mineral deposits, changes in mineral content do not necessarily affect the shape of the bone. In *osteomalacia* (os-tē-ō-ma-LĀ-shē-uh; *malakia*, softness), the bones appear normal, although they are weak and flexible due to poor mineralization. *Rickets*, a form of osteomalacia affecting children,

Figure 6–16 Factors That Alter the Concentration of Calcium Ions in Body Fluids.

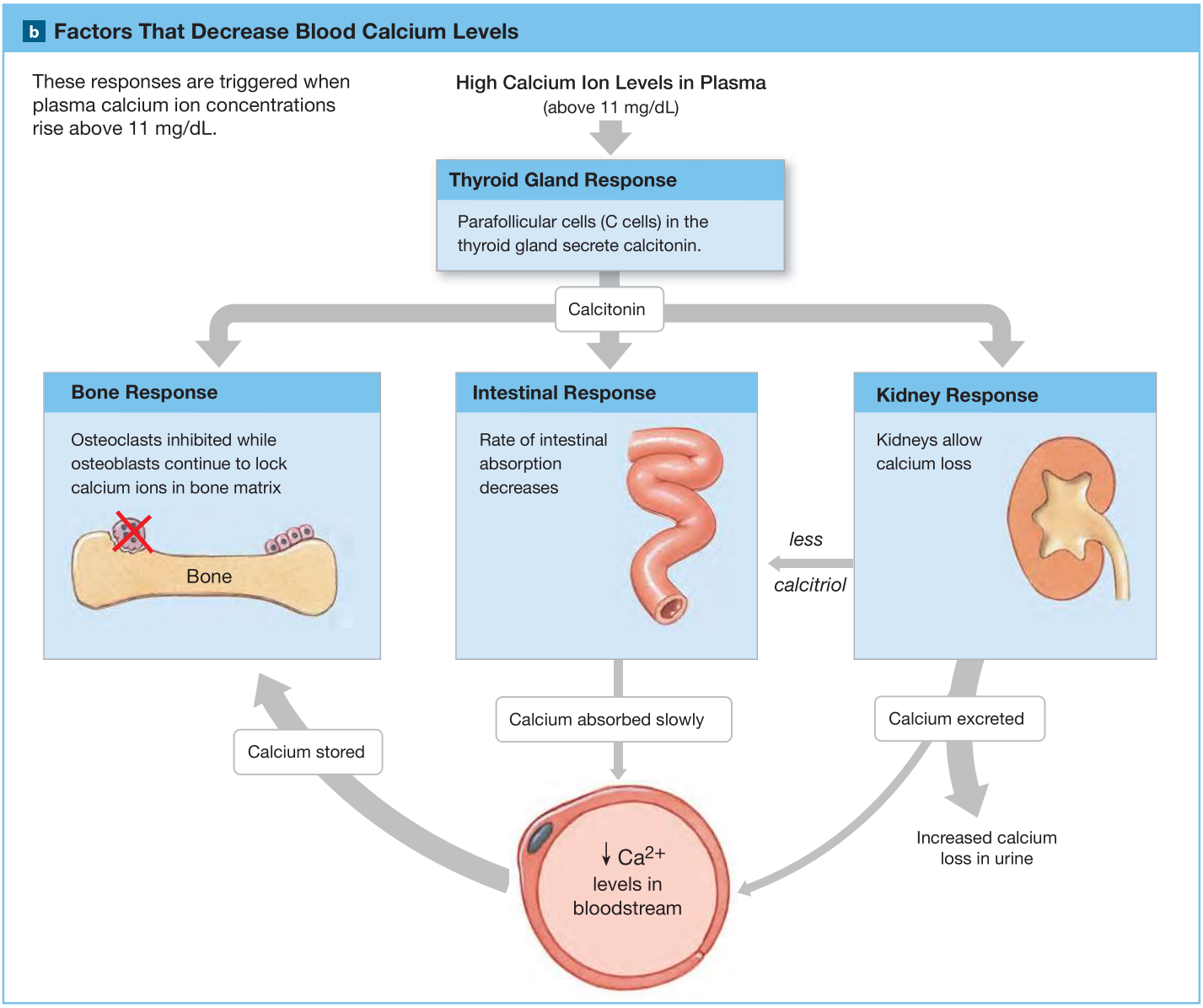


generally results from a vitamin D_3 deficiency caused by inadequate skin exposure to sunlight and an inadequate dietary supply of the vitamin. ↩ p. 152 The bones of children with rickets are so poorly mineralized that they become very flexible. Because the walls of each femur can no longer resist the tension and compression forces applied by the body weight (**Figure 6–7**), the bones bend laterally and affected individuals develop a bowlegged appearance. In the United States, homogenized milk is fortified with vitamin D specifically to prevent rickets.

