chapter 17

Urinary System

HEMOLYTIC UREMIC SYNDROME. Felicia had looked forward to summer camp all year, especially the overnight hikes. A three-day expedition in July was wonderful, but five days after returning to camp, Felicia developed severe abdominal cramps. So did seventeen other campers and two counselors, some of whom had bloody diarrhea, too. Several of the stricken campers were hospitalized, Felicia among them. While the others improved in a few days and were released, Felicia suffered from a complication called hemolytic uremic syndrome (HUS). Her urine had turned bloody, and a blood analysis revealed severe anemia and lack of platelets.

Camp personnel reported the outbreak to public health officials, who quickly recognized the signs of food poisoning and traced the illness to hamburgers cooked outdoors during the camping trip. The burgers were not cooked long enough to kill *Escherichia coli,* bacteria that release a poison called shigatoxin.

Most people who eat meat tainted with the toxin become ill, but usually they just have cramps and diarrhea for several days. However, in about 6% of affected people, mostly children, HUS develops when the bloodstream transports the toxin to the kidneys, where it destroys cells of the microscopic capillaries that normally filter proteins and blood cells from forming urine. With the capillaries compromised, proteins and blood cells, as well as damaged kidney cells, appear in the urine.

Photo:

Undercooked beef tainted with a strain of *E. coli* that produces a powerful toxin is the source of many cases of hemolytic uremic syndrome, which damages the glomerular capillaries of nephrons within the kidneys. Changing the feed given to cattle can prevent colonization of these bacteria.

HUS is a leading cause of acute renal (kidney) failure, killing 3–5% of affected children. Felicia was lucky. Blood clotted around the sites of her damaged kidney cells, and new cells formed. Three weeks after the bloody urine began, her urine was once again clear, and she was healthy.

Chapter Objectives

After studying this chapter, you should be able to do the following:

17.1 Introduction

1. Name and list the general functions of the organs of the urinary system. (p. 454)

17.2 Kidneys

2. Describe the locations and structure of the kidneys. (p. 454)
3. List the functions of the kidneys. (p. 454)
4. Trace the pathway of blood through the major vessels within a kidney. (p. 455)
5. Describe a nephron, and explain the functions of its major parts. (p. 455)

17.3 Urine Formation

6. Explain how glomerular filtrate is produced, and describe its composition. (p. 459)
7. Explain the factors that affect the rate of glomerular filtration and how this rate is regulated. (p. 461)
8. Discuss the role of tubular reabsorption in urine formation. (p. 462)
9. Define tubular secretion, and explain its role in urine formation. (p. 464)

17.4 Urine Elimination

10. Describe the structure of the ureters, urinary bladder, and urethra. (p. 467)
11. Explain the process and control of micturition. (p. 469)

Aids to Understanding Words

calyc- [small cup] major *calyc*es: Cuplike divisions of the renal pelvis.

cort- [covering] renal *cort*ex: Shell of tissues surrounding the inner kidney.

detrus- [to force away] *detrus*or muscle: Muscle within the bladder wall that expels urine.

glom- [little ball] *glom*erulus: Cluster of capillaries within a renal corpuscle.

mict- [to pass urine] *mict*urition: Process of expelling urine from the bladder.

nephr- [pertaining to the kidney] *nephr*on: Functional unit of a kidney.

papill- [nipple] renal *papill*ae: Small elevations that project into a renal calyx.

trigon- [triangular shape] *trigon*e: Triangular area on the internal floor of the urinary bladder.

17.1 Introduction

Cells produce a variety of wastes that are toxic if they accumulate. Body fluids, such as blood and lymph, carry wastes from the tissues that produce them, while other structures remove wastes from the blood and transport them to the outside. The respiratory system removes carbon dioxide from the blood, and the *urinary system* removes certain salts and nitrogenous wastes. The urinary system also helps maintain the normal concentrations of water and electrolytes within body fluids, regulates the pH and volume of body fluids, and helps control red blood cell production and blood pressure.

The urinary system consists of a pair of kidneys, which remove substances from blood, form urine, and help regulate certain metabolic processes; a pair of tubular ureters, which transport urine from the kidneys; a saclike urinary bladder, which stores urine; and a tubular urethra, which conveys urine to the outside of the body. Figure 17.1 and reference plate 6 (p. 28) show these organs.

17.2 Kidneys

A **kidney** is a reddish-brown, bean-shaped organ with a smooth surface. An adult kidney is about 12 centimeters long, 6 centimeters wide, and 3 centimeters thick, and is enclosed in a tough, fibrous capsule (fig. 17.2).

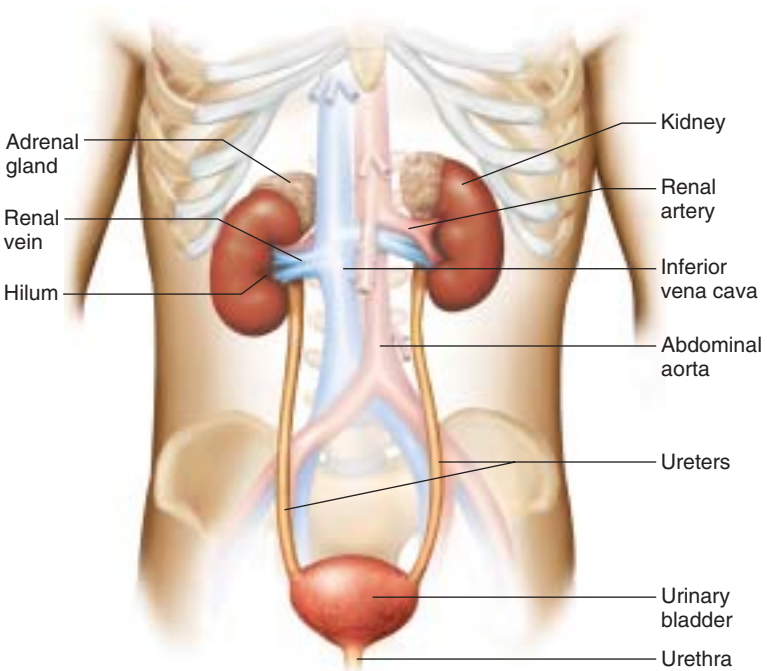


Figure 17.1
The urinary system includes the kidneys, ureters, urinary bladder, and urethra. Notice the relationship of these structures to the major blood vessels.

