



(Objective Checklist, continued)

- Describe the difference in control of the external and internal urethral sphincters.
- Name three common urinary tract problems.

FLUID, ELECTROLYTE, AND ACID-BASE BALANCE (pp. 514–520)

- Name and localize the three main fluid compartments of the body.
- Explain the role of antidiuretic hormone (ADH) in the regulation of water balance by the kidney.
- Explain the role of aldosterone in sodium and potassium balance of the blood.
- Compare and contrast the relative speed of buffers, the respiratory system, and the kidneys in maintaining the acid-base balance of the blood.

DEVELOPMENTAL ASPECTS OF THE URINARY SYSTEM (pp. 520–521)

- Describe three common congenital problems of the urinary system.
- Describe the effect of aging on urinary system functioning.

The kidneys, which maintain the purity and constancy of our internal fluids, are perfect examples of homeostatic organs. Much like sanitation workers who keep a city's water supply drinkable and dispose of its waste, the kidneys are usually unappreciated until there is a malfunction and "internal garbage" piles up. Every day, the kidneys filter gallons of fluid from the bloodstream. They then process this filtrate, allowing wastes and excess ions to leave the body in urine while returning needed substances to the blood in just the right proportions. Although the lungs and the skin also play roles in excretion, the kidneys bear the major responsibility for eliminating nitrogenous (nitrogen-containing) wastes, toxins, and drugs from the body.

Disposing of wastes and excess ions is only one part of the work of the kidneys. As they perform these excretory functions, they also regulate the blood's volume and chemical makeup so that the proper balance between water and salts and between acids and bases is maintained. Frankly, this would be tricky work for a chemical engineer, but the kidneys do it efficiently most of the time.

The kidneys have other regulatory functions as well: By producing the enzyme *renin* (re'nin), they help regulate blood pressure, and their hor-

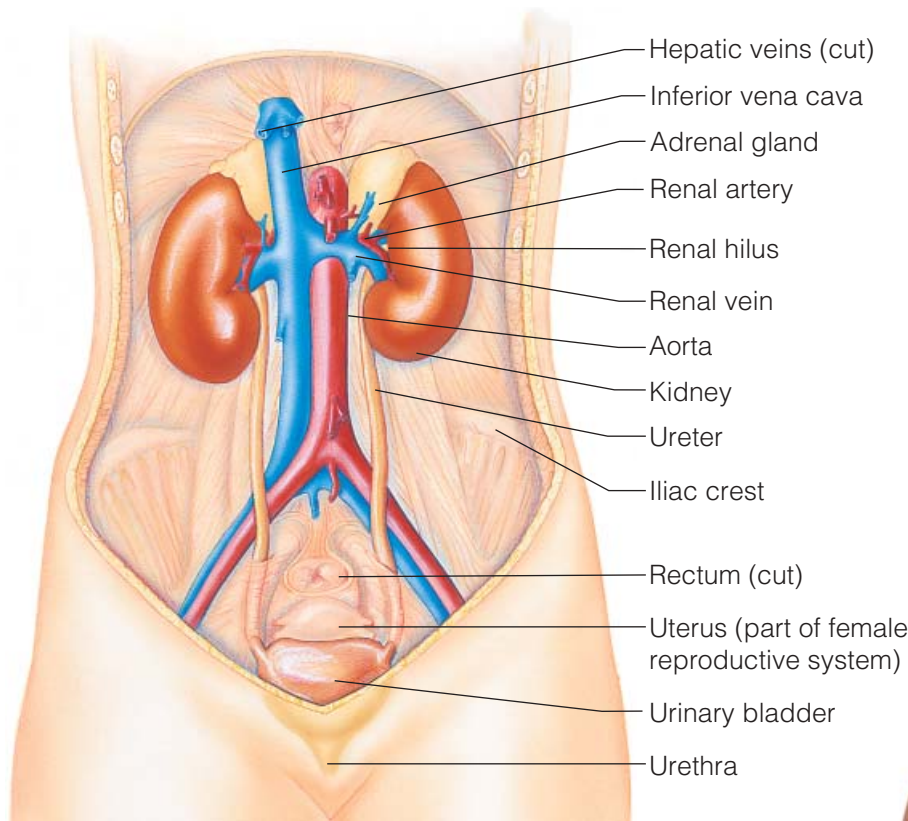
mone *erythropoietin* stimulates red blood cell production in bone marrow (see Chapter 10). Kidney cells also convert vitamin D to its active form.