Checkpoint

17. Identify the hormones involved in stimulating and inhibiting the release of calcium ions from bone matrix.
18. Why does a child who has rickets have difficulty walking?
19. What effect would increased PTH secretion have on blood calcium levels?
20. How does calcitonin help lower the calcium ion concentration of blood?

See the blue Answers tab at the back of the book.



6-9 A fracture is a crack or break in a bone

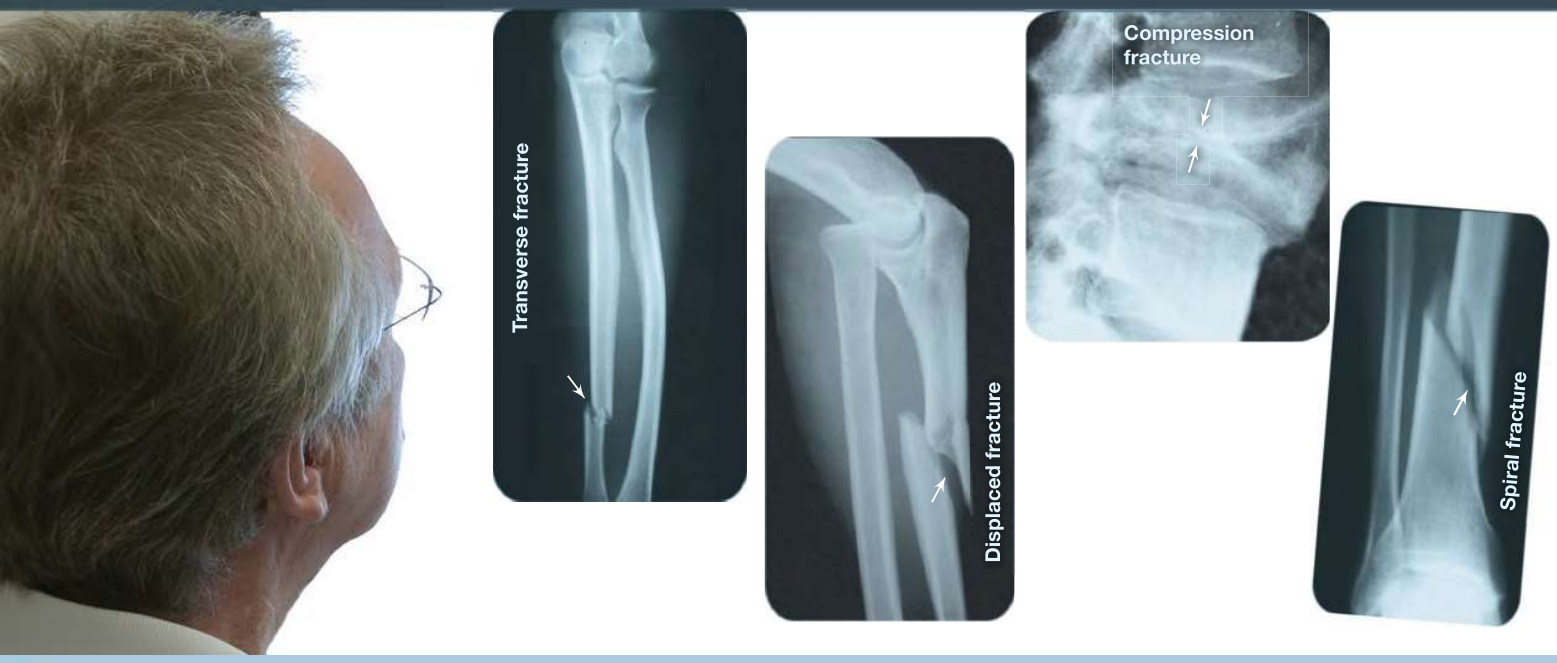
Despite its mineral strength, bone can crack or even break if subjected to extreme loads, sudden impacts, or stresses from unusual directions. The damage produced constitutes a **fracture.** Most fractures heal even after severe damage, provided that the blood supply and the cellular components of the endosteum and periosteum survive. The different types of fractures and the healing process are illustrated in **Spotlight Figure 6–17**.