Location of the Kidneys

The kidneys lie on either side of the vertebral column in a depression high on the posterior wall of the abdominal cavity. The upper and lower borders of the kidneys are generally at the levels of the twelfth thoracic and third lumbar vertebrae, respectively. The left kidney is usually 1.5–2.0 centimeters higher than the right one.

The kidneys are positioned **retroperitoneally,** which means they are behind the parietal peritoneum and against the deep muscles of the back. Connective tissue and masses of adipose tissue surround the kidneys and hold them in position (see fig. 1.11, p. 11).

Kidney Structure

The lateral surface of each kidney is convex, but its medial side is deeply concave. The resulting medial depression leads into a hollow chamber called the **renal sinus.** The entrance to this sinus is termed the *hilum,* and through it pass blood vessels, nerves, lymphatic vessels, and the ureter (see fig. 17.1).

The superior end of the ureter expands to form a funnel-shaped sac called the **renal pelvis** inside the renal sinus. The pelvis subdivides into two or three tubes, called *major calyces* (singular, *calyx*), and these in turn subdivide into several *minor calyces* (fig. 17.2*a*).

A series of small elevations called *renal papillae* project into the renal sinus from its wall. Tiny openings that lead into a minor calyx pierce each projection.

Each kidney has two distinct regions—an inner medulla and an outer cortex. The **renal medulla** is composed of conical masses of tissue called *renal pyramids* and appears striated. The **renal cortex** forms a shell around the medulla and dips into the medulla between renal pyramids, forming *renal columns.* The granular appearance of the cortex is due to the random organization of tiny tubules associated with the **nephrons** (nef´ronz), the kidney's functional units (fig. 17.2*b,c*).

CHECK YOUR RECALL

1. Where are the kidneys located?
2. Describe kidney structure.
3. Name the kidney's functional unit.

Kidney Functions

The primary role of the kidneys is to help maintain homeostasis by regulating the composition, volume, and the pH of the extracellular fluid. They accomplish

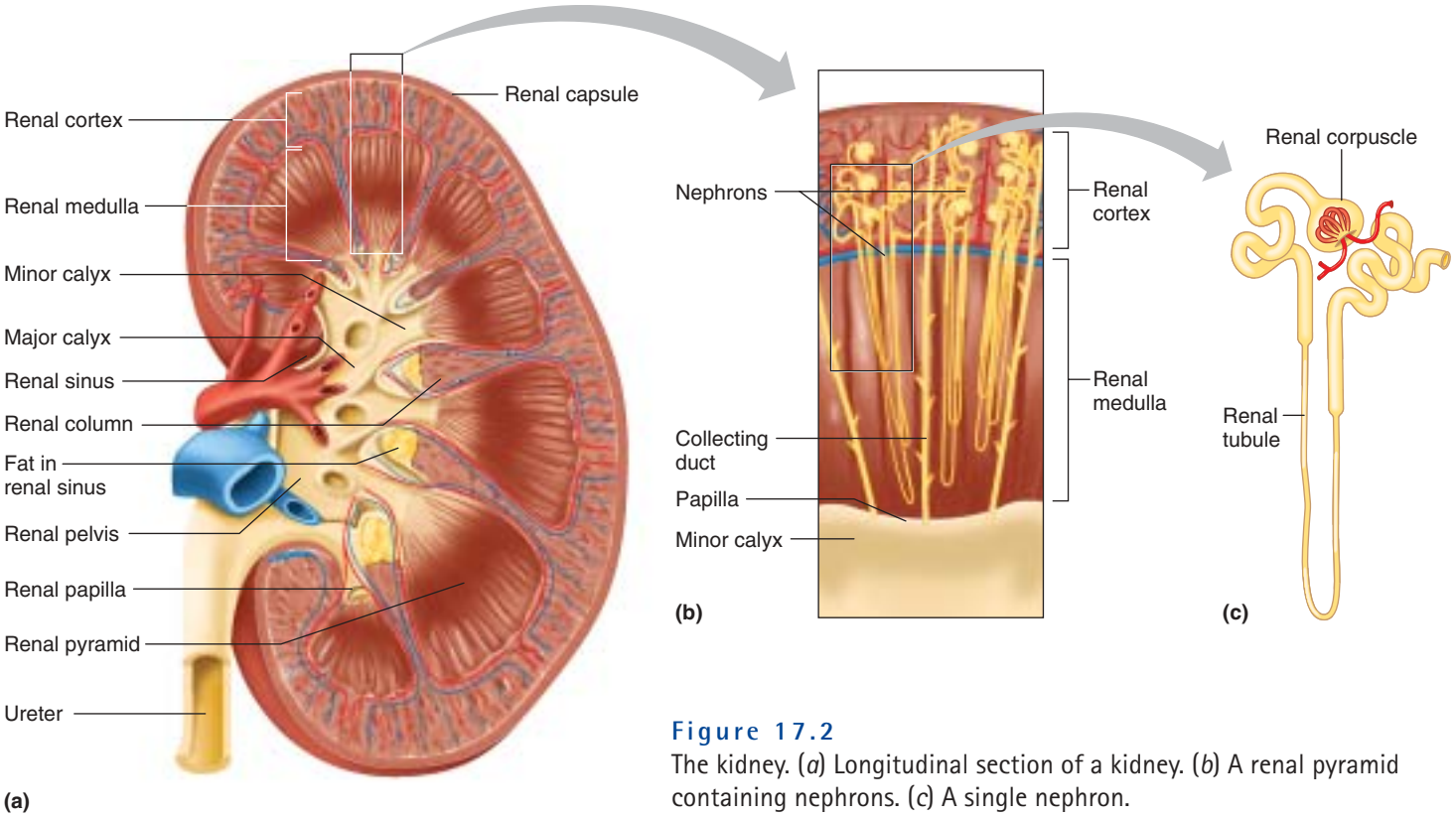


Figure 17.2
The kidney. (*a*) Longitudinal section of a kidney. (*b*) A renal pyramid containing nephrons. (*c*) A single nephron.

