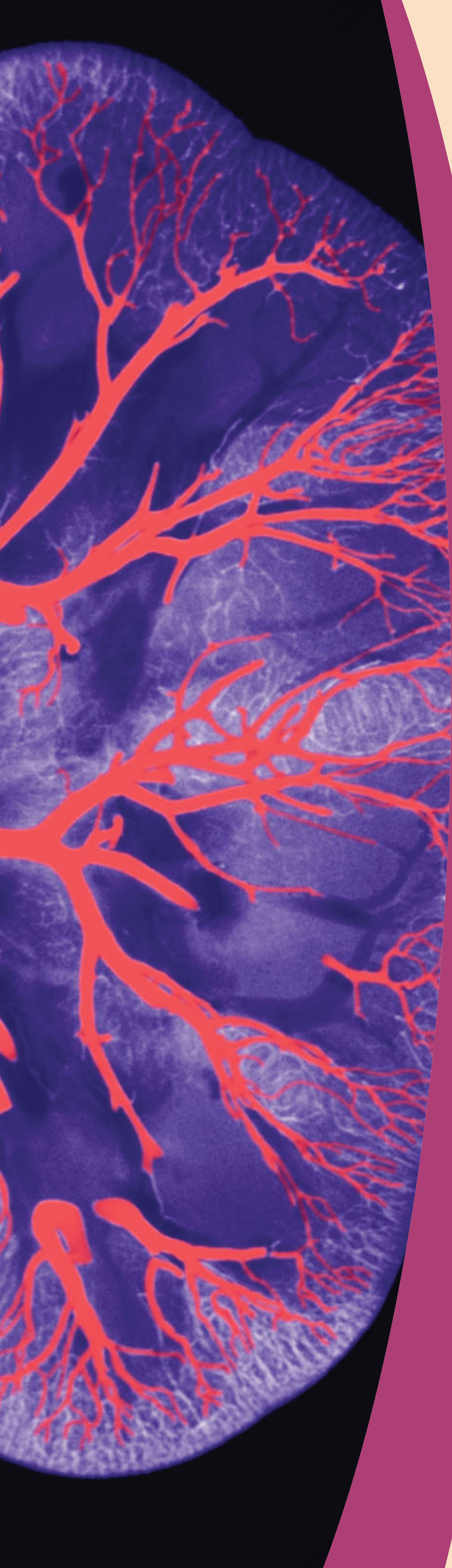


The Urinary System 24

The kidneys maintain the purity and chemical constancy of the blood and the other extracellular body fluids. Much like a water purification plant that keeps a city's water drinkable and disposes of its wastes, the kidneys are usually unappreciated until they malfunction and body fluids become contaminated. Every day, the kidneys filter many liters of fluid from the blood, sending toxins, metabolic wastes, excess water, and excess ions out of the body in urine while returning needed substances from the filtrate to the blood. The main waste products excreted in urine are

Angiogram of the kidney (colored X ray).

three nitrogenous compounds: (1) *urea,* derived from the breakdown of amino acids during normal recycling of the body's proteins; (2) *uric acid,* which results from the turnover of nucleic acids; and (3) *creatinine* (kre-at′ĭ-nin), formed by the breakdown of creatine phosphate, a molecule in muscle that stores energy for the manufacture of adenosine triphosphate (ATP). Although the lungs, liver, and skin also participate in excretion, the kidneys are the major excretory organs.

Disposing of wastes and excess ions is only one aspect of kidney function; the kidneys also regulate the volume and chemical makeup of the blood by maintaining the proper balance of water and salts and of acids and bases. The kidneys perform work that would be tricky for a chemical engineer, and they perform it efficiently most of the time.

Besides the urine-forming kidneys, the other organs of the urinary system **(Figure 24.1)** are the paired *ureters* (u-re′terz; "pertaining to urine"), the *urinary bladder,* and the *urethra* (u-re′thrah). The ureters are tubes that carry urine from the kidney to the bladder, a temporary storage sac for urine. The urethra is a tube that carries urine from the bladder to the body exterior.

KIDNEYS

Gross Anatomy of the Kidneys

- ➤ Describe the location, coverings, and external gross anatomy of the kidney.
- ➤ Describe the internal gross anatomy and the macroscopic blood vessels of the kidney.

Location and External Anatomy

The red-brown, bean-shaped **kidneys** lie retroperitoneal (behind the parietal peritoneum) in the superior lumbar region of the posterior abdominal wall **(Figure 24.2)**. They extend from the level of the 11th or 12th thoracic vertebra superiorly to the 3rd lumbar vertebra inferiorly, and thus they receive some protection from the lower two ribs (Figure 24.2b). The right kidney is crowded by the liver and lies slightly inferior to the left kidney. An average adult kidney is about 12 cm high, 6 cm wide, and 3 cm thick—the size of a large bar of soap. The lateral surface of each kidney is convex; the medial surface is concave and has a vertical cleft called the renal **hilum,** where vessels, ureters, and nerves enter and leave the kidney (see Figure 24.1). On the superior part of each kidney lies an adrenal (suprarenal) gland, an endocrine gland that is functionally unrelated to the kidney.

Several layers of supportive tissue surround each kidney (Figure 24.2a). A thin, tough layer of dense connective tissue called the **fibrous capsule** adheres directly to the kidney's surface, maintaining its shape and forming a barrier that can inhibit the spread of infection from the surrounding regions. Just external to the renal capsule is the **perirenal fat capsule** (per′e-re″nal; "around the kidney"), and external to that is an envelope of **renal fascia.** The renal fascia contains an external layer of fat, the *pararenal fat* (par′ah-re″nal; "near the

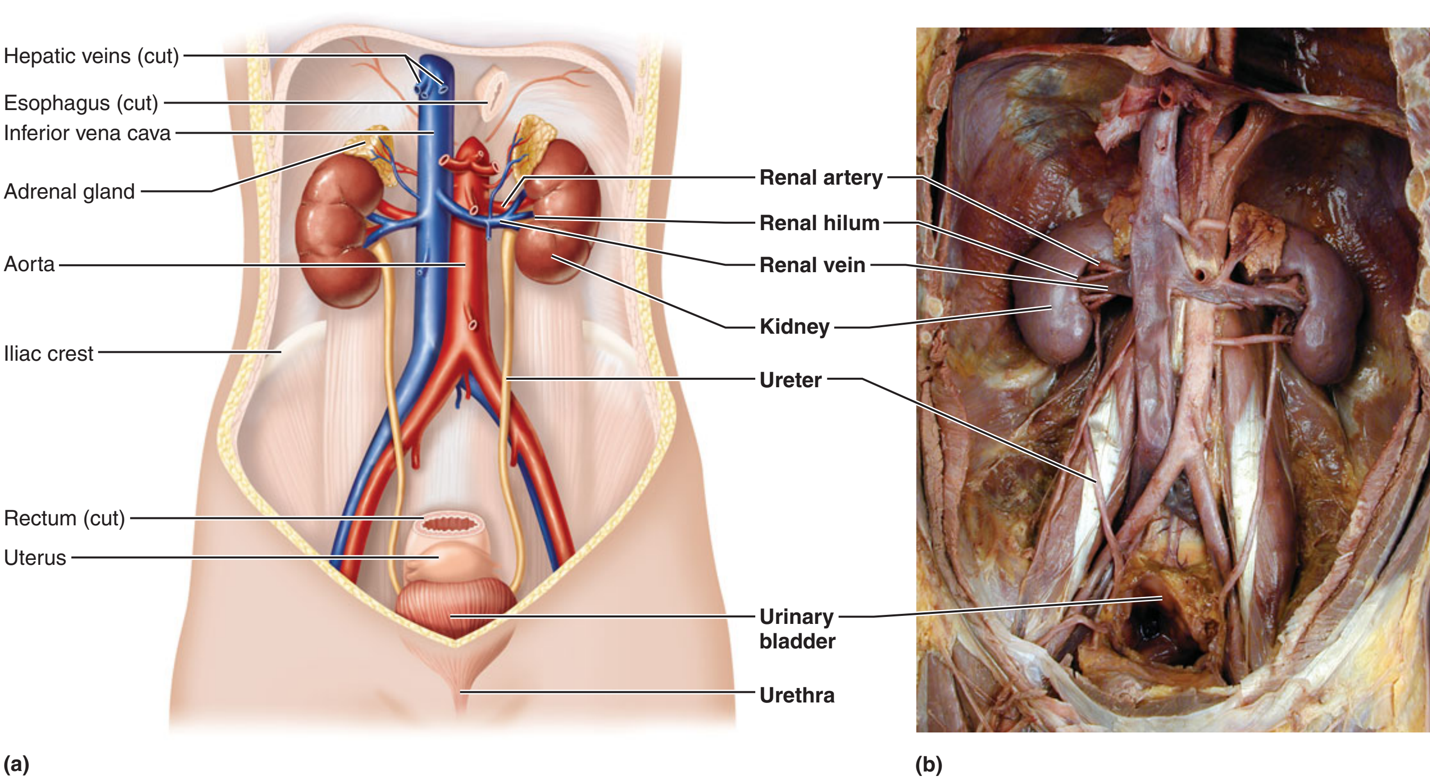
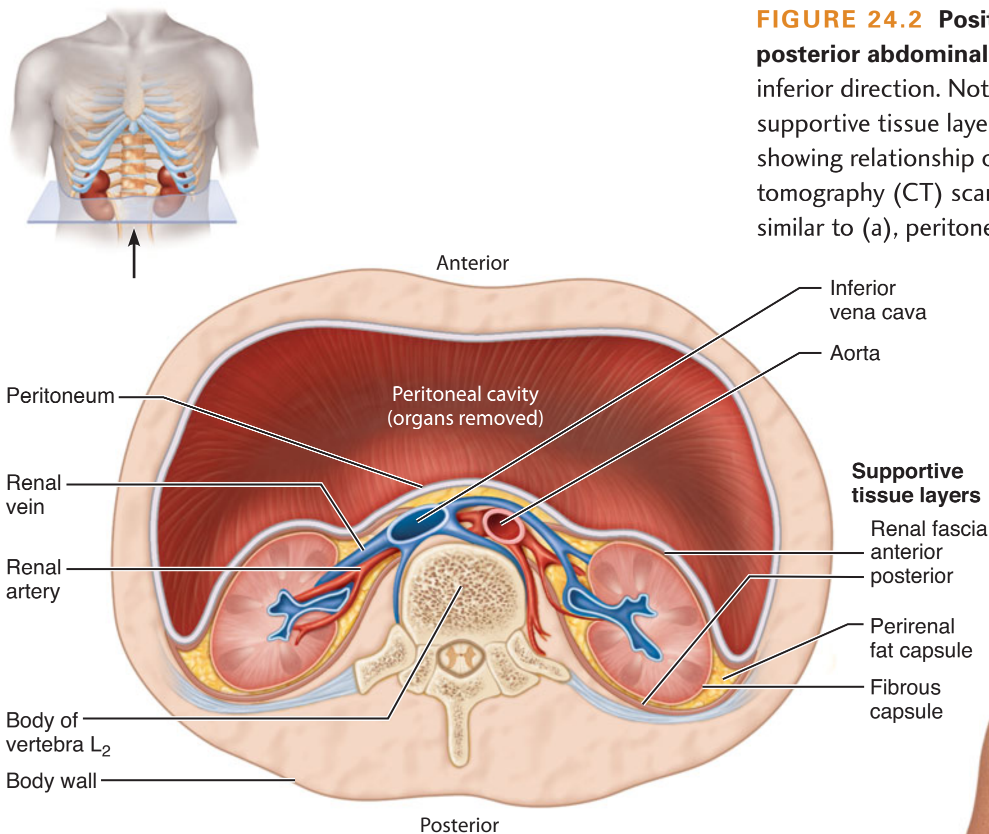
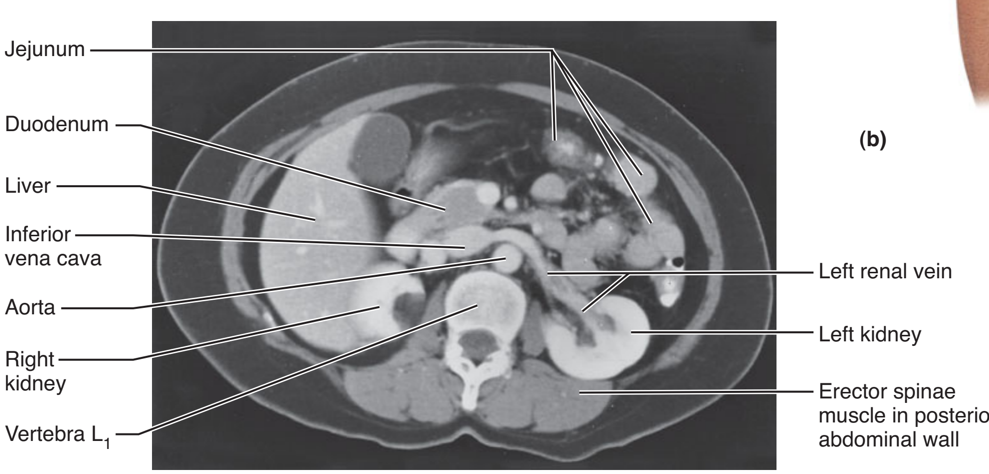


FIGURE 24.1 Organs of the urinary system. (a) Anterior view of the urinary organs in a female. **(b)** Dissection of a view similar to (a) in a male. (See *A Brief Atlas of the Human Body,* Second Edition, Figure 70.)



(a)

(b)



(c)

FIGURE 24.2 Position of the kidneys abutting the posterior abdominal wall. (a) Cross section viewed from the inferior direction. Note the retroperitoneal position and the supportive tissue layers of the kidney. **(b)** Posterior in situ view showing relationship of the kidneys to the ribs. **(c)** Computed tomography (CT) scan through the abdomen showing a view similar to (a), peritoneal organs visible.

kidney"). The perirenal and pararenal fat layers cushion the kidney against blows and help hold the kidneys in place.

The surgical approach to the kidney is usually through the posterolateral abdominal wall, where the kidney lies closest to the body surface (see Figure 24.2). With this approach, very few muscles, vessels, or nerves need to be cut. However, the incision must be made inferior to the level of T_{12} to avoid puncturing the pleural cavity, which lies posterior to the superior third of each kidney. Recall that puncturing the pleural cavity leads to pneumothorax and collapse of the lung (p. 654).