1 In even a small fracture, many blood vessels are broken and extensive bleeding occurs. A large blood clot, or **fracture hematoma,** soon closes off the injured vessels and leaves a fibrous meshwork in the damaged area. The disruption of circulation kills osteocytes around the fracture, broadening the area affected. Dead bone soon extends along the shaft in either direction from the break.

2 In adults, the cells of the periosteum and endosteum are generally inactive. When a fracture occurs, the cells of the intact endosteum and periosteum undergo rapid cycles of cell division, and the daughter cells migrate into the fracture zone.

Spotlight

Figure 6–17
Types of Fractures and Steps in Repair



TYPES OF FRACTURES

Fractures are named according to their external appearance, their location, and the nature of the crack or break in the bone. Important types of fractures are illustrated here by representative x-rays. The broadest general categories are closed fractures and open fractures. **Closed**, or *simple*, fractures are completely internal. They can be seen only on x-rays, because they do not involve a break in the skin. **Open**, or *compound*, fractures project through the skin. These fractures, which are obvious on inspection, are more dangerous than closed fractures, due to the possibility of infection or uncontrolled bleeding. Many fractures fall into more than one category, because the terms overlap.

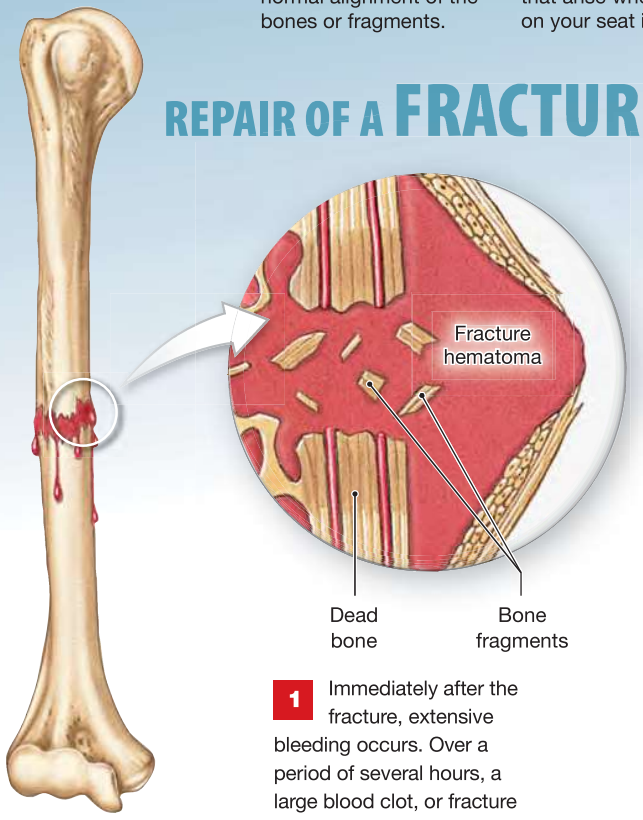
Transverse fractures, such as this fracture of the ulna, break a bone shaft across its long axis.

Displaced fractures produce new and abnormal bone arrangements; **nondisplaced fractures** retain the normal alignment of the bones or fragments.

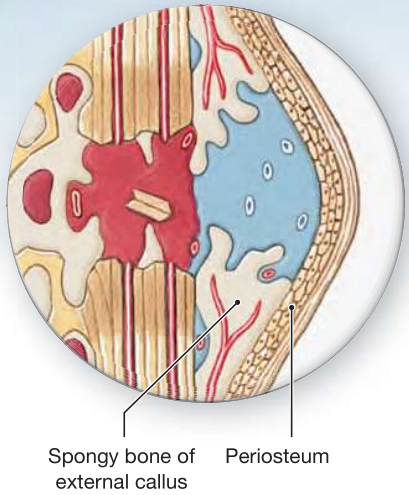
Compression fractures occur in vertebrae subjected to extreme stresses, such as those produced by the forces that arise when you land on your seat in a fall.

Spiral fractures, such as this fracture of the tibia, are produced by twisting stresses that spread along the length of the bone.