The kidneys alone perform the functions just described and manufacture urine in the process. The other organs of the **urinary system**—the paired ureters and the single urinary bladder and urethra (Figure 15.1)—provide temporary storage reservoirs for urine or serve as transportation channels to carry it from one body region to another.

Kidneys

Location and Structure

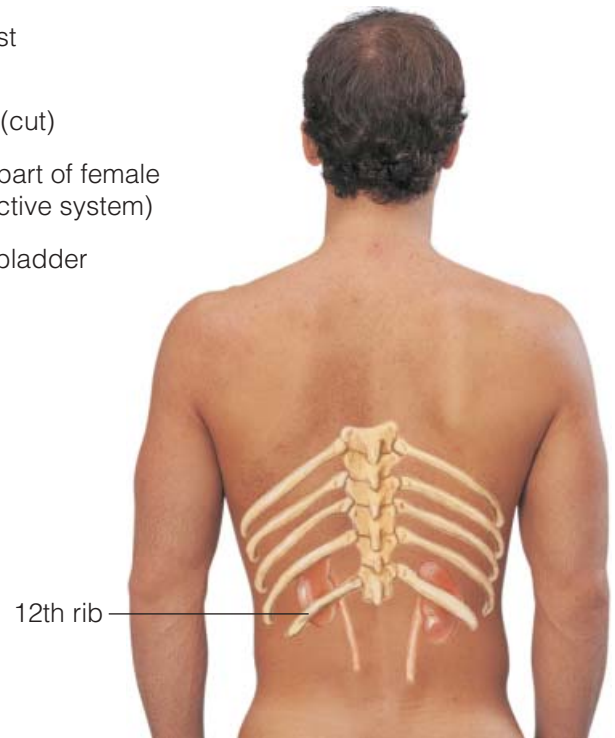
Although many believe that the **kidneys** are located in the lower back, this is *not* their location. Instead, these small, dark red organs with a kidney-bean shape lie against the dorsal body wall in a *retroperitoneal* position (beneath the parietal peritoneum) in the *superior* lumbar region. The kidneys extend from the T₁₂ to the L₃ vertebra; thus they receive some protection from the lower part of the rib cage. Because it is crowded by the liver, the right kidney is positioned slightly lower than the left. An adult kidney is about 12 cm (5 inches)



(a)

FIGURE 15.1 Organs of the urinary system.

(a) Anterior view of urinary organs of a female. (Most unrelated abdominal organs have been removed.) **(b)** Posterior in situ view of a male showing the relationship of the kidneys to the 12th rib pair.



(b)

long, 6 cm (2.5 inches) wide, and 3 cm (1 inch) thick, about the size of a large bar of soap. It is convex laterally and has a medial indentation called the *renal hilus*. Several structures, including the ureters, the renal blood vessels, and nerves, enter or exit the kidney at the hilus (see Figures 15.1 and 15.2). Atop each kidney is an *adrenal gland*, which is part of the endocrine system and is a distinctly separate organ functionally.

A fibrous, transparent **renal capsule** encloses each kidney and gives a fresh kidney a glistening appearance. A fatty mass, the *adipose capsule*, sur-

rounds each kidney and helps hold it in place against the muscles of the trunk wall.

Homeostatic Imbalance

The fat surrounding the kidneys is extremely important in holding them in their normal body position. If the amount of fatty tissue dwindles (as with rapid weight loss), the kidneys may drop to a lower position, a condition called *ptosis* (to'sis; "a fall"). Ptosis creates problems if the ureters, which drain urine from the kidneys, become kinked. When this happens, urine that can no longer pass through the ureters