Internal Gross Anatomy

A frontal section through a kidney **(Figure 24.3)** reveals two distinct regions of kidney tissue: cortex and medulla. The more superficial region, the **renal cortex,** is light in color and has a granular appearance. Deep to the cortex is the darker **renal medulla,** which consists of cone-shaped masses called

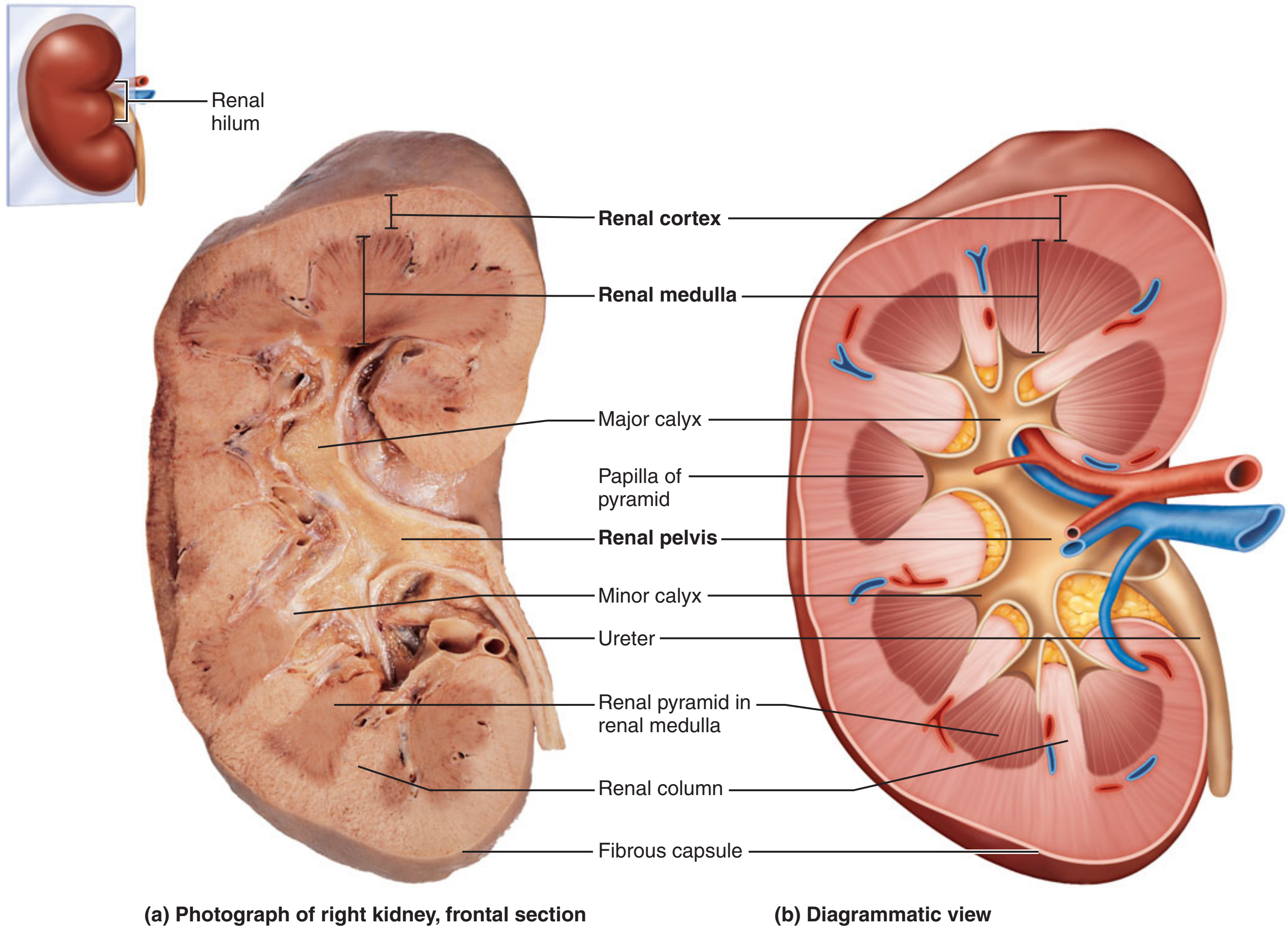


FIGURE 24.3 Internal anatomy of the kidney. Frontal sections. (See *A Brief Atlas of the Human Body,* Second Edition, Figure 71.)

renal pyramids. The broad base of each pyramid abuts the cortex, whereas the pyramid's apex, or papilla, points internally. The renal pyramids exhibit striations because they contain roughly parallel bundles of tiny urine-collecting tubules. The **renal columns,** inward extensions of the renal cortex, separate adjacent pyramids.

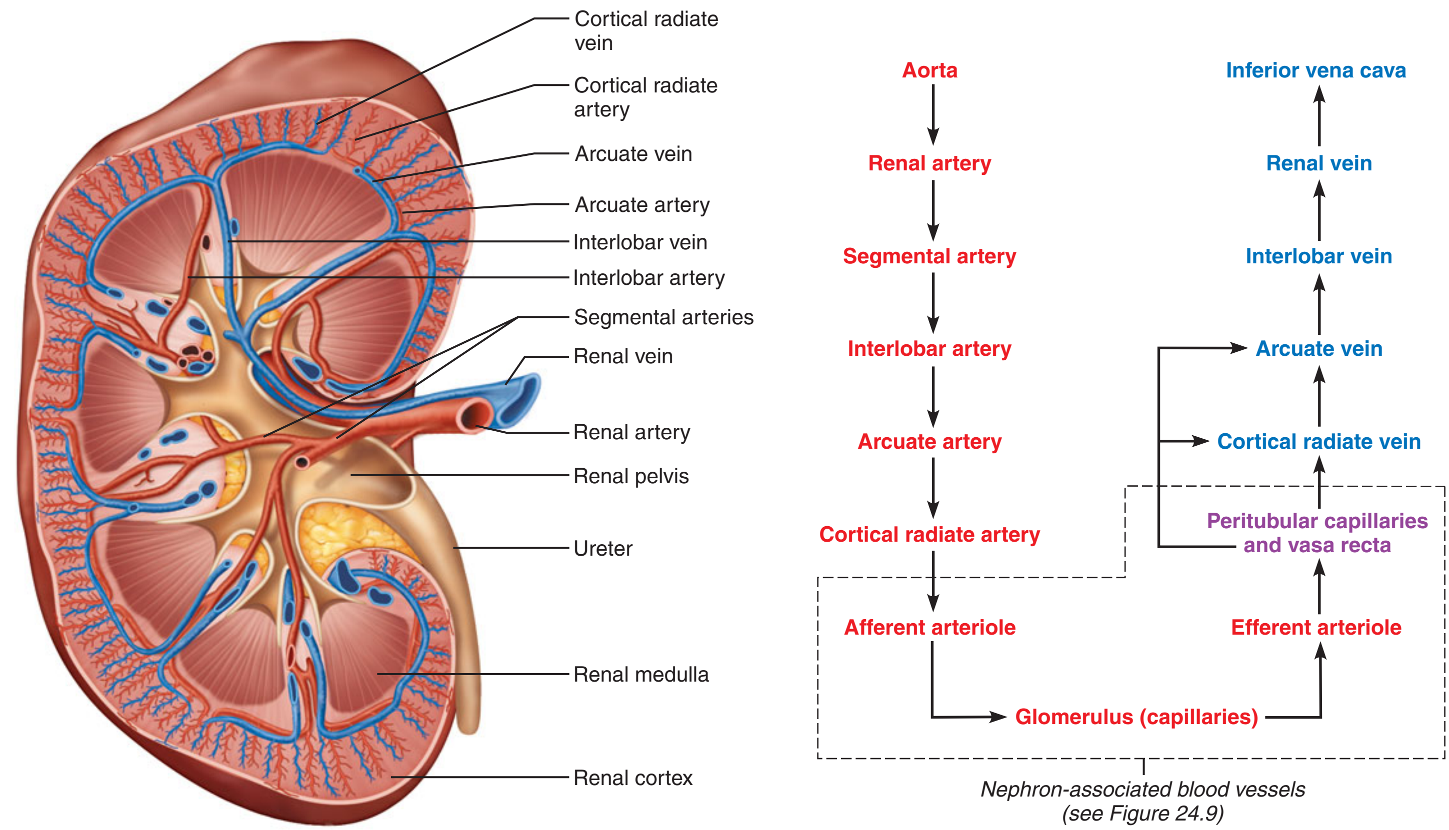
The human kidney is said to have *lobes,* each of which is a single renal pyramid plus the cortical tissue that surrounds that pyramid. There are 5 to 11 lobes and pyramids in each kidney.

The *renal sinus* is a large space within the medial part of the kidney opening to the exterior through the renal hilum. This sinus is actually a "filled space" in that it contains the renal vessels and nerves, some fat, and the urine-carrying tubes called the *renal pelvis* and *calices.* The **renal pelvis** (*pelvis* = basin), a flat, funnel-shaped tube, is simply the expanded superior part of the ureter. Branching extensions of the renal pelvis form two or three **major calices** (ca′lih-sēs; singular, **calyx**) each of which divides to form several **minor calices,** cup-shaped tubes that enclose the papillae of the pyramids (*calyx* = cup). The calices collect urine draining from the papillae and empty it into the renal pelvis; the urine then flows through the renal pelvis and into the ureter, which transports it to the bladder for storage.

PYELONEPHRITIS When an infection of the renal pelvis and calices, called *pyelitis* (pi″ĕ-li′tis; "inflammation of the renal pelvis"), spreads to involve the rest of the kidney as well, the result is **pyelonephritis** (pi″ĕ-lo-nĕ-fri′tis; *nephros* = kidney). Although it usually results from the spread of the fecal bacterium *Escherichia coli* from the anal region superiorly through the urinary tract, pyelonephritis also occurs when bloodborne bacteria lodge in the kidneys and proliferate there. In severe cases, the kidney swells and scars, abscesses form, and the renal pelvis fills with pus. Left untreated, the infected kidneys may be severely damaged, but timely administration of antibiotics usually achieves a total cure.

Gross Vasculature and Nerve Supply

Given that the kidneys continuously cleanse the blood, it is not surprising that they have a rich blood supply. Under normal resting conditions, about one-fourth of the heart's systemic output reaches the kidneys via the large **renal arteries.** These arteries branch at right angles from the abdominal



(a) Frontal section, posterior view, illustrating major blood vessels

(b) Path of blood flow through renal blood vessels

FIGURE 24.4 Blood vessels of the kidney.

aorta, between the first and second lumbar vertebrae (Figure 24.1 and Figure 20.12, p. 596). Because the aorta lies slightly to the left of the body midline, the right renal artery is longer than the left. As each renal artery approaches a kidney, it divides into five **segmental arteries** that enter the hilum **(Figure 24.4)**. Within the renal sinus, each segmental artery divides into **interlobar arteries,** which lie in the renal columns between the renal pyramids.

At the medulla-cortex junction, the interlobar arteries branch into **arcuate arteries** (ar′ku-āt; "shaped like a bow"), which arch over the bases of the renal pyramids. Radiating outward from the arcuate arteries and supplying the cortical tissue are small **cortical radiate arteries.** More than 90% of the blood entering the kidney perfuses the cortex. These arteries give rise to the **glomerular arterioles,** which feed into the **peritubular capillaries** surrounding the tubules in the kidney. These microscopic vessels are described in further detail in the microscopic anatomy discussion on p. 717.

The *veins* of the kidney essentially trace the pathway of the arteries in reverse: Blood leaving the renal cortex drains sequentially into the **cortical radiate, arcuate, interlobar,** and **renal veins** (there are no segmental veins). The renal vein exits from the kidney at the hilum and empties into the inferior vena cava (Figure 24.1). Because the inferior vena cava lies on the right side of the vertebral column, the left renal vein is about twice as long as the right. Each renal vein lies anterior to the corresponding renal artery, and both blood vessels lie anterior to the renal pelvis at the hilum of the kidney.

The nerve supply of the kidney is provided by the *renal plexus,* a network of autonomic fibers and autonomic ganglia on the renal arteries. This plexus is an offshoot of the celiac plexus (see Figure 15.5, p. 468). The renal plexus is supplied by sympathetic fibers from the most inferior thoracic splanchnic nerve, the first lumbar splanchnic nerve, and other sources. These sympathetic fibers both control the diameters of the renal arteries and influence the urine-forming functions of the uriniferous tubules.

check your understanding

1. The kidneys are located in the abdomen, but they are not within the peritoneum. Explain this distinction.
2. Describe the location of the kidneys in reference to the vertebrae. Why is the right kidney located more inferiorly than the left kidney?
3. Name the blood vessels that pass through the renal column.

For answers, see Appendix B.

Microscopic Anatomy of the Kidneys

- Identify the portions of the nephron, and explain the role of each in the formation of urine.
- Describe the location and functions of the arterioles and capillaries surrounding the nephron.

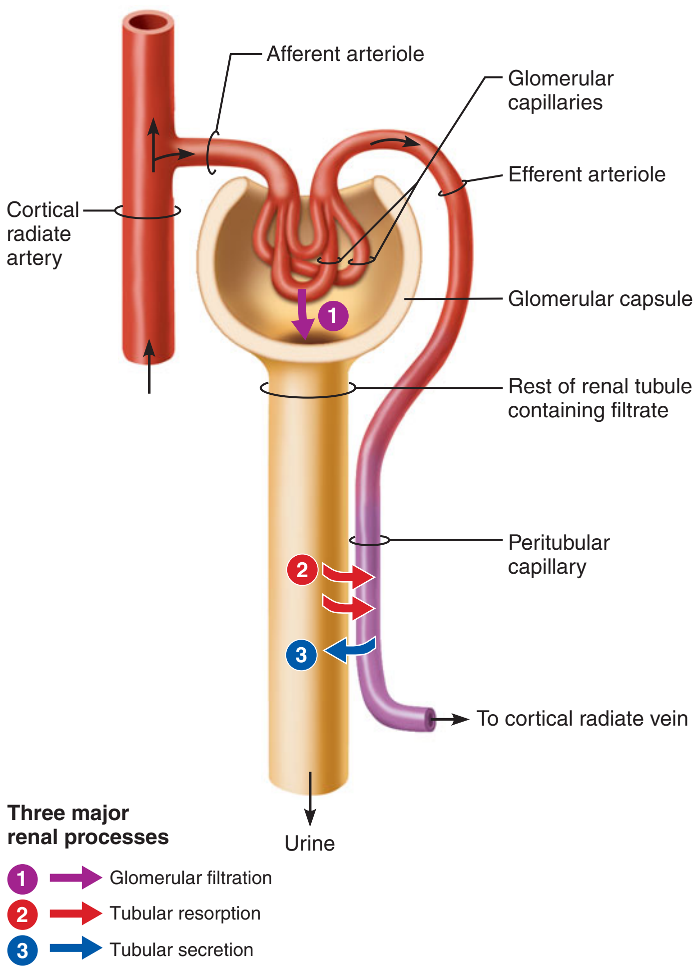


FIGURE 24.5 Basic mechanisms of urine formation. A single nephron is drawn schematically to illustrate the three processes involved in urine formation. A kidney contains more than a million nephrons acting in parallel.