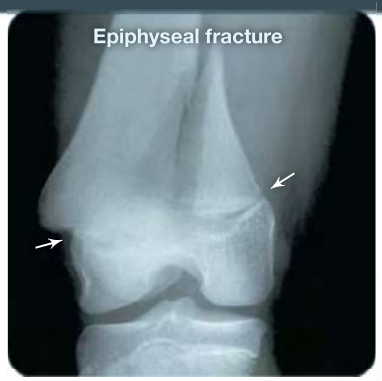
REPAIR OF A FRACTURE

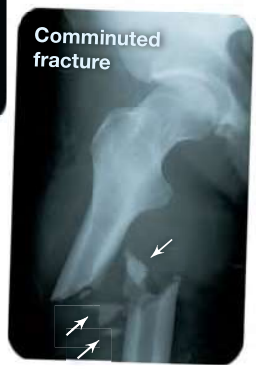


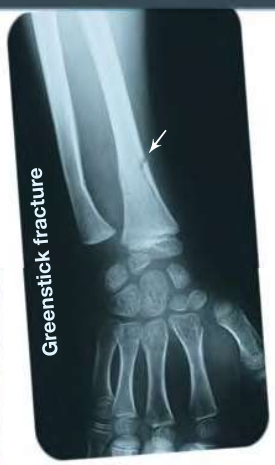
1 Immediately after the fracture, extensive bleeding occurs. Over a period of several hours, a large blood clot, or fracture hematoma, develops.

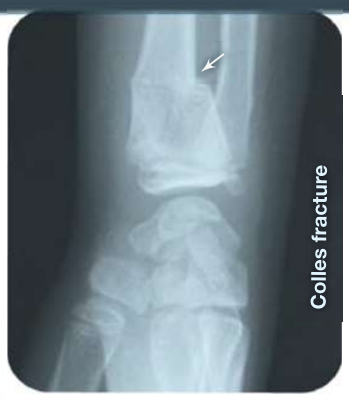


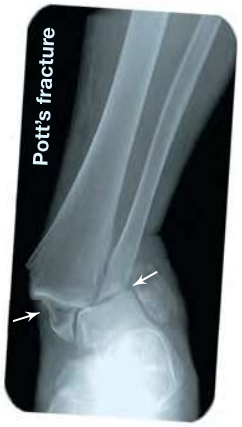
2 An internal callus forms as a network of spongy bone unites the inner edges, and an external callus of cartilage and bone stabilizes the outer edges.











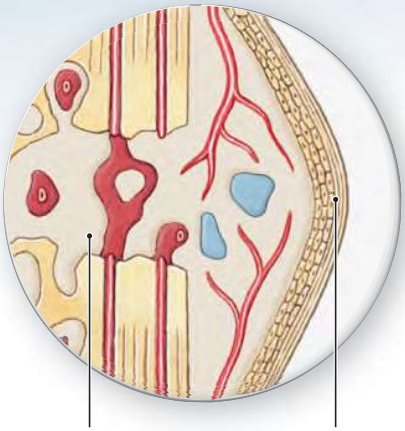
Epiphyseal fractures, such as this fracture of the femur, tend to occur where the bone matrix is undergoing calcification and chondrocytes are dying. A clean transverse fracture along this line generally heals well. Unless carefully treated, fractures between the epiphysis and the epiphyseal cartilage can permanently stop growth at this site.

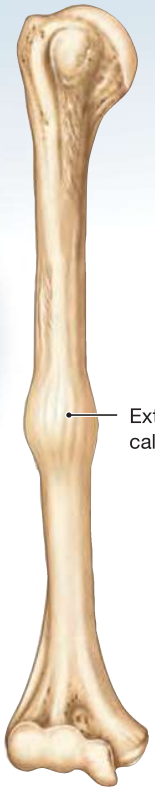
Comminuted fractures, such as this fracture of the femur, shatter the affected area into a multitude of bony fragments.

In a **greenstick fracture**, such as this fracture of the radius, only one side of the shaft is broken, and the other is bent. This type of fracture generally occurs in children, whose long bones have yet to ossify fully.

A **Colles fracture**, a break in the distal portion of the radius, is typically the result of reaching out to cushion a fall.

A **Pott's fracture** occurs at the ankle and affects both bones of the leg.





3 The cartilage of the external callus has been replaced by bone, and struts of spongy bone now unite the broken ends. Fragments of dead bone and the areas of bone closest to the break have been removed and replaced.