this by removing metabolic wastes from the blood and diluting them with water and electrolytes to form urine, which they then excrete.

The kidneys have several other important functions:

- Secreting the hormone erythropoietin (see chapter 12, page 305) to help control the rate of red blood cell production.
- Playing a role in the activation of vitamin D.
- Helping to maintain blood volume and blood pressure by secreting the enzyme renin.

Renal Blood Vessels

The **renal arteries,** which arise from the abdominal aorta, supply blood to the kidneys. These arteries transport a large volume of blood. When a person is at rest, the renal arteries usually carry 15–30% of the total cardiac output into the kidneys.

A renal artery enters a kidney through the hilum and gives off several branches, called *interlobar arteries,* which pass between the renal pyramids. At the junction between the medulla and the cortex, the interlobar arteries branch, forming a series of incomplete arches, the *arcuate arteries,* which in turn give rise to *interlobular arteries.* The final branches of the interlobular arteries, called **afferent arterioles** (af´er-ent ar-te´re-ōlz), lead to the nephrons (figs. 17.3 and 17.4).

Venous blood returns through a series of vessels that correspond generally to arterial pathways. The **renal vein** then joins the inferior vena cava as it courses through the abdominal cavity (see fig. 17.1).

A kidney transplant can help patients with end-stage renal disease. This procedure requires a kidney from a living or recently deceased donor whose tissues are antigenically similar (histocompatible) to those of the recipient. A surgeon places the kidney in the depression on the medial surface of the right or left ilium (iliac fossa). The surgeon then connects the renal artery and vein of the donor kidney to the recipient's iliac artery and vein, respectively, and the ureter of the donor kidney to the dome of the recipient's urinary bladder.

Nephrons

Nephron Structure

A kidney contains about 1 million nephrons. Each nephron consists of a **renal corpuscle** and a **renal tubule** (see fig. 17.2*c*). Fluid flows through renal tubules on its way out of the body.

A renal corpuscle is composed of a tangled cluster of blood capillaries called a **glomerulus** (glo-mer´u-lus). Glomerular capillaries filter fluid, the first step in urine formation. A thin-walled, saclike structure called a **glomerular capsule** (glo-mer´u-lar kap´sul) surrounds

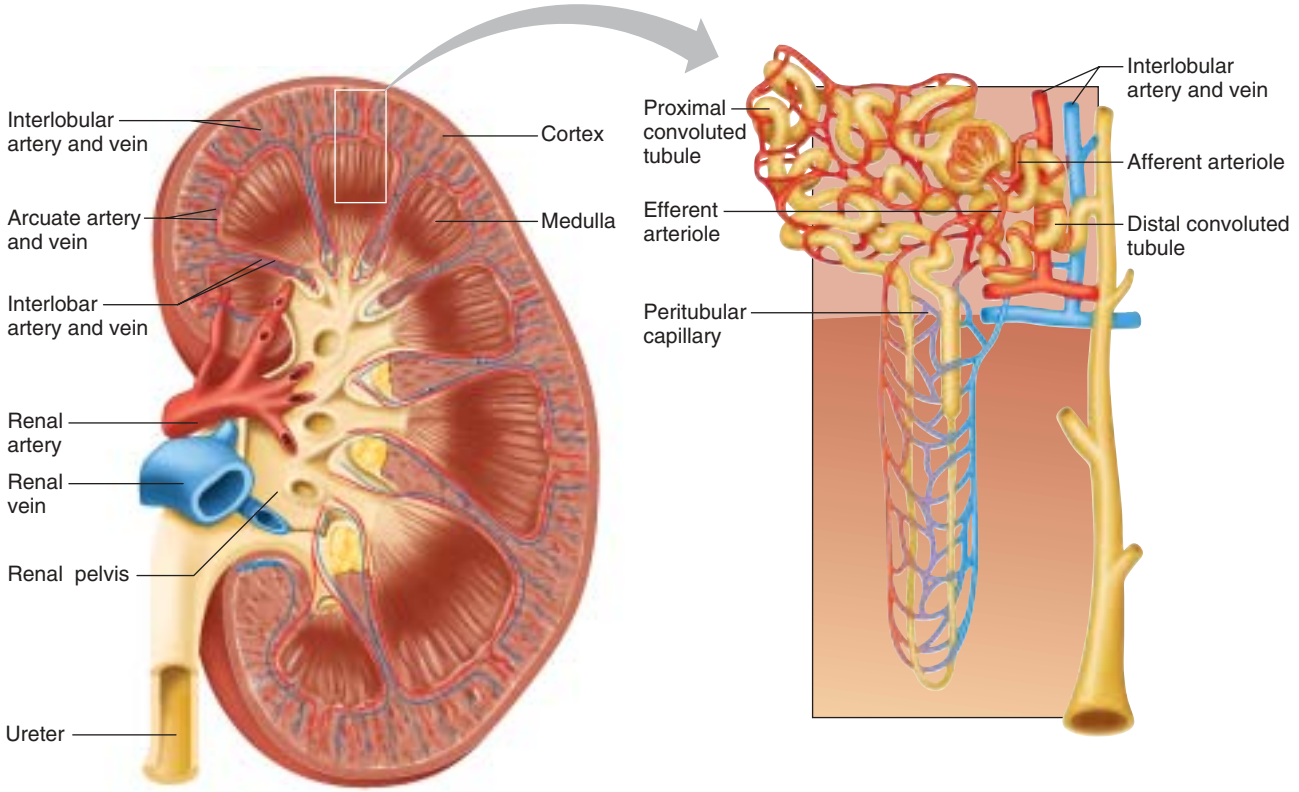


Figure 17.3
Main branches of the renal artery and renal vein.