The main structural and functional unit of the kidney is the **nephron** ("kidney"). More than a million of these tubules are crowded together within each kidney. A generalized diagram of a nephron is shown in Figure 24.5.

Before examining the detailed structure of the nephron, you will learn the mechanisms by which it produces urine.

Mechanisms of Urine Production

The nephron produces urine through three interacting mechanisms: filtration, resorption, and secretion. In **filtration,** a filtrate of the blood leaves the kidney capillaries and enters the renal tubule (arrow 1 in Figure 24.5). This filtrate resembles tissue fluid in that it contains all the small molecules of blood plasma. As it proceeds through the renal tubule, the filtrate is processed into urine by the mechanisms of resorption and secretion. During **resorption,** most of the nutrients, water, and essential ions are recovered from the filtrate and returned to the blood of capillaries in the surrounding connective tissue (arrow 2 in Figure 24.5). In fact, 99% of the volume of the renal filtrate is resorbed in this manner. As the essential molecules are reclaimed from the filtrate, the remaining wastes and unneeded substances contribute to the urine that ultimately leaves the body. Supplementing this passive method of waste disposal is the active process of **secretion,** which moves additional undesirable molecules into the tubule from the blood of surrounding capillaries (arrow 3 in Figure 24.5). Next you will explore the basic portions of the nephron and see how each contributes to the processes of filtration, resorption, and secretion.

Nephron Structure

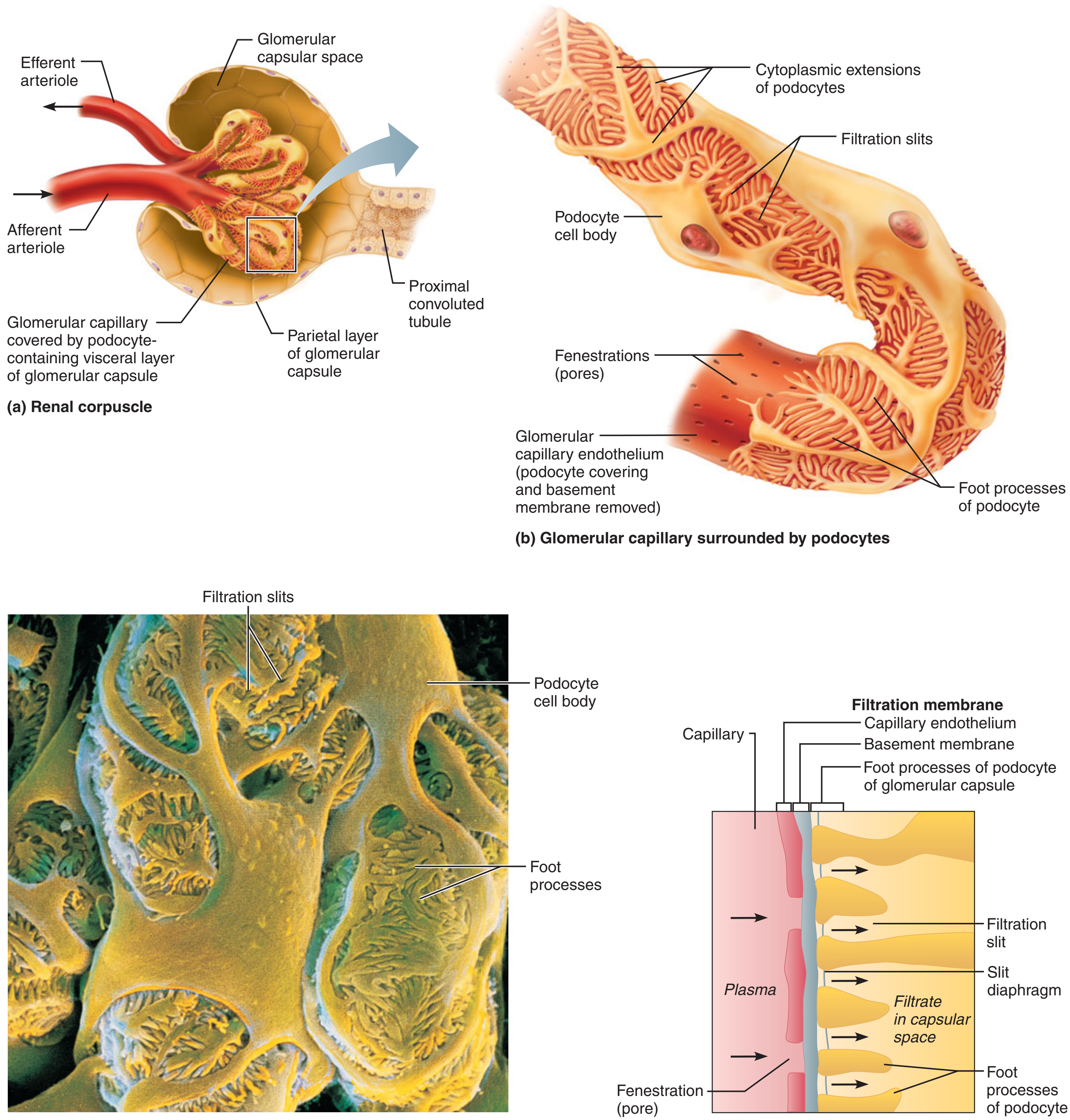
Each **nephron** is composed of the *renal corpuscle* and a *renal tubule*. The renal tubule is divided into portions: the proximal convoluted tubule, the nephron loop (loop of Henle), the distal convoluted tubule, and the collecting duct. Throughout its length, the nephron is lined by a simple epithelium that is adapted for various aspects of the production of urine.

Renal Corpuscle

The first part of the nephron, where filtration occurs, is the spherical **renal corpuscle** (Figure 24.6a). Renal corpuscles occur strictly in the cortex. They consist of a tuft of capillaries called a **glomerulus** (glo-mer′u-lus; "ball of yarn") surrounded by a cup-shaped, hollow **glomerular capsule** *(Bowman's capsule).* The glomerulus lies in its glomerular capsule like a fist pushed deeply into an underinflated balloon. This tuft of capillaries is supplied by an afferent arteriole and drained by an efferent arteriole. The endothelium of the glomerulus is fenestrated (has pores), and thus these capillaries are highly porous (Figure 24.6b), allowing large quantities of fluid and small molecules to pass from the capillary blood into the hollow interior of the glomerular capsule, the **capsular space.** This fluid is the filtrate that is ultimately processed into urine. Only about 20% of the fluid leaves the glomerulus and enters the capsular space; 80% remains in the blood within this capillary.

The external **parietal layer** of the glomerular capsule, which is a simple squamous epithelium (Figure 24.6a), simply contributes to the structure of the capsule and plays no part in the formation of filtrate. By contrast, the capsule's **visceral layer** clings to the glomerulus and consists of unusual, branching epithelial cells called **podocytes** (pod′o-sītz; "foot cells"). The branches of the octopus-like podocytes (Figure 24.6b and c) end in **foot processes,** or *pedicels* ("little feet"), which interdigitate with one another as they surround the glomerular capillaries. The filtrate passes into the capsular space through thin clefts between the foot processes, called **filtration slits.**

The **filtration membrane,** the actual filter that lies between the blood in the glomerulus and the capsular space, consists of three layers (Figure 24.6d): (1) the fenestrated endothelium of the capillary; (2) the filtration slits between the foot processes of podocytes, each of which is covered by a thin **slit diaphragm;** and (3) an intervening basement membrane consisting of the fused basal laminae of the endothelium and the podocyte epithelium. The capillary pores (fenestrations) restrict the passage of the largest elements such as blood cells. The basement membrane and slit diaphragm hold back all but the smallest proteins while letting through small molecules such as water, ions, glucose, amino acids, and urea.



(c) Filtration slits between the podocyte foot processes

(d) Three parts of the filtration membrane

FIGURE 24.6 Renal corpuscle and the filtration membrane. (a) The renal corpuscle consists of a glomerulus surrounded by a glomerular capsule. **(b)** Enlargement of a glomerular capillary covered by the visceral (inner) layer of the glomerular capsule, composed of podocytes. Some podocytes and the basement membrane have been removed to show the fenestrations (pores) in the underlying capillary wall. **(c)** Scanning electron micrograph of the visceral layer clinging to the glomerular capillaries (artificially colored; 2000×). **(d)** Diagram of a section through the filtration membrane, showing its three layers.

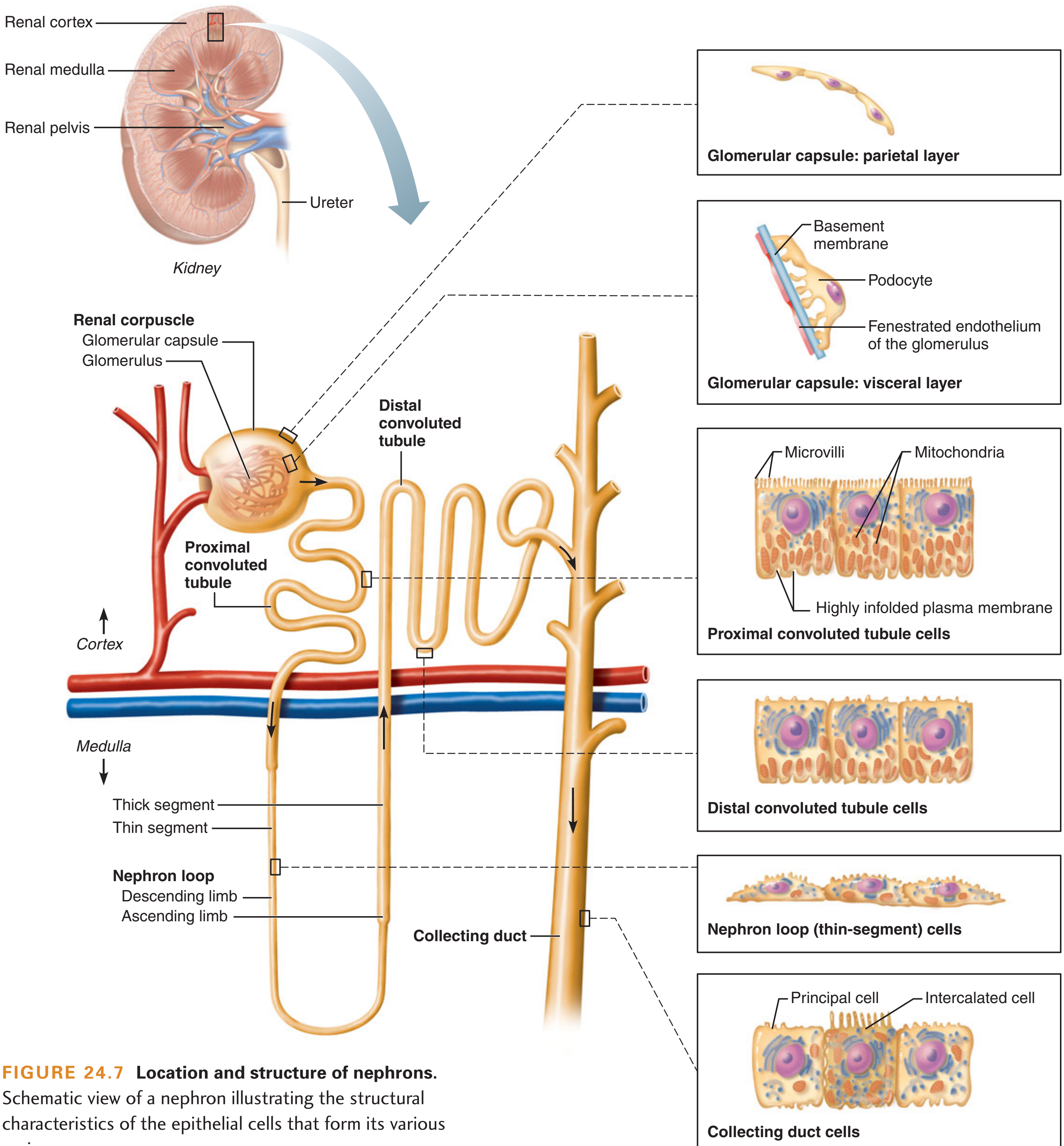
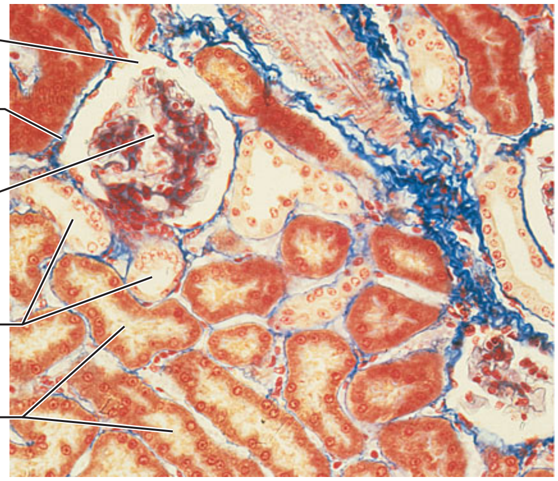


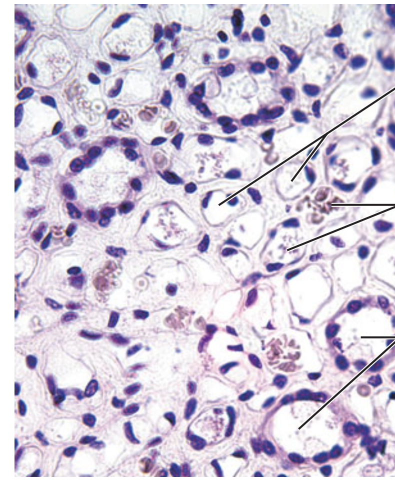
FIGURE 24.7 Location and structure of nephrons. Schematic view of a nephron illustrating the structural characteristics of the epithelial cells that form its various regions.

Renal Tubule After forming in the renal corpuscle, the filtrate proceeds into the long tubular section of the nephron (Figure 24.7), which begins as the elaborately coiled *proximal convoluted tubule,* makes a hairpin loop called the *nephron loop (loop of Henle),* winds and twists again as the *distal convoluted tubule,* and ends by joining a *collecting duct*. This meandering nature of the nephron increases its length and enhances its capabilities in processing the filtrate that flows through it. Each part of the nephron's tubular section has a unique cellular anatomy that reflects its filtrate-processing function.

1. The **proximal convoluted tubule,** confined entirely to the renal cortex, is most active in resorption and secretion.



(a) Photomicrograph of renal cortical tissue (165×)



(b) Photomicrograph through the renal medulla (215×)

FIGURE 24.8 Histology of the nephron. (See *A Brief Atlas of the Human Body,* Second Edition, Plates 48 and 49.)