4 A swelling initially marks the location of the fracture. Over time, this region will be remodeled, and little evidence of the fracture will remain.

An **external callus** (*callum*, hard skin), or enlarged collar of cartilage and bone, forms and encircles the bone at the level of the fracture. An extensive **internal callus** organizes within the medullary cavity and between the broken ends of the shaft. At the center of the external callus, cells differentiate into chondroblasts and produce blocks of hyaline cartilage. At the edges of each callus, the cells differentiate into osteoblasts and begin creating a bridge between the bone fragments on either side of the fracture. At this point, the broken ends have been temporarily stabilized.

3 As the repair continues, osteoblasts replace the central cartilage of the external callus with spongy bone. When this conversion is complete, the external and internal calluses form an extensive and continuous brace at the fracture site. Struts of spongy bone now unite the broken ends. The surrounding area is gradually reshaped as fragments of dead bone are removed and replaced. The ends of the fracture are now held firmly in place and can withstand normal stresses from muscle contractions. If the fracture required external support in the form of a cast, that support can be removed at this stage.

4 Osteoclasts and osteoblasts continue to remodel the region of the fracture for a period ranging from four months to well over a year. When the remodeling is complete, the bone of the calluses is gone and only living compact bone remains. The repair may be "good as new" and leave no indications that a fracture ever occurred, or the bone may be slightly thicker and stronger than normal at the fracture site. Under comparable stresses, a second fracture will generally occur at a different site.

Checkpoint

21. **List the steps involved in fracture repair, beginning at the onset of the bone break.**
22. **At which point in fracture repair would you find an external callus?**

See the blue Answers tab at the back of the book.

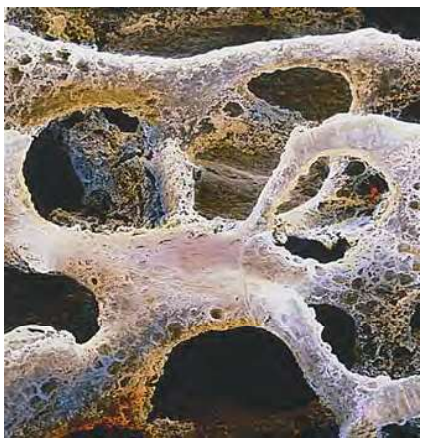
6-10 Osteopenia has a widespread effect on aging skeletal tissue

The bones of the skeleton become thinner and weaker as a normal part of the aging process. Inadequate ossification is called **osteopenia** (os-tē-ō-PĒ-nē-uh; *penia*, lacking), and all of us become slightly osteopenic as we age. This reduction in bone mass begins between ages 30 and 40. Over that period, osteoblast activity begins to decline, while osteoclast activity continues at previous levels. Once the reduction begins, women lose about 8 percent of their skeletal mass every decade, whereas the skeletons of men deteriorate at about 3 percent per decade. Not all parts of the skeleton are equally affected. Epiphyses, vertebrae, and the jaws lose more mass than other sites, resulting in fragile limbs, reduction in height, and loss of teeth.

When the reduction in bone mass is sufficient to compromise normal function, the condition is known as **osteoporosis** (os-tē-ō-po-RŌ-sis; *porosus*, porous). The fragile bones that result are likely to break when exposed to stresses that younger individuals could easily tolerate. For example, a hip fracture can occur when a 90-year-old person simply tries to stand. Any fractures that occur in aged individuals lead to a loss of independence and an immobility that further weakens the skeleton. The extent of the loss of spongy bone mass due to osteoporosis is shown in **Figure 6–18**; the reduction in compact and cortical bone mass is equally severe.

Figure 6–18 The Effects of Osteoporosis on Spongy Bone.

Normal spongy bone SEM × 25



Spongy bone in osteoporosis SEM × 21

Sex hormones are important in maintaining normal rates of bone deposition. Over age 45, an estimated 29 percent of women and 18 percent of men have osteoporosis. In women, the condition accelerates after menopause, due to a decline in circulating estrogens. Because men continue to produce androgens until late in life, severe osteoporosis is less common in men under age 60 than in women of that same age group.

Osteoporosis can also develop as a secondary effect of many cancers. Cancers of the bone marrow, breast, or other tissues release a chemical known as **osteoclast-activating factor.** This compound increases both the number and activity of osteoclasts and produces severe osteoporosis.