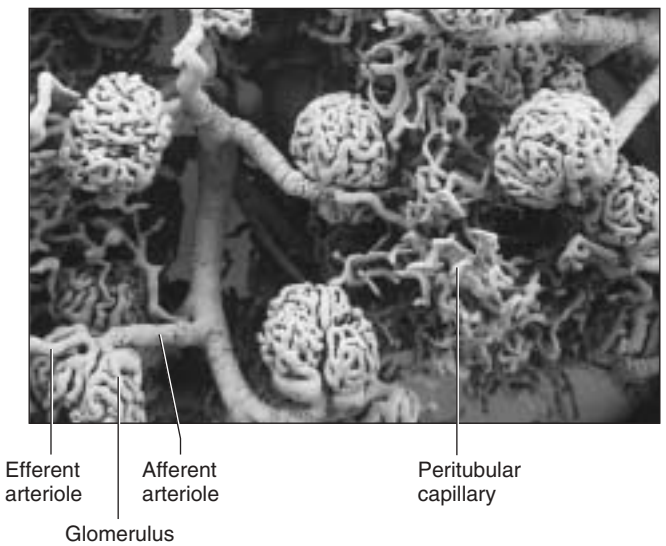


Figure 17.4
Scanning electron micrograph of a cast of the renal blood vessels associated with glomeruli (200×). From *Tissues and Organs: A Text-Atlas of Scanning Electron Microscopy,* by R. G. Kessel and R. H. Kardon, ©1979 W. H. Freeman and Company, all rights reserved.

the glomerulus (fig. 17.5). The glomerular capsule, an expansion at the proximal end of a renal tubule, receives the fluid the glomerulus filters. The renal tubule leads away from the glomerular capsule and becomes highly coiled. This coiled portion is called the *proximal convoluted tubule.*

The proximal convoluted tubule dips toward the renal pelvis, becoming the *descending limb of the nephron loop* (loop of Henle). The tubule then curves back toward its renal corpuscle and forms the *ascending limb of the nephron loop.* The ascending limb returns to the region of the renal corpuscle, where it becomes highly coiled again and is called the *distal convoluted tubule.*

Distal convoluted tubules from several nephrons merge in the renal cortex to form a *collecting duct* (technically not part of the nephron), which in turn passes into the renal medulla and enlarges as other distal convoluted tubules join it. The resulting tube empties into a minor calyx through an opening in a renal papilla. Figure 17.6 summarizes the structure of a nephron and its associated blood vessels.