Its walls are formed by cuboidal epithelial cells whose luminal (exposed) surfaces have long microvilli that seem to fill the tubule lumen with a "fuzz" in photo micrographs (Figure 24.7 and Figure 24.8a). These microvilli increase the surface area of these cells tremendously, maximizing their capacity for resorbing water, ions, and solutes from the filtrate. Furthermore, the cells of the proximal tubule contain many mitochondria, which provide the energy for resorption, and a highly infolded plasma membrane on their basal and lateral cell surfaces that contains many ion-pumping enzymes responsible for resorbing molecules from the filtrate.

2. The U-shaped **nephron loop** (loop of Henle), consists of a descending limb and an ascending limb (Figure 24.7). The first part of the **descending limb** is continuous with the proximal tubule and has a similar structure; the rest of the descending limb is the **thin segment,** the narrowest part of the nephron, with walls consisting of a permeable simple squamous epithelium (Figure 24.8b). The thin segment continues into the ascending limb, joining the **thick segment** of the ascending limb. The thick ascending limb joins the distal convoluted tubule in the cortex. The cell structure of this thick segment resembles that of the distal convoluted tubule.
3. The **distal convoluted tubule,** like the proximal convoluted tubule, is confined to the renal cortex, has walls of simple cuboidal epithelium, and is specialized for the selective secretion and resorption of ions (Figures 24.7 and 24.8a). It is less active in resorption than the proximal tubule, however, and its cells do not have an abundance of absorptive microvilli. Still, cells of the distal tubule have many mitochondria and infoldings of the basolateral membrane, features that are typical of all ion-pumping cells in the body.
4. Urine passes from the distal tubules of the nephrons into the **collecting ducts,** each of which receives urine from several nephrons and runs straight through the cortex into the deep medulla (Figure 24.7). At the papilla of the pyramid, adjacent collecting ducts join to form larger **papillary ducts,** which empty into the minor calices. Histologically, the walls of the collecting ducts consist of a simple cuboidal epithelium (Figure 24.8b), which thickens to become simple columnar epithelium in the papillary ducts. Most of these cells have few organelles, but a few, called *intercalated cells,* are rich in mitochondria and participate in resorption and secretion of ions.

   The most important role of the collecting ducts is to conserve body fluids, a function they share with the distal tubules. When the body must conserve water, the posterior part of the pituitary gland secretes antidiuretic hormone (ADH, see Chapter 17, p. 523), which increases the permeability of the collecting ducts and distal tubules to water. As a result, water is resorbed from the filtrate in these tubules into the surrounding blood vessels, decreasing the total volume of urine produced. Alcohol inhibits the release of antidiuretic hormone, resulting in reduced water resorption from the renal tubules, the production of a copious amount of dilute urine, and the potential for dehydration.

Classes of Nephrons Although all nephrons have the structures just described, they are divided into two categories according to location (Figure 24.9). **Cortical nephrons,** which represent 85% of all nephrons, are located almost entirely within the cortex, with their nephron loops dipping only a short distance into the medulla. The remaining 15% are called **juxtamedullary** ("near the medulla") **nephrons** because their renal corpuscles lie near the cortex-medulla junction. The juxtamedullary nephrons have nephron loops that deeply invade the medulla and thin segments that are much longer than those of cortical nephrons. These long nephron loops, in conjunction with nearby collecting ducts, contribute to the kidney's ability to produce a concentrated urine.

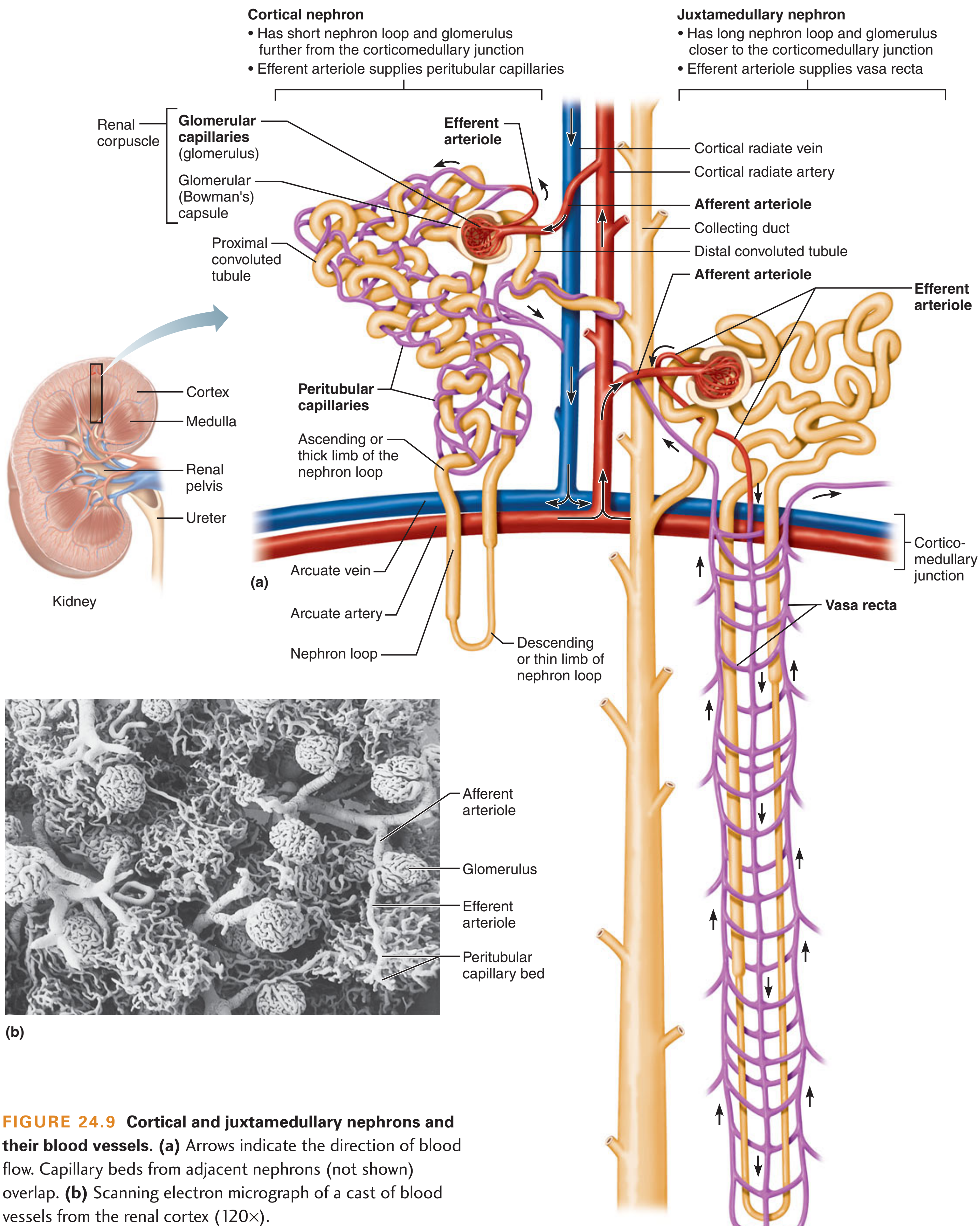


FIGURE 24.9 Cortical and juxtamedullary nephrons and their blood vessels. (a) Arrows indicate the direction of blood flow. Capillary beds from adjacent nephrons (not shown) overlap. **(b)** Scanning electron micrograph of a cast of blood vessels from the renal cortex (120×).
Source: Kessel and Kardon/Visual Unlimited.

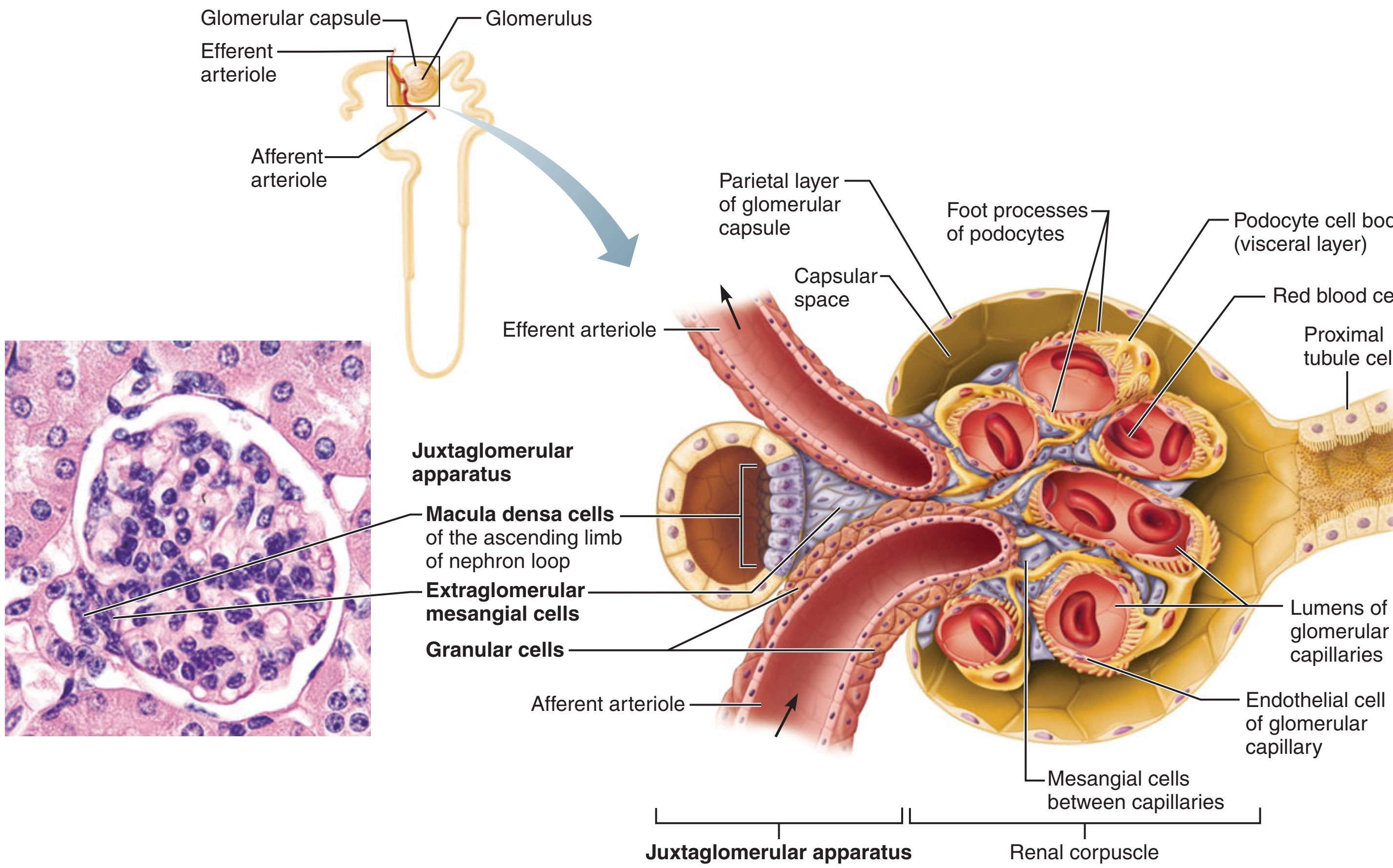


FIGURE 24.10 **Juxtaglomerular apparatus.** Micrograph on the left (415×), illustration on the right. (See *A Brief Atlas of the Human Body,* Second Edition, Plate 48.)

Blood Vessels Associated with Nephrons

Nephrons associate closely with two capillary beds, the *glomerulus* and the *peritubular capillaries* (Figure 24.9). Juxtamedullary nephrons also associate with the capillary-like *vasa recta.*

Glomeruli As previously discussed, the capillaries of the glomerulus produce the filtrate that moves through the rest of the renal tubule and becomes urine. The glomerulus differs from all other capillary beds in the body: It is both fed and drained by arterioles—an **afferent arteriole** and an **efferent arteriole,** respectively. The *afferent arterioles* arise from the cortical radiate arteries that run through the renal cortex. Because arterioles are high-resistance vessels and the efferent arteriole is narrower than the afferent arteriole, the blood pressure in the glomerulus is extraordinarily high for a capillary bed and easily forces the filtrate out of the blood and into the glomerular capsule. The kidneys generate 1 liter (about 1 quart) of this filtrate every 8 minutes, but, as previously mentioned, only 1% ends up as urine; the other 99% is resorbed by the uriniferous tubule and returned to the blood in the peritubular capillary beds.

Peritubular Capillaries The **peritubular capillaries** arise from the efferent arterioles draining the cortical glomeruli (see Figure 24.9a, left side). These capillaries lie in the interstitial connective tissue of the renal cortex, a loose areolar connective tissue that surrounds the renal tubules. The capillaries cling closely to the convoluted tubules and empty into nearby venules of the renal venous system. The peritubular capillaries are adapted for absorption: They are low-pressure, porous capillaries that readily absorb solutes and water from the tubule cells after these substances are resorbed from the filtrate. Furthermore, all molecules that are *secreted* by the nephrons into the urine are from the blood of nearby peritubular capillaries.

Vasa Recta In the deepest part of the renal cortex, efferent arterioles from the juxtamedullary glomeruli continue into thin-walled looping vessels called **vasa recta** (va′sah rek′tah; "straight vessels"). These hairpin loops descend into the medulla, running alongside the nephron loops (Figure 24.9a, right side). The vasa recta are part of the kidney's urine-concentrating mechanism.

The microscopic and gross blood vessels of the kidney are summarized in Figure 24.4b.

Juxtaglomerular Apparatus

The **juxtaglomerular apparatus** (juks″tah-glo-mer′u-lar; "near the glomerulus"), a structure that functions in the regulation of blood pressure, is an area of specialized contact between the terminal end of the thick ascending limb of the nephron loop and the afferent arteriole **(Figure 24.10)**. Within the apparatus, the structures of both the tubule and the arteriole are modified.

The walls of the afferent and efferent arterioles contain **granular cells** *(juxtaglomerular cells),* modified smooth muscle cells with secretory granules containing a hormone called **renin** (re′nin; "kidney hormone"). The granular cells seem to be mechanoreceptors that secrete renin in response to falling blood pressure in the afferent arteriole.

The **macula densa** (mak′u-lah den′sah; "dense spot"), which is the terminal portion of the nephron loop adjacent to the granular cells, consists of tall, closely packed epithelial cells that act as chemoreceptors for monitoring solute concentrations in the filtrate. Whenever such solute concentrations fall below a certain level, the cells of the macula densa signal the granular cells to secrete renin, which initiates a sequence of chemical reactions in the blood (referred to as the renin-angiotensin mechanism) that eventually results in the secretion of the hormone aldosterone from the adrenal cortex. Aldosterone increases sodium (Na^+) resorption from the distal convoluted tubules, increasing blood-solute concentration. When sodium is resorbed, water follows along the osmotic gradient, causing blood volume, and most importantly, blood pressure, to rise. Caffeine and certain medications prescribed for hypertension act as diuretics, substances that increase the amount of urine excreted, by blocking the resorption of sodium from the distal convoluted tubules.