Checkpoint

23. **Define osteopenia.**
24. **Why is osteoporosis more common in older women than in older men?**

See the blue Answers tab at the back of the book.

Related Clinical Terms

achondroplasia: A disorder of bone growth that causes the most common type of dwarfism.
bone marrow transplant: Transferring healthy bone marrow stem cells from one person into another, replacing bone marrow that is either dysfunctional or has been destroyed by chemotherapy or radiation.
bone mineral density test (BMD): A test to predict the risk of bone fractures by measuring how much calcium and other types of minerals are present in the patient's bones.
bone scan: A nuclear scanning test that identifies new areas of bone growth or breakdown. Used to evaluate damage, find cancer in the bones, and/or to monitor the bone's conditions (including infection and trauma).
closed reduction: The correction of a bone fracture by manipulation without incision into the skin.
dual energy x-ray absorptiometry (DEXA): Procedure that uses very small amounts of radiation to measure changes in bone density as small as 1 percent; the test monitors bone density in osteoporosis and osteopenia.
open reduction: The correction of a bone fracture by making an incision into the skin and rejoining the fractured bone parts, often by mechanical means such as a rod, plate, or screw.
orthopedics: The branch of medicine dealing with the correction of deformities of bones or muscles.
osteogenesis imperfecta (OI): An inherited (genetic) disorder characterized by extreme fragility of the bones; also called brittle bone disease.
osteomyelitis: An acute or chronic bone infection.
osteopetrosis: A rare hereditary bone disorder in which the bones become overly dense; it presents in one of three forms: osteopetrosis tarda, osteopetrosis congenita, and "marble bone" disease.
osteosarcoma: A type of cancer that starts in the bones; also called osteogenic sarcoma.
Paget's disease: A chronic disorder that can result in enlarged and misshapen bones due to abnormal bone destruction and regrowth.
traction: The application of a sustained pull on a limb or muscle in order to maintain the position of a fractured bone until healing occurs or to correct a deformity.

Chapter Review

Study Outline

An Introduction to the Skeletal System p. 170

1. Skeletal elements have a variety of purposes, such as providing a framework for body posture and allowing for precise movements.

6-1 The skeletal system has five primary functions p. 170

2. The skeletal system includes the bones of the skeleton and the cartilages, ligaments, and other connective tissues that stabilize or connect the bones. The functions of the skeletal system include support, storage of minerals and lipids, blood cell production, protection, and leverage.

6-2 Bones are classified according to shape and structure, and feature surface markings p. 170

3. Bones may be categorized as **sutural bones,** *(Wormian bones)* **irregular bones, short bones, flat bones, long bones,** and **sesamoid bones.** *(Figure 6–1)*
4. Each bone has characteristic **bone markings,** including elevations, projections, depressions, grooves, and tunnels. *(Table 6–1)*
5. The two types of bone tissue are compact *(dense)* bone and spongy *(cancellous)* bone.

6. A representative long bone has a **diaphysis, epiphyses, metaphyses, articular cartilages,** and a **medullary cavity.** *(Figure 6–2)*
7. The medullary cavity and spaces within spongy bone contain either **red bone marrow** (for blood cell formation) or **yellow bone marrow** (for lipid storage).

6-3 Bone is composed of matrix and several types of cells: osteocytes, osteoblasts, osteoprogenitor cells, and osteoclasts p. 173

8. Osseous tissue is a supporting connective tissue with a solid matrix and is ensheathed by a *periosteum*.
9. Bone matrix consists largely of crystals of **hydroxyapatite;** the minerals are deposited in **lamellae.**
10. **Osteocytes,** located in *lacunae,* are mature bone cells. Adjacent osteocytes are interconnected by **canaliculi. Osteoblasts** synthesize the bony matrix by **ossification,** or **osteogenesis. Osteoclasts** dissolve the bony matrix through **osteolysis. Osteoprogenitor cells** differentiate into osteoblasts. *(Figure 6–3)*

6-4 Compact bone contains parallel osteons, and spongy bone contains trabeculae p. 175

11. The basic functional unit of compact bone is the **osteon,** containing osteocytes arranged around a **central canal. Perforating canals** extend perpendicularly to the bone surface. *(Figures 6–4, 6–5)*
12. Compact bone is located where stresses come from a limited range of directions, such as along the diaphysis of long bones.
13. Spongy bone contains **trabeculae,** typically in an open network. *(Figure 6–6)*
14. Spongy bone is located where stresses are few or come from many directions, such as at the epiphyses of long bones. *(Figure 6–7)*
15. A bone is covered by a **periosteum** and lined with an **endosteum.** *(Figure 6–8)*