CHECK YOUR RECALL

1. List the general functions of the kidneys.
2. Trace the blood supply to the kidney.
3. Name the parts of a nephron.

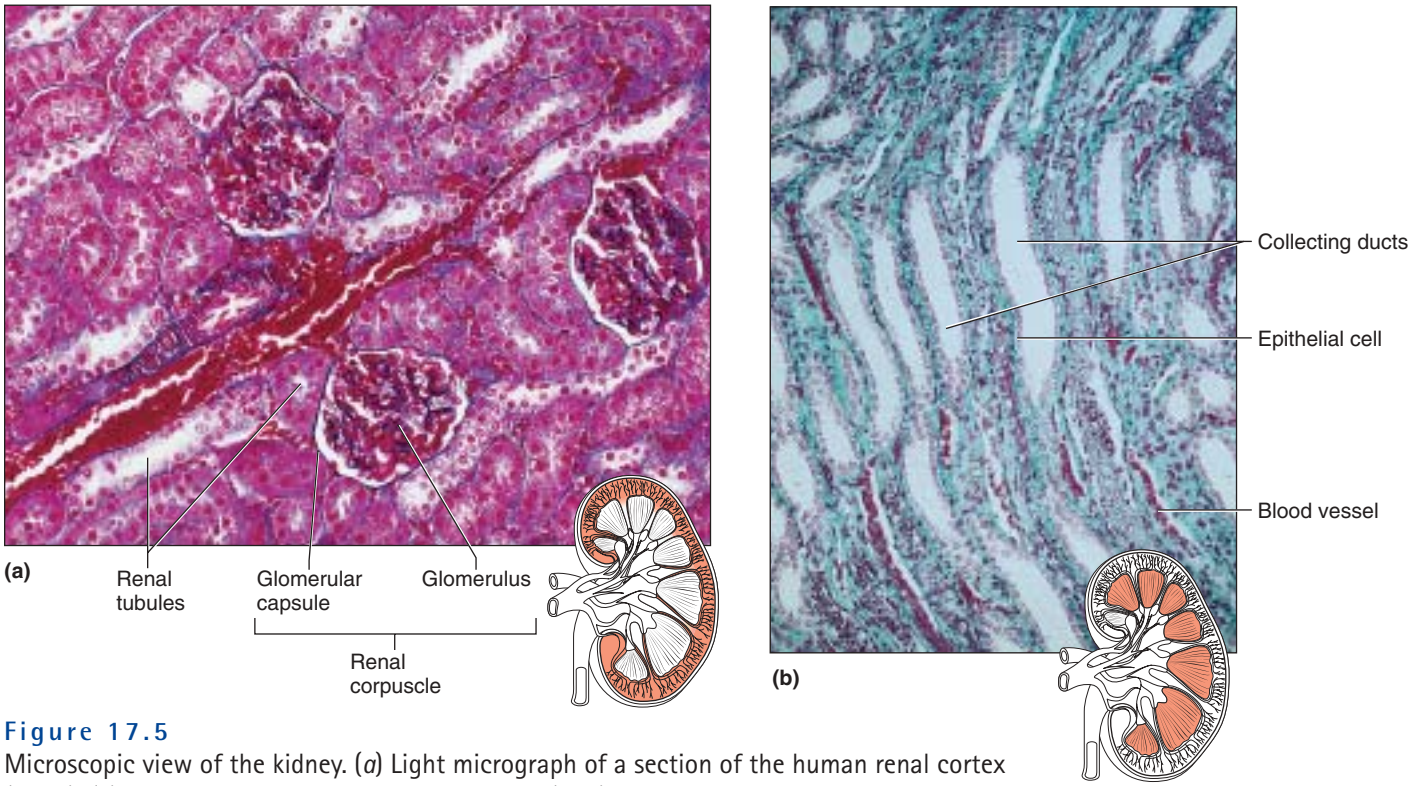


Figure 17.5
Microscopic view of the kidney. (*a*) Light micrograph of a section of the human renal cortex (220×). (*b*) Light micrograph of the renal medulla (80×).

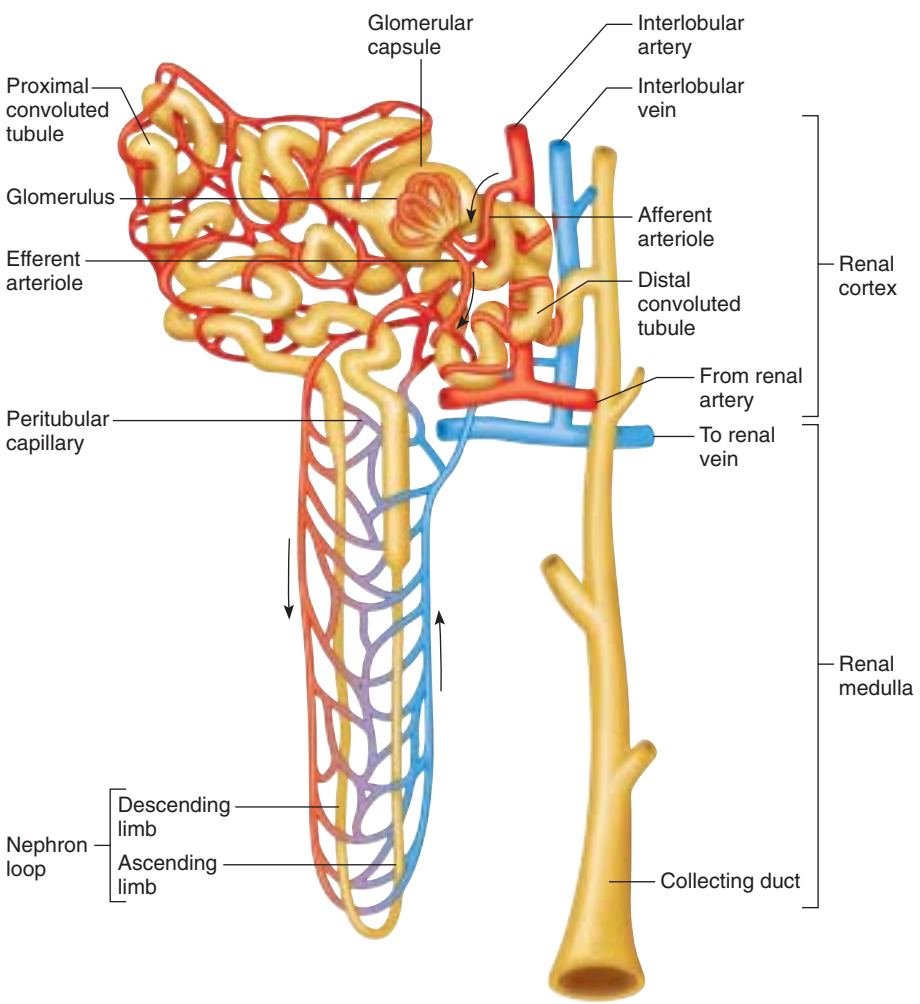


Figure 17.6
Structure of a nephron and the blood vessels associated with it. Arrows indicate the direction of blood flow.

Blood Supply of a Nephron

The cluster of capillaries that forms a glomerulus arises from an afferent arteriole. After passing through the glomerular capillaries, blood (minus any filtered fluid) enters an **efferent arteriole** (ef´er-ent ar-te´re-ōl), whose diameter is smaller than that of the afferent vessel (see fig. 17.4). This is instead of entering a venule, the usual circulatory route. The efferent arteriole resists blood flow to some extent, which backs up blood into the glomerulus, increasing pressure in the glomerular capillary.

The efferent arteriole branches into a complex, freely interconnecting network of capillaries, called the **peritubular capillary** (per´´ĭ-tu´bu-lar kap´ĭ-ler´´e) system, that surrounds the renal tubule (see figs. 17.4 and 17.6). Blood in the peritubular capillary system is under low pressure. After flowing through the capillary network, the blood rejoins blood from other branches of the peritubular capillary system and enters the venous system of the kidney.

Juxtaglomerular Apparatus

Near its origin, the distal convoluted tubule passes between and contacts afferent and efferent arterioles. At the point of contact, the epithelial cells of the distal tubule are quite narrow and densely packed. These cells comprise a structure called the *macula densa*.