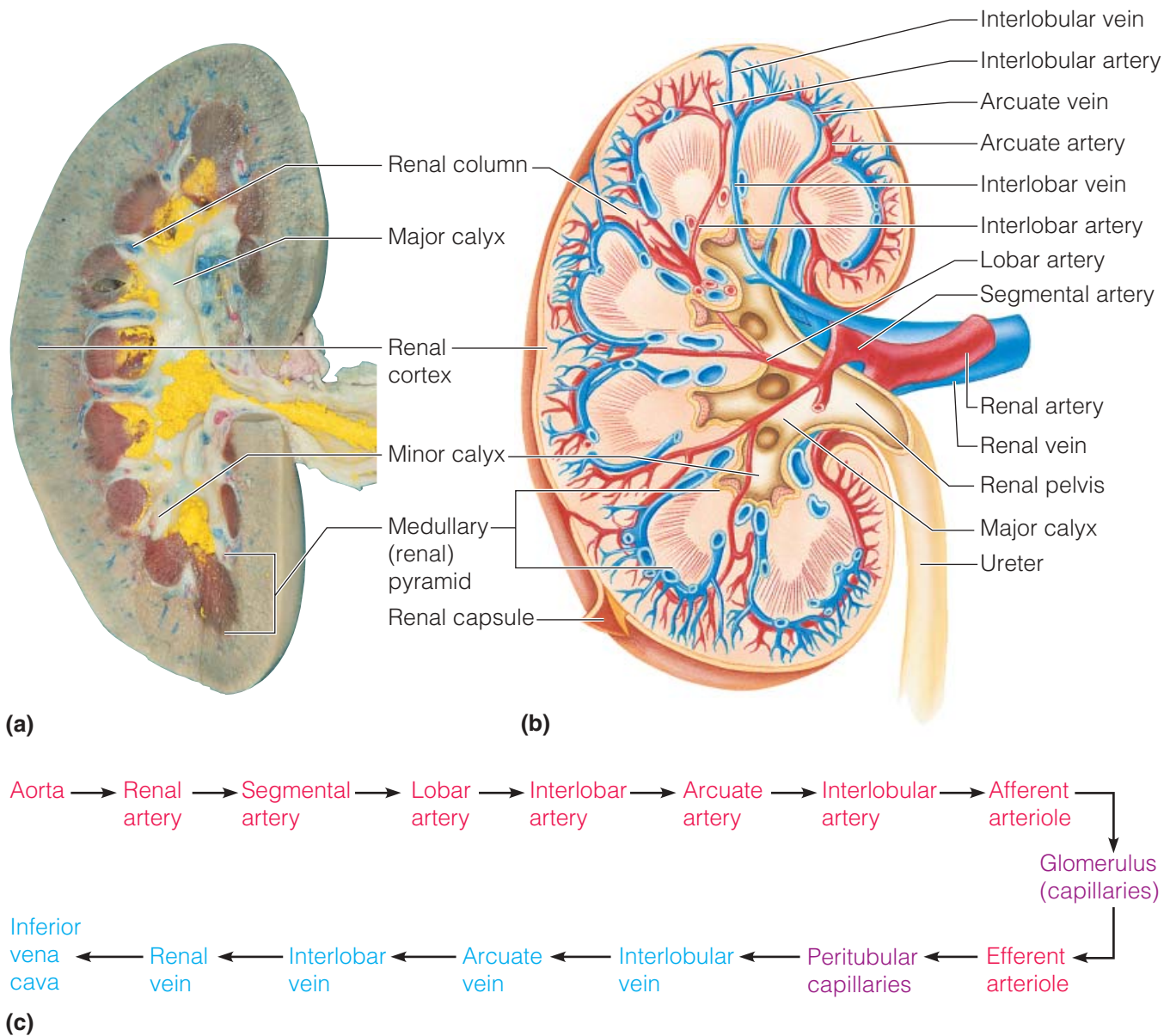


FIGURE 15.2 Internal anatomy of the kidney. (a) Photograph of a coronally sectioned kidney. (b) Diagrammatic view of a coronally sectioned kidney, illustrating major blood vessels. (c) Summary of the pathway of renal blood vessels.

backs up and exerts pressure on the kidney tissue. This condition, called *hydronephrosis* (hi'dro-nēfro'sis), can severely damage the kidney. ▲

When a kidney is cut lengthwise, three distinct regions become apparent, as can be seen in Figure 15.2. The outer region, which is light in color, is the **renal cortex**. (The word *cortex* comes from the Latin word meaning "bark.") Deep to the cortex is a darker reddish-brown area, the **renal medulla**. The medulla has many basically triangular

regions with a striped appearance, the **medullary** (med'u-lar'e) **pyramids**. The broader *base* of each pyramid faces toward the cortex; its tip, the *apex*, points toward the inner region of the kidney. The pyramids are separated by extensions of cortex-like tissue, the **renal columns**.

Medial to the hilus is a flat, basinlike cavity, the **renal pelvis**. As Figure 15.2b shows, the pelvis is continuous with the ureter leaving the hilus. Extensions of the pelvis, **calyces** (kal'ī-sēz; singular

calyx), form cup-shaped areas that enclose the tips of the pyramids. The calyces collect urine, which continuously drains from the tips of the pyramids into the renal pelvis. Urine then flows from the pelvis into the ureter, which transports it to the bladder for temporary storage.