The mesangial cells, shown in Figure 24.10, are irregularly shaped cells located around the base of the glomerular tuft. These cells show contractile properties that regulate blood flow within the glomerulus. The **extraglomerular mesangial cells** interact with cells of the macula densa and granular cells to regulate blood pressure. The details of this interaction are an area of ongoing research.

check your understanding

4. Which parts of the nephron are located in the renal cortex? Which parts are found in the medulla?
5. Which mechanism in the formation of urine involves the glomerular capillaries? Which mechanisms involve the peritubular capillaries?
6. What structure in the kidney functions in regulating blood pressure? How is the renal tubule modified in this region?

For answers, see Appendix B.

URETERS

➤ Describe the location, histology, and function of the ureters.

Gross Anatomy

Leaving the kidneys, the next structures along the urinary tract are the ureters. The **ureters** are slender tubes, about 25 cm (10 inches) long, that carry urine from the kidneys to the bladder (see Figure 24.1). Each ureter begins superiorly, at the level of L_2, as a continuation of the renal pelvis. From there, it descends retroperitoneal through the abdomen, enters the true pelvis by crossing the pelvic brim at the sacroiliac joint, enters the posterolateral corner of the bladder, and then runs medially within the posterior bladder wall before opening into the bladder's interior. This oblique entry into the bladder prevents backflow of urine from the bladder into the ureters, because any increase of pressure within the bladder compresses the bladder wall, thereby closing the distal ends of the ureters.

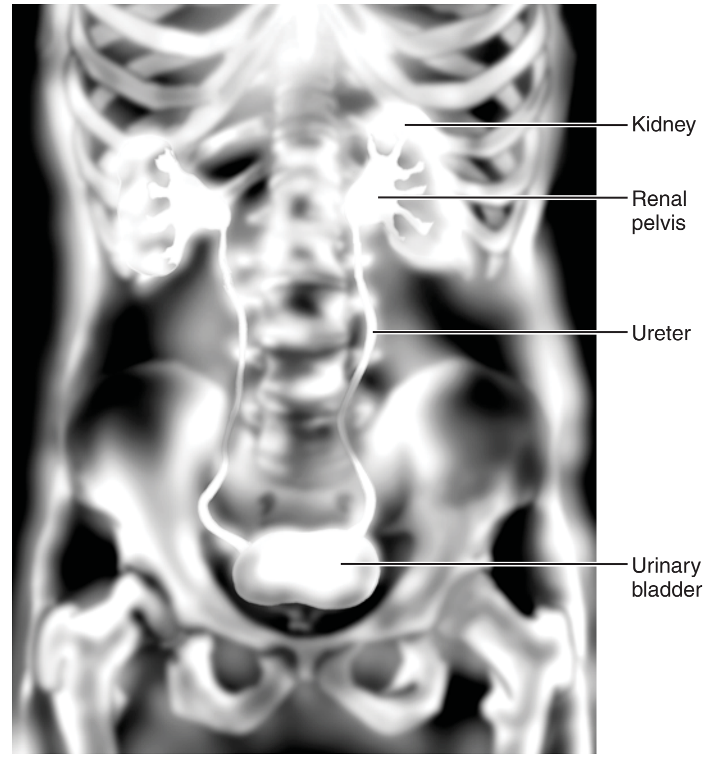


FIGURE 24.11 Pyelogram. This X-ray image was obtained using a contrast medium to show the ureters, kidneys, and bladder.

PYELOGRAPHY The radiographic procedure for examining the ureters and renal calices is called pyelography (pi″ĕ-log′rah-fe; "recording the renal pelvis"); the resulting image is called a **pyelogram** (Figure 24.11). Radiologists introduce the X-ray contrast medium via one of two routes: either by injecting it into the ureters through a catheter in the bladder *(retrograde pyelography)* or by injecting it through a vein so that it reaches the ureters when excreted by the kidneys *(intravenous pyelography)*. Pyelography enables the clinician to examine the ureters along their course from the kidneys to the bladder as these tubes extend along an imaginary line defined by the transverse processes of the five lumbar vertebrae.

Microscopic Anatomy

The histological structure of the tubular ureters is the same as that of the renal calices and renal pelvis, with walls having three basic layers: a mucosa, a muscularis, and an adventitia

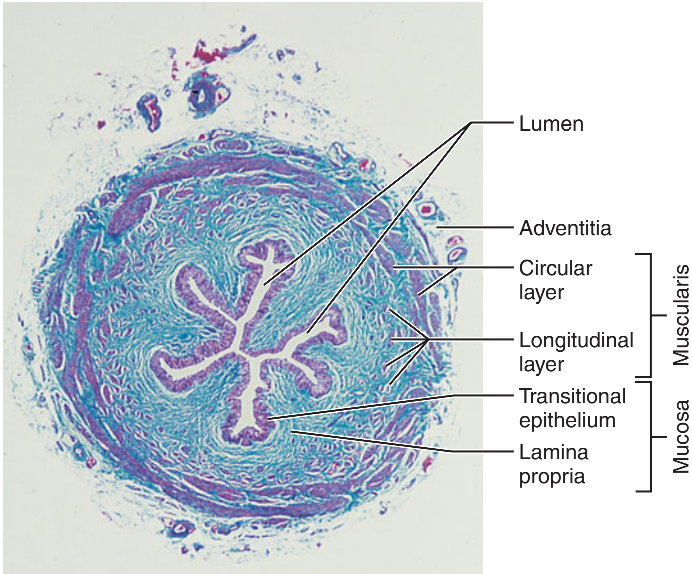


FIGURE 24.12 Microscopic structure of the ureter, cross section (10×). The mucosal folds, shown here in an empty ureter, stretch and flatten to accommodate large pulses of urine.

(Figure 24.12). The lining **mucosa** is composed of a *transitional epithelium* that stretches when the ureters fill with urine (see p. 72 and Figure 24.14b) and a lamina propria composed of a stretchy, fibroelastic connective tissue containing rare patches of lymphoid tissue. The middle **muscularis** consists of two layers: an inner longitudinal layer and an outer circular layer of smooth muscle. A third layer of muscularis, an external longitudinal layer, appears in the inferior third of the ureter. The external **adventitia** of the ureter wall is a typical connective tissue.

The ureters play an active role in transporting urine. Distension of the ureter by entering urine stimulates its muscularis to contract, setting up peristaltic waves that propel urine to the bladder. This means that urine does *not* reach the bladder by gravity alone. Although the ureters are innervated by both sympathetic and parasympathetic nerve fibers, neural control of their peristalsis appears to be insignificant compared to the local stretch response of ureteric smooth muscle.

URINARY BLADDER

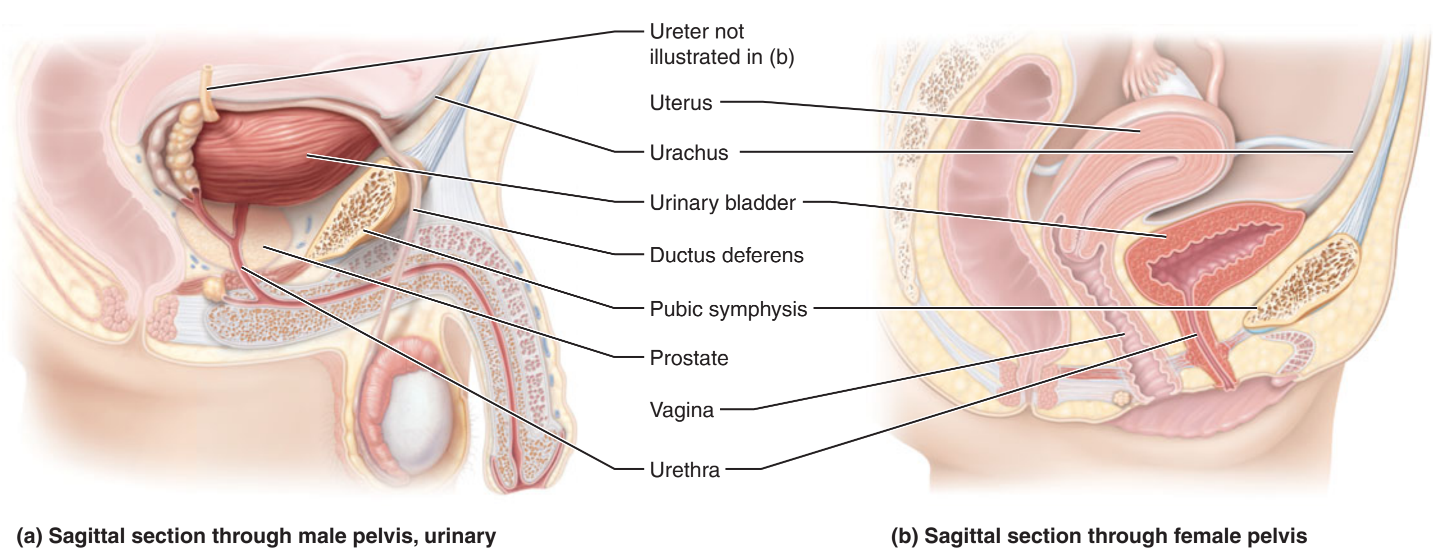
➤ Describe the shape, location, histology, and function of the bladder.

Gross Anatomy

The **urinary bladder,** a collapsible, muscular sac that stores and expels urine, lies inferior to the peritoneal cavity on the pelvic floor, just posterior to the pubic symphysis **(Figure 24.13)**. In males, the bladder lies anterior to the rectum; in females, the bladder lies just anterior to the vagina and uterus.

A full bladder is roughly spherical and expands superiorly into the abdominal cavity; an empty bladder, by contrast, lies entirely within the pelvis. When full, the bladder becomes firm and can be palpated through the anterior abdominal wall just superior to the pubic symphysis. A bladder that can be palpated more than a few centimeters above this symphysis is dangerously full of urine and requires drainage by catheterization.

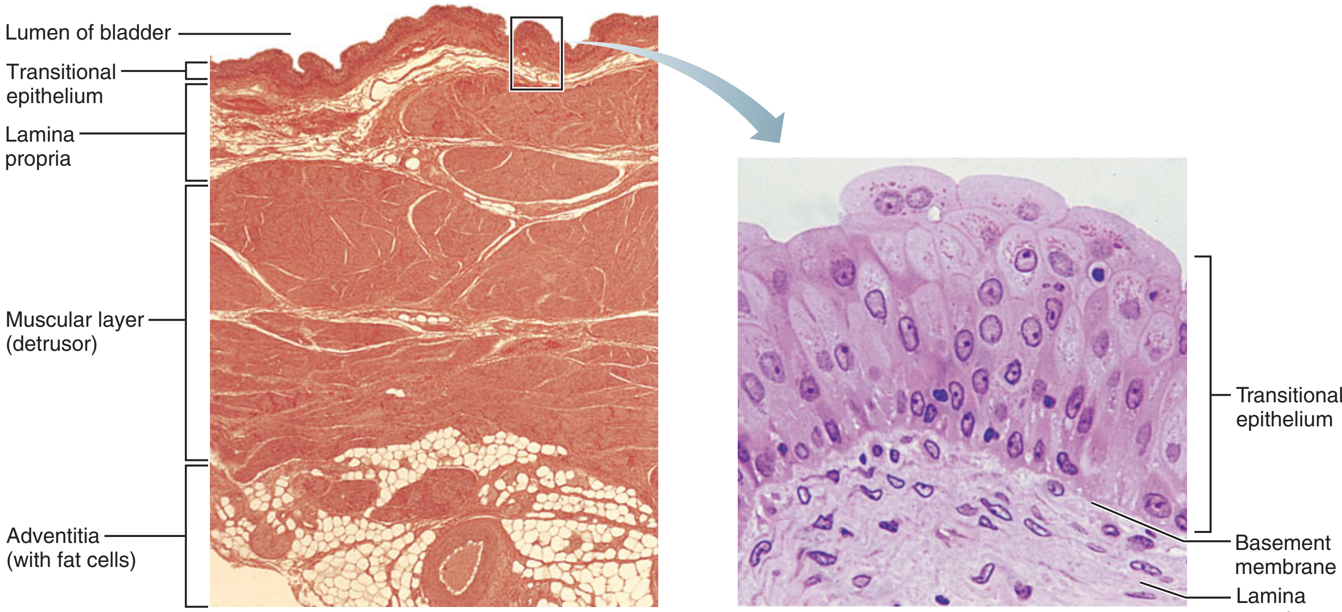
The empty bladder has the shape of an upside-down pyramid with four triangular surfaces and four corners, or angles (Figure 24.13a). The two *posterolateral angles* receive the ureters. At the bladder's *anterior angle* (or apex) is a fibrous band called the **urachus** (u′rah-kus; "urinary canal of the fetus"), the closed remnant of an embryonic tube called the allantois. The *inferior angle (neck)* drains into the urethra. In males, the prostate, a reproductive gland, lies directly inferior to the bladder, where it surrounds the urethra.



(a) Sagittal section through male pelvis, urinary bladder shown in lateral view

(b) Sagittal section through female pelvis

FIGURE 24.13 Position of the urinary bladder in reference to the pelvic organs.



(a) Micrograph of the bladder wall (17×)

(b) Epithelium lining the lumen of the bladder (360×)

FIGURE 24.14 Histology of the bladder.

In the interior of the bladder, openings for both ureters and the urethra define a triangular region on the posterior wall called the **trigone** (tri′gon; "triangle") (see Figure 24.15). The trigone is of special clinical importance because infections tend to persist in this region.

The arteries supplying the bladder are branches of the internal iliac arteries, primarily the *superior* and *inferior vesical arteries* (*vesical* = sac = the bladder) (see Figure 20.14 p. 598). Veins draining the bladder form a plexus on the bladder's inferior and posterior surfaces that empties into the internal iliac veins. Nerves extending to the bladder from the hypogastric plexus consist of parasympathetic fibers (ultimately from the pelvic splanchnic nerves), a few sympathetic fibers (ultimately from the lower thoracic and upper lumbar splanchnic nerves), and visceral sensory fibers.