Close by, in the walls of the arterioles near their attachments to the glomerulus, are some enlarged smooth muscle cells called *juxtaglomerular cells*. With cells of the macula densa, they constitute the **juxtaglomerular apparatus** (juks´´tah-glo-mer´u-lar ap´´ah-ra´tus), or juxtaglomerular complex (fig. 17.7). Its function in the control of renin secretion is described later in this chapter.

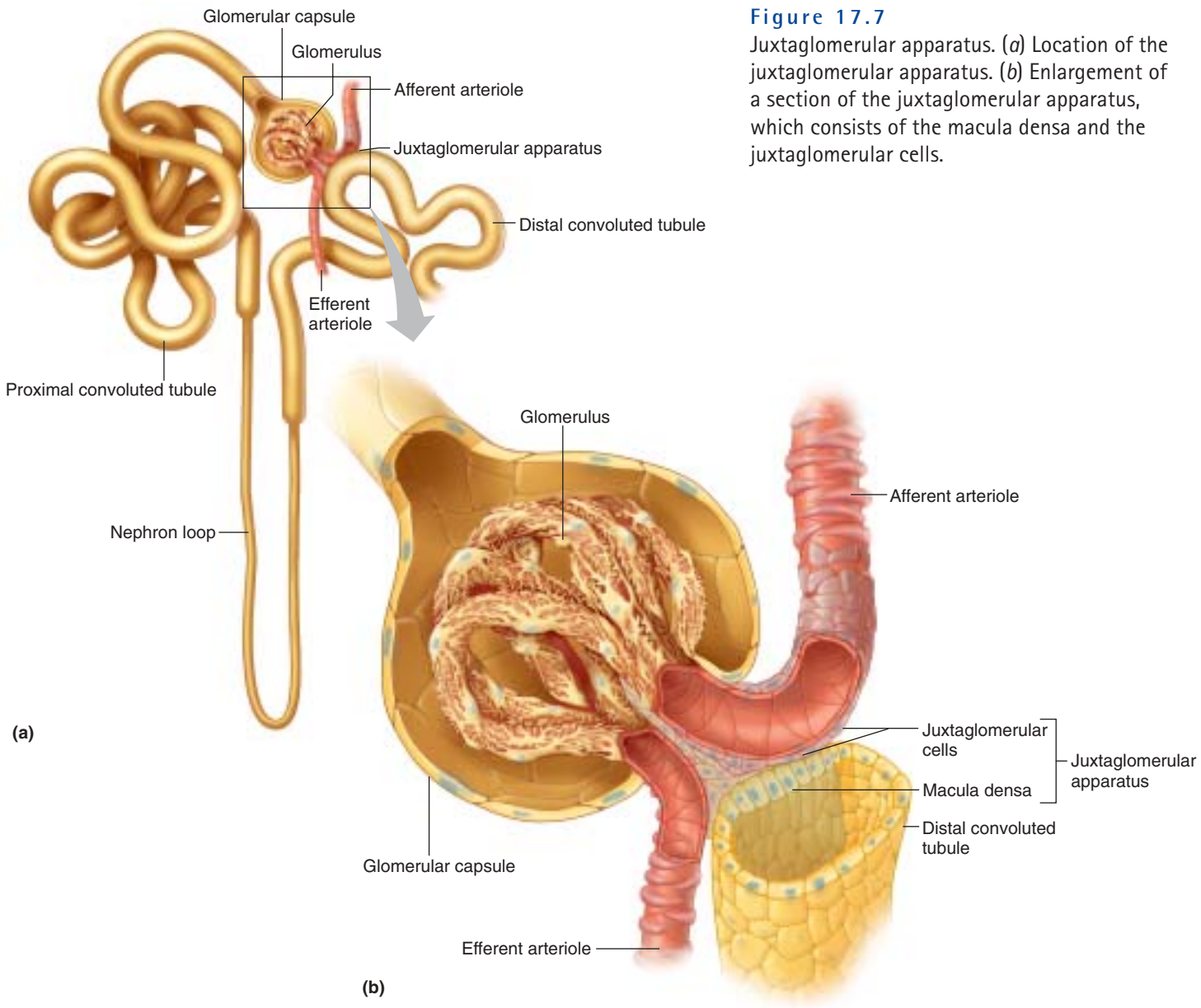


Figure 17.7
Juxtaglomerular apparatus. (*a*) Location of the juxtaglomerular apparatus. (*b*) Enlargement of a section of the juxtaglomerular apparatus, which consists of the macula densa and the juxtaglomerular cells.

CHECK YOUR RECALL

1. Describe the system of blood vessels that supplies a nephron.
2. What structures form the juxtaglomerular apparatus?

17.3 Urine Formation

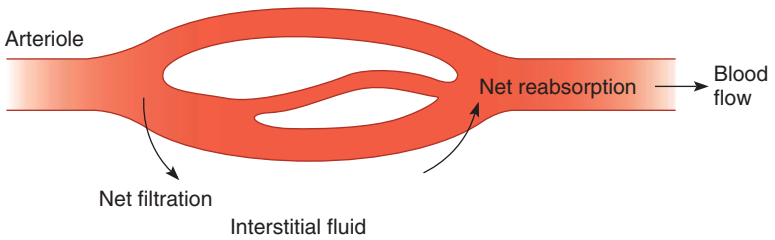
Urine formation begins with filtration of plasma by the glomerular capillaries, a process called **glomerular filtration.** Recall from chapter 13 (p. 339) that the force of blood pressure causes filtration to occur at capillaries throughout the body, but most of this fluid is reabsorbed into the bloodstream by the colloid osmotic pressure of the plasma (fig. 17.8*a*). Nephrons have taken this to another level, using two capillaries working in series. The first capillary bed is specialized only to filter, and instead of forming interstitial fluid, the filtered fluid (filtrate) moves into the renal tubule, where much of it is destined to become urine (fig. 17.8*b*).