Blood Supply

The kidneys continuously cleanse the blood and adjust its composition, so it is not surprising that they have a very rich blood supply (see Figure 15.2b and c). Approximately one-quarter of the total blood supply of the body passes through the kidneys each minute. The arterial supply of each kidney is the **renal artery**. As the renal artery approaches the hilus, it divides into **segmental arteries**. Once inside the pelvis, the segmental arteries break up into **lobar arteries**, each of which gives off several branches called **interlobar arteries**, which travel through the renal columns to reach the cortex. At the cortex-medulla junction, interlobar arteries give off the **arcuate** (ar'ku-at) **arteries**, which curve over the medullary pyramids. Small **interlobular arteries** then branch off the arcuate arteries and run outward to supply the cortical tissue. Venous blood draining from the kidney flows through veins that trace the pathway of the arterial supply but in a reverse direction—**interlobular veins** to **arcuate veins** to **interlobar veins** to the **renal vein**, which emerges from the kidney hilus. (There are no lobar or segmental veins.)

Nephrons and Urine Formation

Nephrons

Each kidney contains over a million tiny structures called **nephrons** (nef'ronz). Nephrons are the structural and functional units of the kidneys and, as such, are responsible for forming urine. Figure 15.3 shows the anatomy and relative positioning of nephrons in each kidney.

Each nephron consists of two main structures: a **glomerulus** (glo-mer'u-lus), which is a knot of capillaries, and a **renal tubule**. The closed end of the renal tubule is enlarged and cup-shaped and completely surrounds the glomerulus. This portion of the renal tubule is called the **glomerular** (*glom* = little ball), or **Bowman's, capsule**. The inner (visceral) layer of the capsule is made up of highly modified octopus-like cells called **podocytes** (pod'o-sitz). Podocytes have long branching processes called *foot*

processes that intertwine with one another and cling to the glomerulus. Because openings, the so-called *filtration slits*, exist between their extensions, the podocytes form a porous, or “holey,” membrane around the glomerulus (Figure 15.3c and d).

The rest of the tubule is about 3 cm (approximately 1.25 inches) long. As it extends from the glomerular capsule, it coils and twists before forming a hairpin loop and then again becomes coiled and twisted before entering a collecting tubule called the **collecting duct**. These different regions of the tubule have specific names (see Figure 15.3); in order from the glomerular capsule they are the **proximal convoluted tubule (PCT)**, the **loop of Henle** (hen'le), and the **distal convoluted tubule (DCT)**. The lumen surfaces (surface exposed to the filtrate) of the tubule cells in the proximal convoluted tubules are covered with dense microvilli, which increases their surface area tremendously. Microvilli also occur on the tubule cells in other parts of the tubule but in much reduced numbers.

Most nephrons are called **cortical nephrons** because they are located almost entirely within the cortex. In a few cases, the nephrons are called **juxtamedullary nephrons** because they are situated close to the cortex-medulla junction, and their loops of Henle dip deep into the medulla (see Figure 15.3a). The **collecting ducts**, each of which receives urine from many nephrons, run downward through the medullary pyramids, giving them their striped appearance. They deliver the final urine product into the calyces and renal pelvis.

Each and every nephron is associated with two capillary beds—the glomerulus (mentioned earlier) and the *peritubular* (per"i-tu'bu-lar) *capillary bed*. The glomerulus is both fed and drained by *arterioles*. The **afferent arteriole**, which arises from an *interlobular artery*, is the “feeder vessel,” and the **efferent arteriole** receives blood that has passed through the glomerulus. The glomerulus, specialized for filtration, is unlike any other capillary bed in the entire body. Because it is both fed *and* drained by arterioles, which are high-resistance vessels, and the afferent arteriole has a larger diameter than the efferent, blood pressure in the glomerular capillaries is much higher than in other capillary beds. This extremely high pressure forces fluid and solutes (smaller than proteins) out of the blood into the glomerular capsule. Most of this filtrate (99 percent) is eventually reclaimed by the

Q What path would a creatinine molecule in the glomerular blood take to reach the renal pelvis?