Microscopic Anatomy

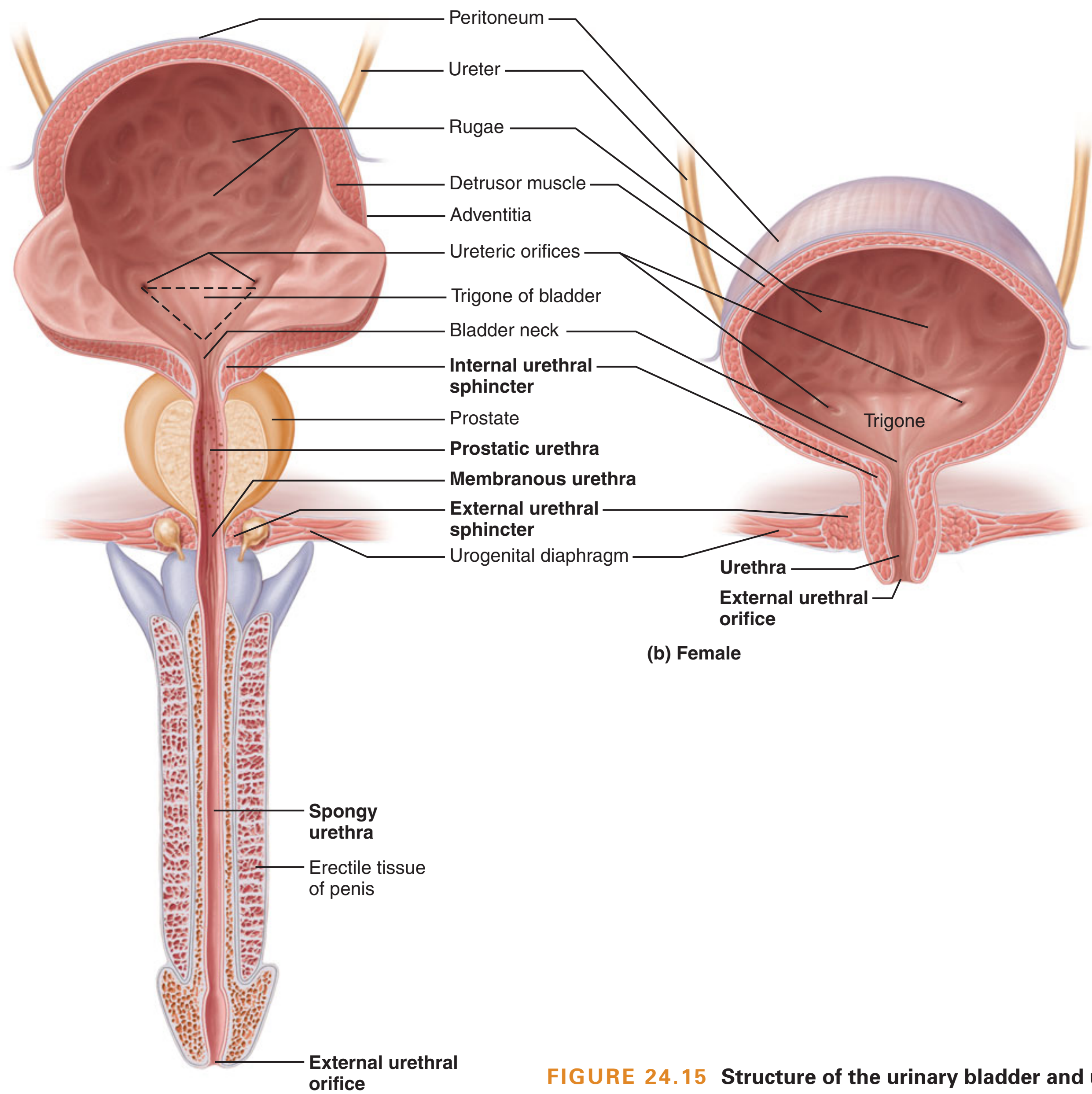
The wall of the bladder has three layers **(Figure 24.14)**: (1) a mucosa with a distensible transitional epithelium and a lamina propria; (2) a thick muscular layer; and (3) a fibrous adventitia (except on the superior surface of the bladder, which is covered by parietal peritoneum). The muscular layer, called the **detrusor muscle** (de-tru′sor; "to thrust out"), consists of highly intermingled smooth muscle fibers arranged in inner and outer longitudinal layers and a middle circular layer. Contraction of this muscle squeezes urine from the bladder during urination. The bladder's great distensibility makes it uniquely suited for its function of storing urine. When there is little urine in it, the bladder collapses into its basic pyramidal shape, its walls thick and its mucosa thrown into folds, or rugae **(Figure 24.15)**. But as urine accumulates, the rugae flatten, and the wall of the bladder thins as it stretches, allowing the bladder to store larger amounts of urine without a significant rise in internal pressure (at least until 300 ml has accumulated). A full adult bladder holds about 500 ml (or 1 pint) of urine, 15 times its empty volume.

URETHRA

- Describe the structure and function of the urethra in both sexes.
- Define micturition, and explain its neural control.

The **urethra** is a thin-walled tube that drains urine from the bladder and conveys it out of the body (Figure 24.15). This tube consists of smooth muscle and an inner mucosa. In males, the muscle layer becomes very thin toward the distal end of the urethra. The lining epithelium changes from a transitional epithelium near the bladder to a stratified and pseudostratified columnar epithelium in midurethra (sparse in females), and then to a stratified squamous epithelium near the end of the urethra.

At the bladder-urethra junction, a thickening of the detrusor muscle forms the **internal urethral sphincter.** This is an involuntary sphincter of smooth muscle that keeps the urethra closed when urine is not being passed and prevents dribbling of urine between voidings. A second sphincter, the **external urethral sphincter,** surrounds the urethra within the sheet of muscle called the *urogenital diaphragm.* This external sphincter is a skeletal muscle used to inhibit urination voluntarily until the proper time. The levator ani muscle of the pelvic floor also serves as a voluntary constrictor of the urethra. (For more information on the external urethral sphincter and levator ani muscles, see Table 11.9 on pp. 294–295).



(a) Male. The long male urethra has three regions: prostatic, membranous, and spongy.

FIGURE 24.15 Structure of the urinary bladder and urethra. The anterior wall of the bladder has been cut away to reveal the position of the trigone.

The length and functions of the urethra differ in the two sexes. In females, the urethra is just 3–4 cm (1.5 inches) long and is bound to the anterior wall of the vagina by connective tissue (see Figure 24.13b). It opens to the outside at the **external urethral orifice,** a small, often difficult-to-locate opening that lies anterior to the vaginal opening and posterior to the clitoris (shown in Figure 25.20, p. 753).

In males, the urethra is about 20 cm long (8 inches) and has three named regions: the **prostatic urethra,** which is about 2.5 cm long and runs in the prostate; the **membranous urethra,** which runs for about 2.5 cm through the membranelike urogenital diaphragm; and the **spongy urethra,** which is about 15 cm long, passes through the entire penis, and opens at the tip of the penis via the **external urethral orifice.** The male urethra carries ejaculating semen as well as urine (although not simultaneously) from the body. The reproductive function of the male urethra is covered in Chapter 25, p. 737.

MICTURITION

Micturition (mik″tu-rish′un), also called *voiding* or *urination*, is the act of emptying the bladder. It is brought about by the contraction of the bladder's detrusor muscle, assisted by the muscles of the abdominal wall, which contract to raise intra-abdominal pressure. Micturition is controlled by the brain. The neuronal pathways involved are diagrammed in Figure 24.16. As urine accumulates in the bladder, distension of the bladder wall activates stretch receptors, which send sensory impulses through visceral sensory neurons (Figure 24.16, 1) to the

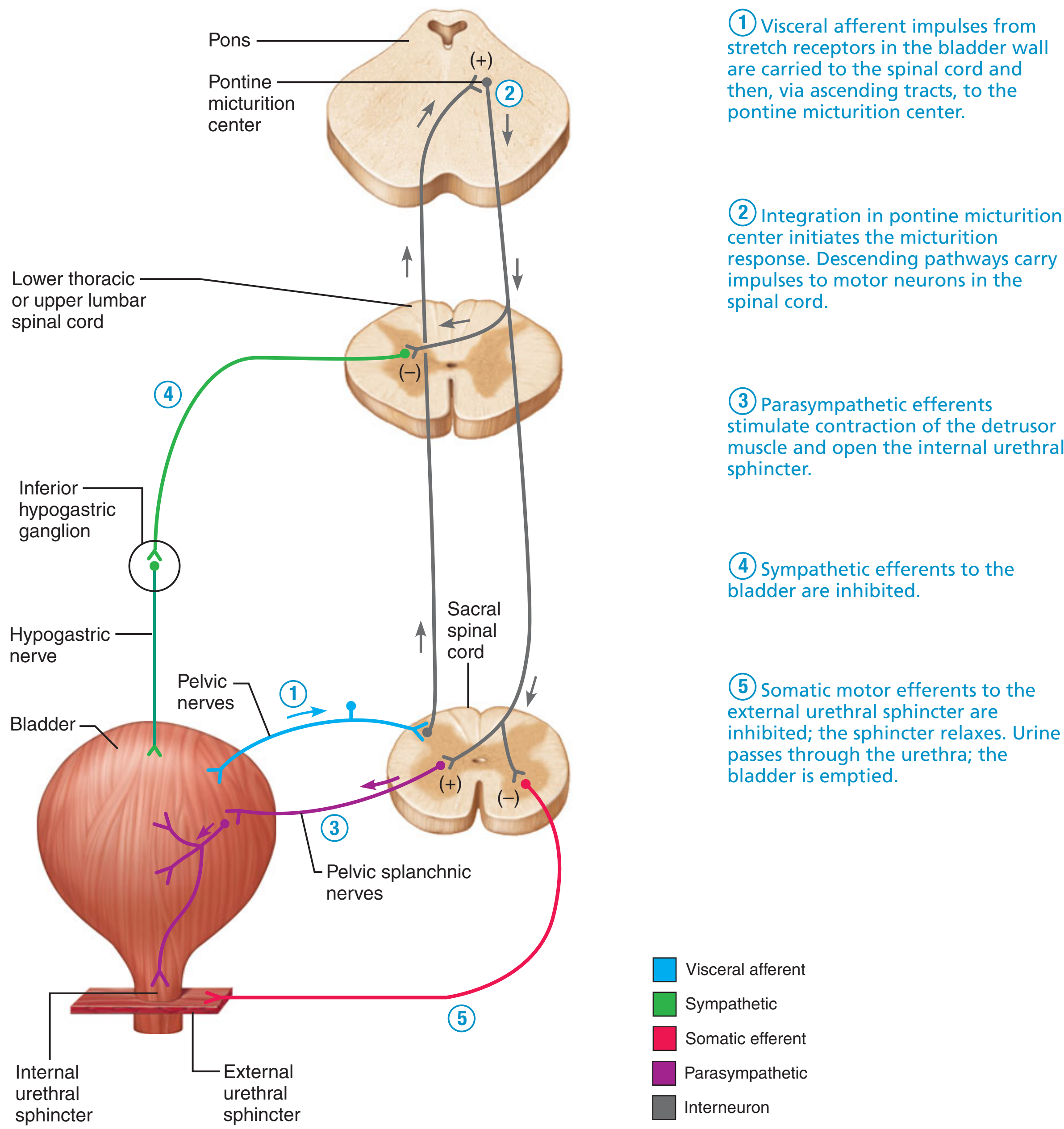


FIGURE 24.16 Micturition.

sacral region of the spinal cord, and then up to a micturition center in the dorsal part of the pons. Acting as an on/off switch, the neurons in the micturition center in the lower pons signal the parasympathetic neurons (Figure 24.16, 2) that stimulate contraction of the detrusor muscle, thereby emptying the bladder (Figure 24.16, 3). At the same time, the sympathetic pathways to the bladder (Figure 24.16, 4)—which would prevent micturition by relaxing the detrusor muscle—are inhibited. The somatic motor neurons to the external urethral sphincter are also inhibited, thus relaxing this voluntary muscle and allowing urine to pass through the urethra (Figure 24.16, 5).

The micturition center in the pons is heavily influenced by rostral brain regions, such as the inferior frontal region of the cerebral cortex (which enables a conscious decision that it is safe to micturate) and the anterior cingulate gyrus (involved in emotional evaluation of the urge to micturate).

The pons, cerebral cortex, and other parts of the CNS also *inhibit* micturition. They do so by (1) stimulating the somatic motor neurons to the external urethral sphincter, causing contraction of this muscle, and (2) activating sympathetic pathways that relax the detrusor and stimulate the internal urethral sphincter to contract.

The inability to control micturition is normal in babies who have not learned voluntarily to close their external urethral sphincter. Reflexive voiding occurs each time a baby's bladder fills enough to activate its stretch receptors, but the internal sphincter prevents dribbling of urine between voidings just as it does in adults.

MICTURITION DYSFUNCTIONS **Urinary incontinence** is very common in the elderly, affecting half of those who are in nursing homes or are homebound. Its many causes can be divided into three main types: (1) **urge incontinence,** in which the detrusor has uncontrolled contractions; (2) **stress incontinence,** in which the urethral sphincter mechanisms malfunction, such that coughing and sneezing can force urine through these sphincters; and (3) **overflow incontinence,** in which the bladder overfills and urine dribbles from the urethra. Incontinence should not be viewed as an inevitable result of aging; up to 80% of the elderly with this condition can be helped by behavioral training, medications, or surgery.

Urinary retention, in which the bladder is unable to expel its contained urine, is common in patients recovering from surgeries involving general anesthesia, after which the detrusor muscle apparently needs time to recover before resuming activity. It is also common in older men, because enlargement of the prostate squeezes the urethra. If urinary retention is prolonged, a slender rubber drainage tube called a **catheter** (kath′ĕ-ter; "thrust in") must be inserted through the urethra and into the bladder to drain the urine and prevent overfilling of the bladder. The straight, short urethra of females is much easier to catheterize than the long, curved urethra of males.

check your understanding

7. Distinguish the ureter from the urethra.
8. What type of epithelium lines the lumen of the ureter, the bladder, and the proximal portions of the urethra?
9. Which urethral sphincter is innervated by somatic motor neurons?

For answers, see Appendix B.

DISORDERS OF THE URINARY SYSTEM

➤ Describe the basic causes, symptoms, and treatment of urinary tract infections, kidney stones (calculi), and bladder and kidney cancers.

Urinary Tract Infections

Most **urinary tract infections** occur in sexually active young women. Intercourse drives bacteria from the vagina and the external genital region (and from the anus as well) through the nearby opening of the short urethra and toward the bladder. The use of spermicides magnifies the problem because they tend to kill normal resident bacteria and allow pathogenic fecal bacteria to colonize the vagina. *Escherichia coli,* a normal resident bacterium of the lower digestive tract that seldom causes problems there, produces 80% of all urinary tract infections. Sexually transmitted diseases, which are chiefly infections of the reproductive tract, can also inflame the urinary tract, clogging some urinary ducts.

Overall, urinary tract infections occur in about 40% of women. Infection of the bladder, called **cystitis,** can spread superiorly to infect the ureters and kidneys, causing **pyelitis** and **pyelonephritis** (discussed on p. 710). Symptoms of urinary tract infections include a burning sensation during micturition, increased urgency and frequency of micturition, fever, and sometimes cloudy or blood-tinged urine. When the kidneys are involved, back pain and severe headache often occur as well. Most urinary tract infections are easily cured by antibiotics.

In men, urinary tract infections usually result from long-term catheterization of the penile urethra because it is difficult to keep indwelling catheters sterile.