Glomerular filtration produces 180 liters of fluid, more than four times the total body water, every 24 hours. However, glomerular filtration could not continue for very long unless most of this filtered fluid were returned to the internal environment. Thus, in addition to filtration, two other processes contribute to urine formation. **Tubular reabsorption** moves substances from the tubular fluid back into the blood within the peritubular capillary. **Tubular secretion,** the reverse process, moves substances from the blood within the peritubular capillary into the renal tubule (fig. 17.8*b*). In tubular reabsorption, the kidney selectively reclaims just the right amounts of substances, such as water, electrolytes, and glucose, that the body requires. Waste and excess substances exit the body. In tubular secretion, by contrast, some substances that the body must eliminate, such as hydrogen ions and certain toxins, are removed even faster than through filtration alone.

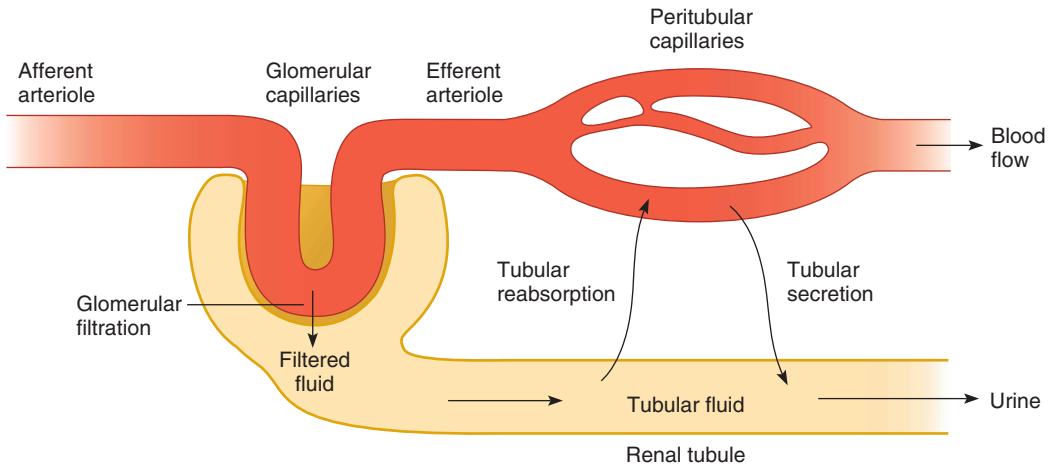
The final product of these three processes is **urine.** The following relationship determines the amount of any given substance excreted in the urine:

Amount filtered at the glomerulus
– Amount reabsorbed by the tubule
+ Amount secreted by the tubule
= Amount excreted in the urine

As the kidneys selectively excrete waste products and excess materials in the urine, they contribute to



(a) In most systemic capillaries, filtration predominates at the arteriolar end and osmotic reabsorption predominates at the venular end.



(b) In the kidneys, the glomerular capillaries are specialized for filtration. The renal tubule is specialized to control movements of substances back into the blood of the peritubular capillaries (tubular reabsorption) or from the blood into the renal tubule (tubular secretion).

Figure 17.8
To come.

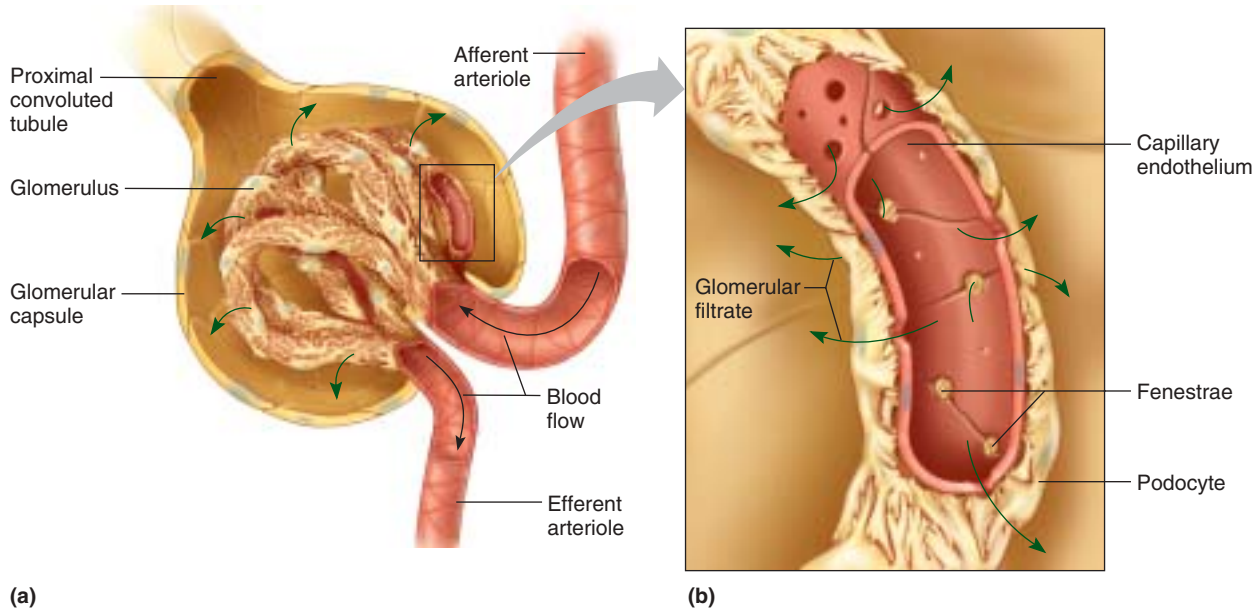


Figure 17.9
Glomerular filtration. (*a*) The first step in urine formation is filtration of substances out of glomerular capillaries and into the glomerular capsule. (*b*) Glomerular filtrate passes through the fenestrae of the capillary endothelium.

homeostasis by maintaining the composition of the internal environment.