6-5 Bone forms through ossification and enlarges through appositional growth and remodeling p. 179

16. **Ossification** (or **osteogenesis**) is the process of bone formation. **Calcification** is the process of depositing calcium salts within a tissue.
17. **Endochondral ossification** begins with a cartilage model that is gradually replaced by bone at the metaphysis. In this way, bone length increases. *(Figure 6–10)*
18. The timing of *epiphyseal closure* of the **epiphyseal cartilage** differs among bones and among individuals. *(Figure 6–11)*
19. Bone diameter increases through *appositional growth*.
20. **Intramembranous ossification** begins when osteoblasts differentiate within connective tissue. The process produces dermal bones. Such ossification begins at an **ossification center.** *(Figure 6–12)*
21. Three major sets of blood vessels provide an extensive supply of blood to bone. *(Figure 6–13)*

6-6 Bone growth and development depend on a balance between bone formation and bone resorption p. 184

22. The organic and mineral components of bone are continuously recycled and renewed through **remodeling.**

6-7 Exercise, hormones, and nutrition affect bone development and the skeletal system p. 184

23. The shapes and thicknesses of bones reflect the stresses applied to them.
24. Normal ossification requires a reliable source of minerals, vitamins, and hormones.
25. *Growth hormone* and *thyroxine* stimulate bone growth. Calcitonin and parathyroid hormone control blood calcium levels. *(Table 6–2)*

6-8 Calcium plays a critical role in bone physiology p. 186

26. Calcium is the most abundant mineral in the human body; about 99 percent of it is located in the skeleton. *(Figure 6–15)*
27. Interactions among the bones, digestive tract, and kidneys affect the calcium ion concentration. *(Figure 6–16)*
28. Two hormones, **calcitonin** and **parathyroid hormone (PTH),** regulate calcium ion homeostasis. Calcitonin leads to a decline in the calcium concentration in body fluids, whereas parathyroid hormone increases the calcium concentration in body fluids. *(Figure 6–16)*

6-9 A fracture is a crack or break in a bone p. 189

29. A break or crack in a bone is a **fracture.** The repair of a fracture involves the formation of a **fracture hematoma,** an **external callus,** and an **internal callus.** *(Spotlight Figure 6–17)*

6-10 Osteopenia has a widespread effect on aging skeletal tissue p. 192

30. The effects of aging on the skeleton include **osteopenia** and **osteoporosis.** *(Figure 6–18)*

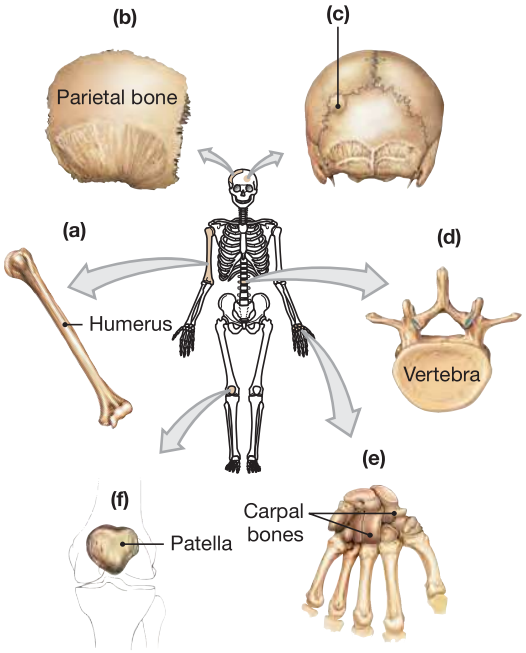
Review Questions

See the blue Answers tab at the back of the book.

LEVEL 1 Reviewing Facts and Terms

1. Blood cell formation occurs in
   (a) yellow bone marrow.
   (b) red bone marrow.
   (c) the matrix of bone tissue.
   (d) the ground substance of bones.
2. Two-thirds of the weight of bone is accounted for by
   (a) crystals of calcium phosphate.
   (b) collagen fibers.
   (c) osteocytes.
   (d) calcium carbonate.
3. The membrane found wrapping the bones, except at the joint cavity, is the
   (a) periosteum. (b) endosteum.
   (c) perforating fibers. (d) a, b, and c are correct.
4. The basic functional unit of compact bone is the Haversian system or
   (a) osteocyte.
   (b) osteoclast.
   (c) osteon.
   (d) osseous matrix.
   (e) osseous lamellae.