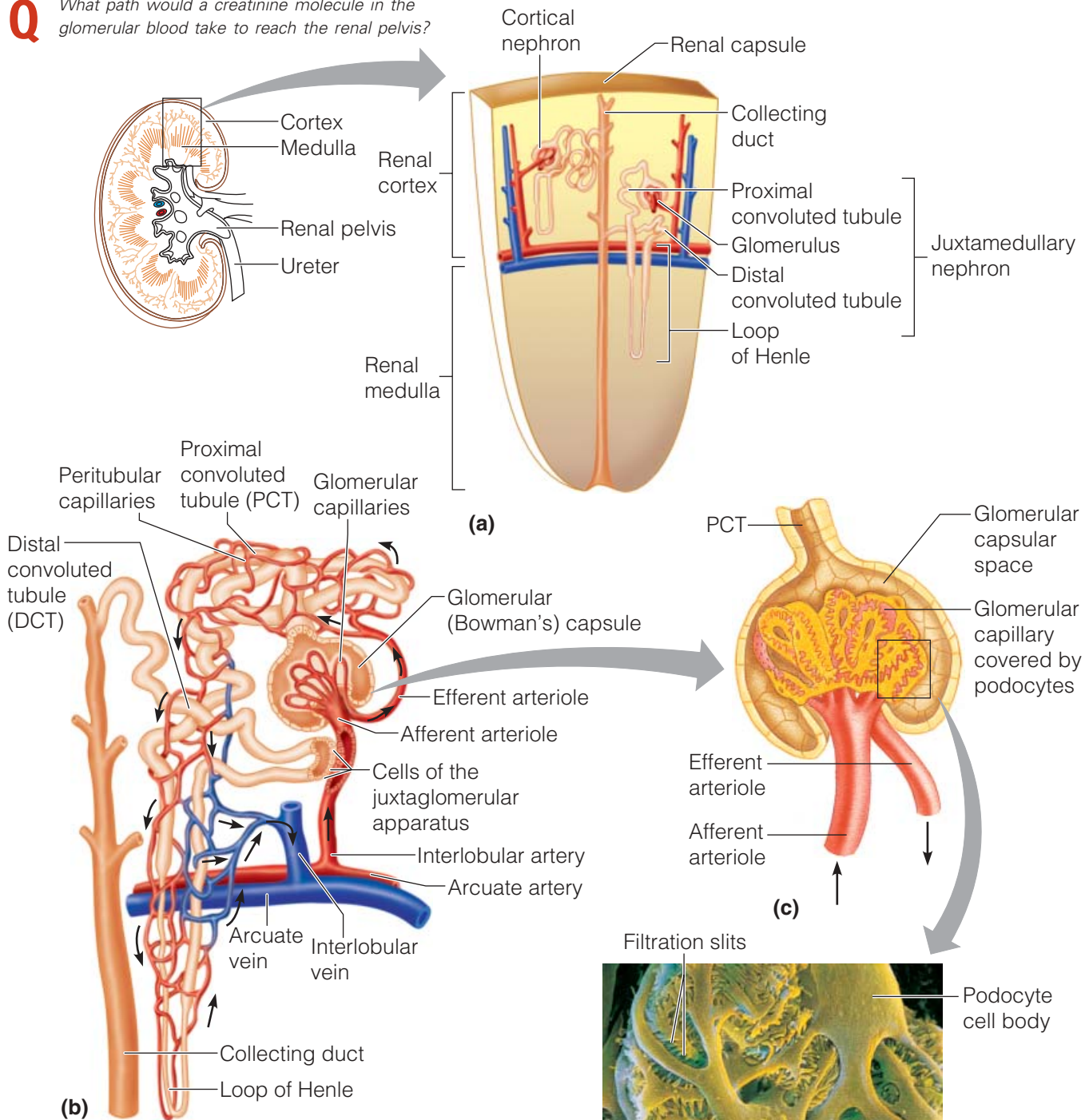


FIGURE 15.3 Structure of the nephron. (a) Wedge-shaped section of kidney tissue indicating the positioning of nephrons in the kidney. (b) Detailed anatomy of a nephron and its associated blood supply. Part of the distal convoluted tubule and afferent arteriole have been sectioned to reveal the location of the juxtaglomerular apparatus. (c) Diagrammatic view of the relationship of the visceral layer of the glomerular capsule to the glomerular capillaries. (d) Scanning electron micrograph of podocytes clinging to the glomerular capillaries.

A From the glomerular blood into the glomerular capsular space, then the proximal convoluted tubule to the loop of Henle, the distal convoluted tubule, the collecting duct through the renal medulla to a calyx, and finally the renal pelvis.

renal tubule cells and returned to the blood in the peritubular capillary beds.