Renal Calculi

In 12% of men and 5% of women in North America, calcium, magnesium, or uric acid salts in the urine crystallize and precipitate in the calices or renal pelvis, forming kidney stones, or **renal calculi** (kal′ku-li; "little stones"). Most calculi are smaller than 5 mm in diameter and thus can pass through the urinary tract without causing serious problems. The calculi, however, cause pain when they obstruct a ureter, thereby blocking the drainage of urine and increasing intrarenal pressure. The most severe pain results when the contracting walls of the ureter contact the sharp calculi during their periodic peristaltic contractions. Pain from kidney stones radiates from the lateral abdominal region to the anterior abdominal wall, and then perhaps to the groin. Calculi tend to lodge in three especially narrow regions of the ureters: (1) at the level of L_2, where the renal pelvis first narrows into the ureter; (2) at the sacroiliac joint, where the ureter enters the true pelvis; and (3) where the ureters enter the bladder. The clinician should be aware of these three points when searching for kidney stones on X-ray, CT, and ultrasound images.

Predisposing factors for calculi are (1) oversaturation of the renal filtrate with calcium ions, uric acid, or a substance called oxalate, which leads to the precipitation of crystals from the urine; (2) abnormal acidity or alkalinity of the urine; (3) dehydration; (4) blockage of urine flow in the urinary tract; and (5) bacterial infection, because at least some calculi precipitate around bacteria. Individuals with a history of kidney stones are encouraged to drink large volumes of water because this leads to a urine so dilute that salts will not precipitate and form calculi.

Surgical removal of calculi has been the traditional treatment, but now, surgery has been largely replaced by *extracorporeal shock wave therapy,* in which ultrasonic shock waves delivered from outside the patient's body break up the calculi.

Cancer of Urinary Organs

Bladder cancer, which accounts for about 3% of cancer deaths and is five times more common in men than in women, typically involves neoplasms of the bladder's lining epithelium. Blood in the urine is a common warning sign. This form of cancer may be induced by organic carcinogens that are deposited in the urine after being absorbed from the environment. Substances that have been linked to bladder cancer include tars from tobacco smoke, certain industrial chemicals, and some artificial sweeteners. Bladder cancer is usually lethal if it metastasizes. Surgical removal of the bladder and chemotherapy increase survival time significantly, to an average of 5 years after detection.

Kidney cancer—a cancer arising from the epithelial cells of either the renal tubules or the renal pelvis and calices—accounts for 2% of cancer deaths in the United States, but its incidence is rising. Risk factors for this type of cancer, which is twice as common in men as in women, include obesity, high blood pressure, and, perhaps, a high-protein diet. Most tumors are over 3 cm in diameter and have metastasized when detected (typically during a kidney examination using ultrasound imaging, CT, or MRI). In such cases the prognosis is poor, and the average survival time is only 12–18 months. Because renal cancers are resistant to radiation and chemotherapy, standard treatment is the surgical removal of the entire kidney and the associated adrenal gland and lymph nodes.

KIDNEY TRANSPLANT A kidney transplant is the transfer of a functioning kidney from a donor to a recipient whose kidneys are failing. About 30% of transplanted kidneys come from living donors (usually a relative or spouse), and 70% come from cadavers (whose kidneys can be maintained for about 36 hours after death). Kidney transplants are more common than transplants of any other major organ. This procedure has a high rate of success (80% to 90% survival after 3 years if from a living donor, 70% if from a cadaver) and is comparatively easy to perform (only a few vessels need to be cut and rejoined). A single kidney is transplanted, because one is sufficient to carry out excretory functions. The failing kidney is usually left in place, and the new kidney is transplanted into the right iliac fossa of the pelvis, which has more room than the crowded lumbar region. As with other organ transplants, the recipient must take immunosuppressive drugs. Current efforts are directed toward improving long-term survival rates, which are diminished by chronic rejection and other factors.

THE URINARY SYSTEM THROUGHOUT LIFE

- Trace the embryonic development of the urinary organs.
- List several effects of aging on the structure and function of the urinary system.

The embryo develops not just one pair of kidneys but three pairs, one after another, starting cranially and proceeding caudally. The three pairs are the pronephros, mesonephros, and metanephros. These different kidneys develop from the *urogenital ridges,* paired elevations of intermediate mesoderm on the dorsal abdominal wall **(Figure 24.17)**. Of the three pairs of kidneys that form, only the last pair persists to become the adult kidneys. Initially, during week 4, the first kidney, or **pronephros** (pro-nef′ros), forms as a set of nephrons and then quickly degenerates. Although the pronephros is never functional and is gone by week 6, it sends a **pronephric duct** *(primary excretory duct)* to the cloaca, and this duct is used by the kidneys that develop later. As the second nephron system, called the **mesonephros** ("middle kidney"), claims the pronephric duct, this duct becomes the **mesonephric duct.** The nephrons of the mesonephros, in turn, degenerate after the third kidney, the **metanephros** (met″ah-nef′ros), becomes functional.

The metanephros is the definitive kidney (*metanephros* means "ultimate kidney"). It develops in the pelvic region in the following way: Starting in week 5, a hollow **ureteric bud** grows from the mesonephric duct into the urogenital ridge, inducing the mesoderm there to form the nephrons (Figure 24.17a). The ureteric bud, in turn, develops into the renal pelvis, calices, and collecting ducts; its unexpanded proximal part becomes the ureter. Failure of the metanephros to develop results in **renal agenesis,** the absence of kidneys. In unilateral agenesis, a single kidney forms on one side and, just as an adult can donate a kidney and still retain adequate kidney function, the neonate can survive with a single functioning kidney. Bilateral agenesis (absence of both kidneys) is not compatible with life.

As the metanephric kidneys develop, the *cloaca*, located at the junction of the hindgut and the allantois, divides into two parts: (1) the future rectum and anal canal, and (2) the **urogenital sinus,** into which the urinary and genital ducts empty (Figure 24.17b). The urogenital sinus becomes the urinary bladder and the urethra. The allantois, an extension of the urogenital sinus into the umbilical cord, becomes the urachus of the bladder.

After forming in the pelvis, the metanephric kidneys ascend to their final position in the abdomen (Figure 24.14c and d), receiving their blood supply from successively higher sources as they ascend. Whereas the lower renal vessels usually degenerate as the upper ones appear, these early vessels often fail to degenerate. As a result, 30% of people have multiple renal arteries.

As the embryonic kidneys ascend through the narrow pelvic brim, they face a tight squeeze during which the right and left kidneys come close together, and in about 1 out of every 600 people they fuse into one U-shaped **horseshoe kidney.** This condition is usually harmless, but it can be associated with obstructed drainage and **hydronephrosis,** in which the backed-up urine stretches and enlarges the renal pelvis. A kidney that fails to ascend into its normal position is called an **ectopic kidney.** Complications of this condition are primarily associated with difficulties draining the kidney, such as urinary tract infections and kidney stones. In **pelvic kidney,** one of the two kidneys stays in the bony pelvis throughout life. Because a pelvic kidney often blocks the birth canal, a woman with such a kidney may have difficulty while giving birth.

The metanephric kidneys are actively forming urine by month 3 of fetal life. Even though the placenta performs all excretory functions before birth, the production of urine by the fetal kidneys is an important function because the urine is voided into the amniotic sac, where it helps maintain a sufficient volume of amniotic fluid.

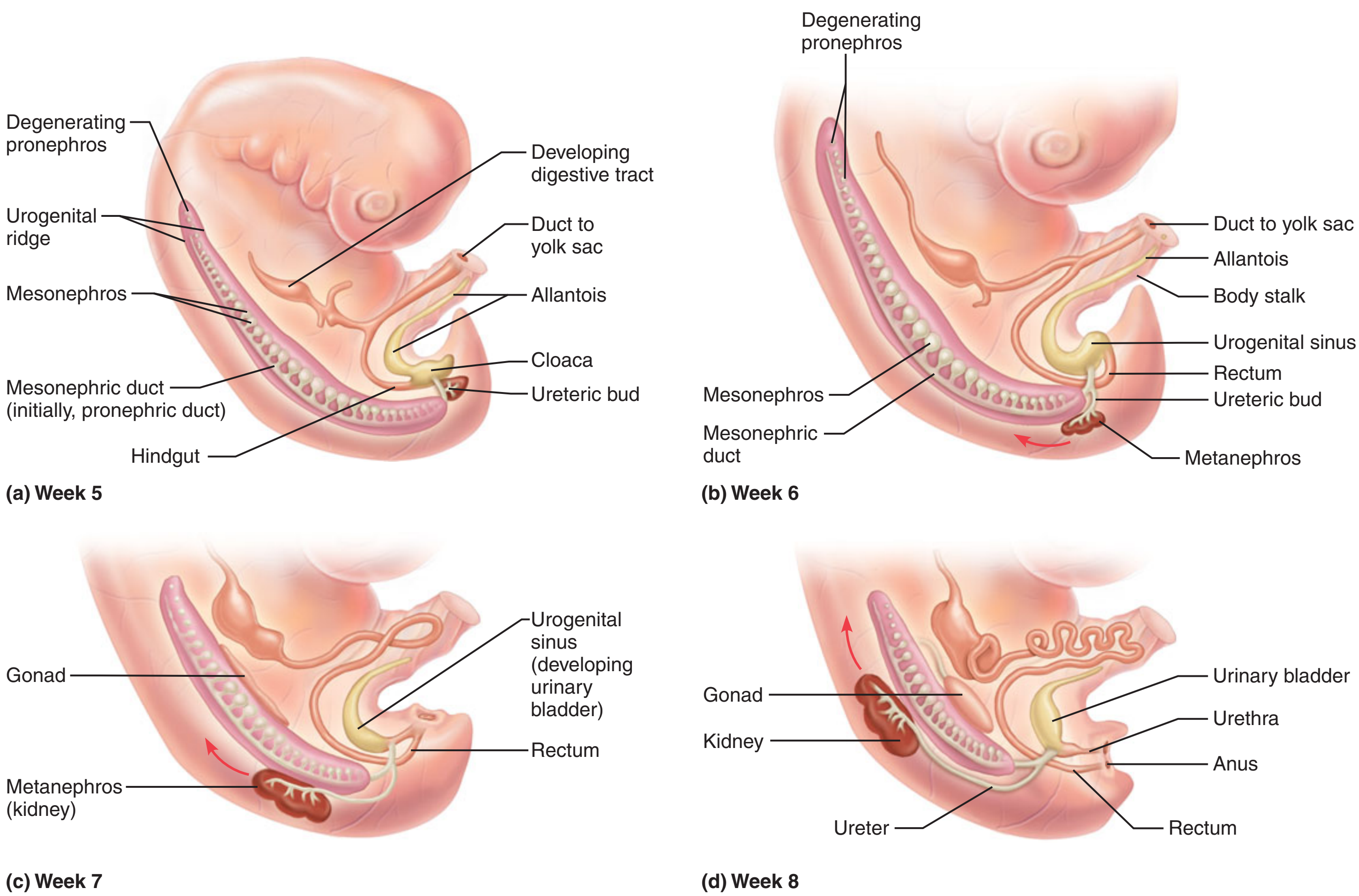


FIGURE 24.17 Development of the urinary organs in the embryo. Red arrows indicate the direction of metanephros migration.

At birth, an infant's bladder is small, and the kidneys cannot concentrate urine for the first 2 months. A newborn baby voids 5 to 40 times a day, depending on the amount of fluid intake. As the child grows, she or he voids less often but produces progressively more urine. By adolescence, the adult rate of urine output—an average of 1500 ml/day—is achieved.

Control of the voluntary external urethral sphincter is attained as the nervous system matures. By 15 months, most toddlers are aware of having voided. By 18 months, most children can hold urine in the bladder for about 2 hours, the first sign that toilet training for micturition can begin. Daytime control usually is achieved well before nighttime control. As a rule, it is unrealistic to expect complete nighttime control before the age of 4 years.

From childhood through late middle age, most problems that affect the urinary system are infections. Childhood streptococcal infections, such as a severe strep throat or scarlet fever, can lead to long-term inflammatory damage of the kidneys.

Only about 3% of elderly people have histologically normal kidneys, and kidney function declines with advancing age. The kidneys shrink, the nephrons decrease in size and number, and the tubules become less efficient at secretion and reabsorption. By age 70, the average rate of filtration is only half that of middle-aged adults, a functional decline believed to result from narrowing of the renal arteries by atherosclerosis. Diabetics are particularly at risk for renal disease, and over 50% of individuals who have had diabetes mellitus for 20 years (regardless of their age) are in renal failure owing to the vascular ravages of this disease.

The bladder of an aged person is shrunken, and the desire to urinate is often delayed. Loss of muscle tone in the bladder causes an annoying increased frequency of urination. Other common age-related problems are incontinence and urethral constriction by an enlarged prostate.

check your understanding

10. Why are urinary tract infections more common in females than in males?
11. What embryonic germ layer forms the metanephric kidney?
12. What is a cloaca? (Birds have a cloaca, which is why bird "poop" contains dark fecal matter and a white precipitate of uric acid.)

For answers, see Appendix B.

RELATED CLINICAL TERMS

CYSTOCELE (sis-to′-sél) (*cyst* = the bladder; *cele* = sac, hernia) Condition in women in which the urinary bladder pushes on the vagina and bulges into the anterior superior vaginal wall; may result from tearing of the supportive muscles of the pelvic floor during childbirth, which then causes the unsupported pelvic viscera to sink inferiorly. This condition changes the position of the upper urethra in ways that can lead either to urinary retention or incontinence; a tearing or weakening of the external urethral sphincter also promotes stress incontinence.

CYSTOSCOPY (sis-tos′ko-pe) The threading of a thin viewing tube through the urethra into the bladder to examine the surface of the bladder mucosa. Can detect bladder tumors, kidney stones, and infections.

DIALYSIS (di-al′ĭ-sis) A technique for removing wastes from the blood and replenishing acid-base buffers in individuals with failing kidneys; involves the diffusion of solutes across a membrane situated between the blood and a dialysis solution. The membrane can be either in an artificial kidney machine, through which the patient's blood is run (a process called *hemodialysis*), or in the patient's own peritoneum (a process called *peritoneal dialysis*). In the latter case, the dialysis fluid is injected into the patient's peritoneal cavity and removed when it has accumulated wastes.

RENAL INFARCT Area of dead (necrotic) renal tissue; may result from infection, hydronephrosis, or blockage of the blood supply to the kidney; commonly caused by blockage of an interlobar artery, which lacks anastomoses.

VESICOURETERIC REFLUX (ves″ĭ-ko-u-re′ter-ik; "bladder to ureter") Abnormal backflow of urine from the bladder into the ureter during micturition. In infants, it often reflects a congenital abnormality of the valve mechanism of the ureters in the bladder wall (see p. 718). When it appears in adults, it can result from increased pressures during voiding or from an obstruction of the urethra. Reflux can lead to pressure damage in the kidneys, kidney stones, and infection of the entire urinary tract as bacteria are flushed upward from the urethra. Treatment is with antibiotics, surgical reconstruction of the vesicoureteric valves or, in severe cases, by moving the end of the ureter so that it empties into the intestine.