5. The vitamins essential for normal adult bone maintenance and repair are
   (a) A and E.
   (b) C and D.
   (c) B and E.
   (d) B complex and K.
6. The hormones that coordinate the storage, absorption, and excretion of calcium ions are
   (a) growth hormone and thyroxine.
   (b) calcitonin and parathyroid hormone.
   (c) calcitriol and cholecalciferol.
   (d) estrogens and androgens.
7. Classify the bones in the following diagram according to their shape.



   (a) _____ (b) _____
   (c) _____ (d) _____
   (e) _____ (f) _____
8. The presence of an epiphyseal line indicates
   (a) epiphyseal growth has ended.
   (b) epiphyseal growth is just beginning.
   (c) growth of bone diameter is just beginning.
   (d) the bone is fractured at the location.
   (e) no particular event.
9. The *primary* reason that osteoporosis accelerates after menopause in women is
   (a) reduced levels of circulating estrogens.
   (b) reduced levels of vitamin C.
   (c) diminished osteoclast activity.
   (d) increased osteoblast activity.
10. The nonpathologic loss of bone that occurs with aging is called
    (a) osteomyelitis.
    (b) osteoporosis.
    (c) osteopenia.
    (d) osteoitis.
    (e) osteomalacia.
11. What are the five primary functions of the skeletal system?
12. List the four distinctive cell populations of osseous tissue.
13. What are the primary parts of a typical long bone?
14. What is the primary difference between endochondral ossification and intramembranous ossification?
15. List the organic and inorganic components of bone matrix.
16. (a) What nutritional factors are essential for normal bone growth and maintenance?
    (b) What hormonal factors are necessary for normal bone growth and maintenance?
17. Which three organs or tissues interact to assist in the regulation of calcium ion concentration in body fluids?
18. What major effects of parathyroid hormone oppose those of calcitonin?

LEVEL 2 Reviewing Concepts

19. If spongy bone has no osteons, how do nutrients reach the osteocytes?
20. Why are stresses or impacts to the side of the shaft in a long bone more dangerous than stress applied to the long axis of the shaft?
21. Why do extended periods of inactivity cause degenerative changes in the skeleton?
22. What are the functional relationships between the skeleton, on the one hand, and the digestive and urinary systems, on the other?
23. Why would a physician concerned about the growth patterns of a young child request an x-ray of the hand?
24. Why does a second fracture in the same bone tend to occur at a site different from that of the first fracture?
25. The process of bone growth at the epiphyseal cartilage is similar to
    (a) intramembranous ossification.
    (b) endochondral ossification.
    (c) the process of osteopenia.
    (d) the process of healing a fracture.
    (e) the process of calcification.
26. How might bone markings be useful in identifying the remains of an individual who was shot and killed years ago?

LEVEL 3 Critical Thinking and Clinical Applications

27. While playing on her swing set, 10-year-old Sally falls and breaks her right leg. At the emergency room, the doctor tells her parents that the proximal end of the tibia where the epiphysis meets the diaphysis is fractured. The fracture is properly set and eventually heals. During a routine physical when she is 18, Sally learns that her right leg is 2 cm shorter than her left, probably because of her accident. What might account for this difference?
28. Which of the following conditions would you possibly observe in a child who is suffering from rickets?
    (a) abnormally short limbs
    (b) abnormally long limbs
    (c) oversized facial bones
    (d) bowed legs
    (e) weak, brittle bones

29. Frank does not begin puberty until he is 16. What effect would you predict this will have on his stature?
    (a) Frank will probably be taller than if he had started puberty earlier.
    (b) Frank will probably be shorter than if he had started puberty earlier.
    (c) Frank will probably be a dwarf.
    (d) Frank will have bones that are heavier than normal.
    (e) The late onset of puberty will have no effect on Frank's stature.

30. In physical anthropology, cultural conclusions can be drawn from a thorough examination of the skeletons of ancient peoples. What sorts of clues might bones provide as to the lifestyles of those individuals?

6

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