The second capillary bed, the **peritubular capillaries**, arises from the efferent arteriole that drains the glomerulus. Unlike the high-pressure glomerulus, these capillaries are low-pressure, porous vessels that are adapted for absorption instead of filtration. They cling closely to the whole length of the renal tubule, where they are in an ideal position to receive solutes and water from the tubule cells as these substances are reabsorbed from the filtrate percolating through the tubule. The peritubular capillaries drain into interlobular veins leaving the cortex.

Urine Formation

Urine formation is a result of three processes—*filtration*, *tubular reabsorption*, and *tubular secretion*. Each of these processes is illustrated in Figure 15.4 and described in more detail next.

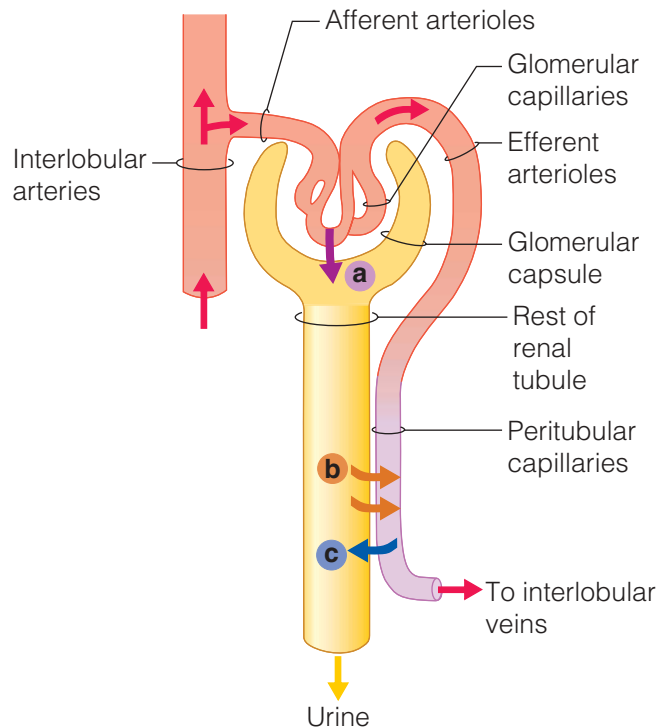
Filtration As just described, the glomerulus acts as a filter. **Filtration** is a nonselective, passive process. The filtrate that is formed is essentially blood plasma without blood proteins. Both proteins and blood cells are normally too large to pass through the filtration membrane, and when either of these appear in the urine, it is a pretty fair bet that there is some problem with the glomerular filters. As long as the systemic blood pressure is normal, filtrate will be formed. If arterial blood pressure drops too low, the glomerular pressure becomes inadequate to force substances out of the blood into the tubules, and filtrate formation stops.

Homeostatic Imbalance

▲ An abnormally low urinary output is called *oliguria* (ol'i-gu're-ah) if it is between 100 and 400 ml/day, and *anuria* (ah-nu're-ah) if it is less than 100 ml/day. Low urinary output usually indicates that glomerular blood pressure is too low to cause filtration, but anuria may also result from transfusion reactions and acute inflammation or from crush injuries of the kidneys. ▲

Tubular Reabsorption Besides wastes and excess ions that must be removed from the blood, the filtrate contains many useful substances (including water, glucose, amino acids, and ions), which must be reclaimed from the filtrate and returned to the blood. **Tubular reabsorption** begins as soon as the filtrate enters the proximal convoluted tubule

Q How would liver disease, in which the liver is unable to make many of the blood proteins, affect process a? (Reviewing Chapter 10 might help.)



KEY:

- a** **Filtration:** Water and solutes smaller than proteins are forced through the capillary walls and pores of the glomerular capsule into the renal tubule.
- b** **Tubular Reabsorption:** Water, glucose, amino acids, and needed ions are transported out of the filtrate into the tubule cells and then enter the capillary blood.
- c** **Tubular Secretion:** H^+ , K^+ , creatinine, and drugs are removed from the peritubular blood and secreted by the tubule cells into the filtrate.

FIGURE 15.4 The kidney depicted schematically as a single large, uncoiled nephron. A kidney actually has millions of nephrons acting in parallel. The three processes by which the kidneys adjust the composition of plasma are (a) filtration, (b) tubular reabsorption, and (c) tubular secretion.

A The amount of renal filtrate formed is a function of filtration (blood) pressure and blood osmotic pressure (exerted largely by blood proteins). Normally the osmotic pressure is a constant; but, in the situation described, more filtrate than normal will be formed because the blood pressure is opposed to a lesser extent by osmotic pressure of the blood.