CHAPTER SUMMARY

You can use the following media study tool for additional help when you review specific key topics in Chapter 24.

PAL = **Practice Anatomy Lab™**

1. In forming urine, the kidneys cleanse the blood of nitrogenous wastes, toxins, excess ions and water, and other unnecessary or undesirable substances. Kidneys also maintain the proper chemical composition of the blood and other body fluids. The organs for transporting and storing urine are the ureters, the bladder, and the urethra.

Kidneys (pp. 708–718)

Gross Anatomy of the Kidneys (pp. 708–711)

2. The bean-shaped kidneys lie retroperitoneally in the posterior abdominal wall, extending from the level of T_{11} or T_{12} to L_3.
3. The supportive and protective layers around the kidney are the fibrous capsule, the perirenal fat capsule, and the renal fascia.
4. A kidney has an external cortex, a deeper medulla consisting of renal pyramids, and a medial renal sinus that contains the main vessels and nerves of the kidney as well as the renal pelvis (the wide upper part of the ureter). Tributaries of the renal pelvis, the major and minor calices, collect urine draining from the papillae of the medullary pyramids. The medial, slitlike opening of the renal sinus is the hilum.
5. The vascular pathway through a kidney is as follows: renal artery → segmental arteries → interlobar arteries → arcuate arteries → cortical radiate arteries → afferent arterioles → glomeruli → efferent arterioles → peritubular capillary beds (or vasa recta) → cortical radiate veins → arcuate veins → interlobar veins → renal vein.
6. The nerve supply of the kidneys, consisting largely of sympathetic fibers, is from the renal plexus.

Microscopic Anatomy of the Kidneys (pp. 711–718)

7. The production of urine by the nephron involves three processes: filtration (which produces a filtrate of the blood that is modified into urine); resorption (which reclaims the desirable molecules from the filtrate and returns them to the blood); and secretion (in which undesirable molecules are pumped from the peritubular capillaries into the nephron).
8. The main structural and functional unit of the kidney is the nephron. The nephron, which forms the urine, consists of a renal corpuscle and a renal tubule. The renal tubule is composed of a proximal convoluted tubule, a nephron loop (loop of Henle), a distal convoluted tubule, and the collecting duct.
9. Filtration occurs at the renal corpuscles in the renal cortex. Each renal corpuscle consists of a glomerulus (a capillary tuft) surrounded by a glomerular capsule. The visceral (inner) layer of this capsule consists of octopus-shaped podocytes, which surround the capillaries of the glomerulus.
10. In passing from the glomerulus to the capsular space, the filtrate passes through the filtration membrane, which consists of the fenestrated glomerular endothelium, the basement membrane, and the filtration slits between podocytes. The main filters are the basement membrane and slit diaphragms covering the filtration slits; these structures retain molecules that are larger than small proteins.
11. From the glomerular capsule, the filtrate enters the proximal convoluted tubule (in the renal cortex), whose simple cuboidal epithelial cells show extreme specializations for resorption and secretion: many long microvilli, many mitochondria, and infoldings of the basolateral plasma membrane.
12. The nephron loop (loop of Henle) extends into the renal medulla. It consists of descending and ascending limbs. The first part of the descending limb, which resembles the proximal tubule, narrows to join the thin segment, whose walls consist of a simple squamous

epithelium. The thin segment joins the thick segment of the ascending limb, which is structurally similar to the distal convoluted tubule.

13. The distal convoluted tubule (in the renal cortex) is active in resorption and secretion, but less so than the proximal tubule. Its simple cuboidal epithelial cells exhibit abundant mitochondria and infoldings of the basolateral membrane, but no elaboration of the surface microvilli.

14. From the distal convoluted tubule, filtrate enters the collecting duct. Collecting ducts play a minor role in resorbing and secreting ions. More importantly, collecting ducts (along with distal tubules) resorb water in response to ADH (antidiuretic hormone) to concentrate urine.

15. There are two kinds of nephrons: cortical and juxtamedullary. The loops of the cortical nephrons extend only a short distance into the medulla. The loops of the juxtamedullary nephrons project deeply into the medulla and contribute to the mechanism that concentrates urine.

16. Each nephron is associated with a glomerulus (the capillary in the renal corpuscle from which the filtrate arises). Also associated with the nephrons are peritubular capillaries (which surround the convoluted tubules and are involved in resorption and secretion) and vasa recta (capillary-like vessels around the nephron loop of juxtamedullary nephrons, which function in concentrating urine). Glomeruli are supplied by afferent arterioles and drained by efferent arterioles, which in turn are continuous with the peritubular capillaries or the vasa recta.

17. The juxtaglomerular apparatus, which occurs at the point of contact between the afferent arteriole and the terminal portion of the ascending limb of the nephron loop, consists of granular cells and a macula densa. It functions in the hormonal correction of low blood pressure and low blood volume.

Ureters (pp. 718–719)

Gross Anatomy (p. 718)

18. The ureters are slender tubes descending retroperitoneally from the kidneys to the bladder. Each ureter enters the true pelvis by passing over the sacroiliac joint.

Microscopic Anatomy (pp. 718–719)

19. From external to internal, the layers of the ureter wall are (1) an adventitia of connective tissue, (2) a muscularis of smooth muscle, and (3) a highly distensible mucosa consisting of a lamina propria and a transitional epithelium. The muscularis squeezes urine inferiorly through the ureters.

Urinary Bladder (pp. 719–720)

Gross Anatomy (pp. 719–720)

20. The urinary bladder, a distensible muscular sac for storing urine, lies in the pelvis just posterior to the pubic symphysis.

21. A full bladder expands superiorly into the abdominal cavity and can be palpated through the anterior abdominal wall superior to the pubic symphysis. An empty bladder is an inverted pyramid with four angles (the neck drains into the urethra, the anterior angle is continuous with the urachus, and the two posterolateral angles are where ureters enter). The trigone is an elevated triangle on the inner surface of the posterior wall that is defined by the ureteric and urethral openings.

Microscopic Anatomy (p. 720)

22. The bladder wall, from internal to external, consists of a mucosa with a transitional epithelium, the detrusor muscle, and an adventitia (or, on the superior surface of the bladder, parietal peritoneum).

Urethra (pp. 720–721)

23. The urethra is the tube that conveys urine from the bladder out of the body. Various types of stratified epithelium line its lumen.

24. Where the urethra leaves the bladder, it is surrounded by the internal urethral sphincter, an involuntary sphincter of smooth muscle. Inferior to this, where the urethra passes through the urogenital diaphragm, it is surrounded by the external urethral sphincter, a voluntary sphincter of skeletal muscle.

25. In females, the urethra is 3–4 cm long and conducts only urine. In males, the urethra is about 20 cm long and conducts both urine and semen.

PAL = **Human Cadaver/Urinary System**

Micturition (pp. 721–723)

26. Micturition is the act of emptying the bladder.

27. As accumulating urine stretches the bladder, sensory neurons carry this information up the spinal cord to the micturition center in the pons. This center initiates micturition by signaling the parasympathetic neurons to the detrusor muscle.

28. Because the external urethral sphincter is controlled voluntarily, micturition can be delayed temporarily.

Disorders of the Urinary System (pp. 723–724)

29. Disorders of the urinary system include urinary tract infections (in which fecal bacteria spread up the urinary tract), calculi (kidney stones) that precipitate from the urine and can painfully block the ureter, bladder cancer, and kidney cancer.

The Urinary System Throughout Life (pp. 724–725)

30. Three sets of kidneys (pronephric, mesonephric, and metanephric) develop in sequence from the intermediate mesoderm of the embryo. The metanephros—the definitive kidney—forms in the pelvis as the ureteric bud signals nephrons to form in the intermediate mesoderm. The metanephric kidney moves cranially from the pelvis to the lumbar region.

31. The embryonic cloaca forms the urogenital sinus, which becomes both the bladder and the urethra.

32. The kidneys of newborns cannot concentrate urine. Their bladders are small, and voiding is frequent. Neuromuscular maturation generally allows toilet training for micturition to begin by 18 months of age.

33. From youth to middle age, the most common urinary problems are bacterial infections.

34. With age, nephrons are lost, the filtration rate decreases, and the kidneys become less efficient at concentrating urine. The capacity and tone of the bladder decrease with age, leading to frequent voiding and (often) incontinence. Urinary retention is a common problem of elderly men.

REVIEW QUESTIONS

Multiple Choice/Matching Questions

For answers, see Appendix B.

1. The inferior border of the right kidney is at the level of which vertebra? (a) T_{12}, (b) L_1, (c) L_2, (d) L_3.

2. The capillaries of the glomerulus differ from other capillary networks in the body in that they (a) form an anastomosing network, (b) drain into arterioles instead of venules, (c) contain no endothelium, (d) are the only capillaries from which a fluid leaves the blood.

3. Which of the following structures occurs exclusively in the renal medulla? (a) renal corpuscles, (b) distal convoluted tubules, (c) vasa recta, (d) proximal convoluted tubules.

4. Which of the following extend into the renal pyramid? (a) glomerulus, (b) distal convoluted tubules, (c) nephron loops, (d) proximal convoluted tubules, (e) renal columns.

5. The arrangement of the major blood vessels and urine-carrying vessels at the hilum of the kidney (from anterior to posterior) is: (a) renal artery branches, renal pelvis, renal vein; (b) renal vein, renal pelvis, renal artery branches; (c) renal pelvis, renal vein, renal artery branches; (d) renal vein, renal artery branches, renal pelvis.

6. The part of the nephron whose epithelial cells contain the longest microvilli and the most mitochondria is the (a) glomerular capsule (podocytes), (b) proximal tubule, (c) thin segment, (d) distal tubule.

7. The only part of the nephron that originates from the embryonic ureteric bud is the (a) glomerular capsule, (b) proximal convoluted tubule, (c) nephron loop, (d) distal convoluted tubule, (e) collecting duct.

8. The main function of the transitional epithelium in the ureter is (a) not the same as that of the transitional epithelium in the bladder, (b) protection against kidney stones, (c) secretion of mucus, (d) resorption, (e) stretching.

9. Jim was standing at a urinal in a crowded public restroom, and a long line was forming behind him. He became anxious (a sympathetic response) and suddenly found he could not micturate no matter how hard he tried. Jim's problem was that (a) his internal urethral sphincter was constricted and would not relax, (b) he had formed a kidney stone on the spot, and it was blocking his urethra, (c) his detrusor muscle was contracting too hard, (d) he almost certainly had a burst bladder.

10. A major function of the collecting ducts is (a) secretion, (b) filtration, (c) concentrating urine, (d) lubrication with mucus, (e) stretching.

11. Urine passes downward through the ureters by which mechanism(s)? (a) ciliary action, (b) peristalsis and gravity, (c) gravity alone, (d) suction exerted on the ureters and renal pelvis as the bladder expands with urine.

12. Parasympathetic stimulation of the bladder causes (a) inhibition of the detrusor muscle and relaxation of the external urethral sphincter, (b) contraction of the detrusor muscle and relaxation of the internal urethral sphincter, (c) relaxation of the internal and external urethral sphincters, (d) contraction of the detrusor muscle and contraction of the internal urethral sphincter.

13. Follow the path of filtrate from production in the renal corpuscle to excretion out of the body. Number the structures in the order that filtrate or urine passes through them beginning with #1, formation of filtrate in the glomerular capillaries.

_____ **(a)** glomerular capillaries

_____ **(b)** collecting duct

_____ **(c)** urethra

_____ **(d)** proximal convoluted tubule

_____ **(e)** papillary duct

_____ **(f)** ureter

_____ **(g)** glomerular capsule

_____ **(h)** distal convoluted tubule

_____ **(i)** renal pelvis

_____ **(j)** urinary bladder

_____ **(k)** nephron loop

_____ **(l)** calyx

14. Match the renal vessels listed in column B with their location listed in column A.

Column A	Column B
_____ **(1)** located in the renal columns	**(a)** glomerular capillaries
_____ **(2)** located around the renal tubules	**(b)** arcuate arteries and veins
_____ **(3)** branches off the renal artery that enter the hilum	**(c)** interlobar arteries and veins
_____ **(4)** located at the medulla-cortex junction	**(d)** peritubular capillaries
_____ **(5)** located in the renal corpuscle	**(e)** segmental arteries

Short Answer Essay Questions

15. Name the layers of fat and fascia around the kidney; explain the functions of the fat layers.

16. Pairs of urinary structures that are often confused are the ureters and the urethra; the perirenal and pararenal fat; and the renal sinus and renal pelvis. For each pair, differentiate one structure from the other.

17. Trace the path taken by the renal filtrate (and urine) from the glomerulus to the urethra. Name every microscopic and gross tube and structure that it passes through on its journey.

18. (a) Describe the basic process and purpose of tubular resorption. (b) Explain the location and function of the peritubular capillaries.

19. List all the layers of the filtration membrane in a renal corpuscle and describe the function of each layer.

20. Name (a) the four angles of the empty bladder and (b) the tube or band that attaches to each angle. (c) What three openings define the trigone of the bladder?

21. Define micturition, and describe its neural control.

22. Describe the changes that occur in the anatomy and function of the kidney with age.

23. How does the path of the ureters through the bladder wall minimize the chances of vesicoureteric reflux (see Related Clinical Terms) and hydronephrosis occurring (see "The Urinary System Throughout Life")?

24. Review the types of epithelium found throughout the structures of the urinary system. How does each epithelial type reflect the function of each structure?

CRITICAL REASONING & CLINICAL APPLICATION QUESTIONS

1. Recently, people at risk for developing bladder cancer have been encouraged to drink more fluids. Describe why this lowers one's chances of getting bladder cancer.

2. What is cystitis? Why do women suffer from cystitis more often than men?

3. Hattie, aged 55, is awakened by excruciating pain that radiates from her right abdomen to the lumbar and inguinal regions on the same side. The pain does not occur continuously but recurs at intervals of 3–4 minutes. Diagnose her problem, and cite factors that might favor its occurrence. Also, explain why Hattie's pain comes in "waves."

4. Felicia, a medical student, arrived late to a surgery in which she was to observe the removal of an extensive abscess from the fat around a patient's kidney. Felicia was startled to find the surgical team working to reinflate the patient's lung and to remove air from the pleural cavity. How could renal surgery lead to such events?

5. Maliki, a radiologist, was examining a pyelogram for renal calculi in a patient's right ureter. Which three regions of the ureter did he scrutinize first?

6. Why should parents teach their young daughters to wipe from front to back after defecation? Why does using a spermicide for birth control increase a woman's chance of getting a urinary tract infection?