Glomerular Filtration

Urine formation begins when water and certain dissolved substances are filtered out of glomerular capillaries and into glomerular capsules (fig. 17.9*a*). This filtration is similar to filtration at the arteriolar ends of other capillaries. However, many tiny openings (fenestrae) in glomerular capillary walls make glomerular capillaries much more permeable than capillaries in other tissues, even though cells called *podocytes* cover these capillaries and help make them impermeable to plasma proteins (fig. 17.9*b*).

The glomerular capsule receives the resulting **glomerular filtrate,** which is similar in composition to the filtrate that becomes tissue fluid elsewhere in the body. That is, glomerular filtrate is mostly water and the same components as blood plasma, except for the large protein molecules. Table 17.1 shows the relative concentrations of some substances in plasma, glomerular filtrate, and urine.

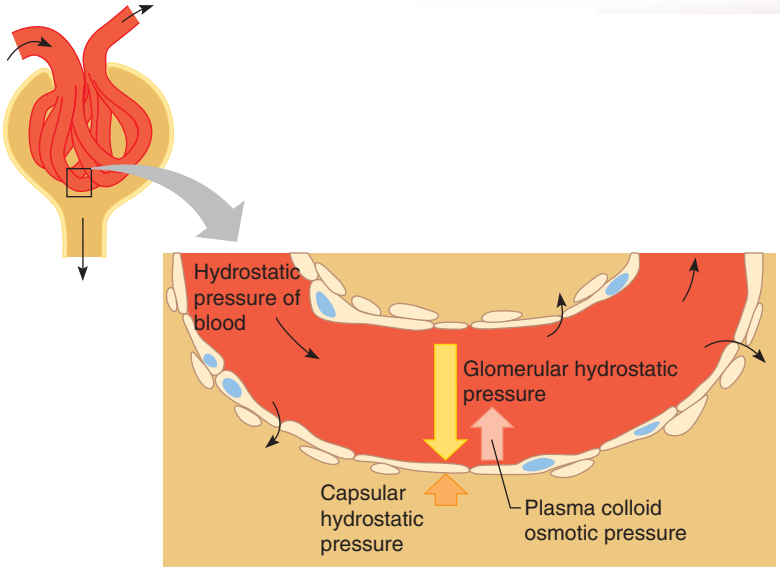
TABLE 17.1 RELATIVE CONCENTRATIONS OF SUBSTANCES IN THE PLASMA, GLOMERULAR FILTRATE, AND URINE

	CONCENTRATIONS (mEq/L)		
SUBSTANCE	PLASMA	GLOMERULAR FILTRATE	URINE
Sodium (Na^+)	142	142	128
Potassium (K^+)	5	5	60
Calcium (Ca^{+2})	4	4	5
Magnesium (Mg^{+2})	3	3	15
Chloride (Cl^-)	103	103	134
Bicarbonate (HCO_3^-)	27	27	14
Sulfate (SO_4^{-2})	1	1	33
Phosphate (PO_4^{-3})	2	2	40
	CONCENTRATIONS (mg/100 mL)		
SUBSTANCE	PLASMA	GLOMERULAR FILTRATE	URINE
Glucose	100	100	0
Urea	26	26	1,820
Uric acid	4	4	53

Note: mEq/L = milliequivalents per liter.

Filtration Pressure

As in other capillaries, the hydrostatic pressure of blood forces substances through the glomerular capillary wall. (Recall that glomerular capillary pressure is high compared to that of other capillaries.) The osmotic pressure of plasma in the glomerulus and the hydrostatic pressure inside the glomerular capsule also influence this movement. An increase in either of these pressures opposes movement out of the capillary and thus reduces filtration. The net pressure forcing substances out of the glomerulus is the **net filtration pressure,** and it is normally always positive, favoring filtration at the glomerulus (fig. 17.10).



Net Outward Pressure		
Outward force, glomerular hydrostatic pressure	=	+60 mm
Inward force of plasma colloid osmotic pressure	=	−32 mm
Inward force of capsular hydrostatic pressure	=	−18 mm
Net filtration pressure	=	+10 mm

Figure 17.10
Normally the glomerular net filtration pressure is positive causing filtration. The forces involved include the hydrostatic and osmotic pressure of the plasma and the hydrostatic pressure of the fluid in the glomerular capsule.

If arterial blood pressure plummets, as can occur during *shock,* glomerular hydrostatic pressure may fall below the level required for filtration. At the same time, epithelial cells of the renal tubules may not receive sufficient nutrients to maintain their high metabolic rates. As a result, cells die (tubular necrosis), impairing renal functions. Such changes can cause renal failure.

Filtration Rate

The glomerular filtration rate is directly proportional to net filtration pressure. Consequently, factors that affect glomerular hydrostatic pressure, glomerular plasma osmotic pressure, or hydrostatic pressure in the glomerular capsule also affect filtration rate. For example, any change in the diameters of the afferent and efferent arterioles changes glomerular hydrostatic pressure, also altering the glomerular filtration rate.

The afferent arteriole, which delivers blood to the glomerulus, may constrict in response to sympathetic nerve impulses. Blood flow diminishes, filtration pressure decreases, and filtration rate drops. On the other hand, if the efferent arteriole (which transports blood from the glomerulus) constricts, blood backs up into the glomerulus, net filtration pressure increases, and filtration rate rises. Vasodilation of these vessels causes opposite effects.

In capillaries, the plasma colloid osmotic pressure that attracts water inward (see chapter 12, p. 312) opposes the blood pressure that forces water and dissolved substances outward. During filtration through the capillary wall, proteins remaining in the plasma raise colloid osmotic pressure within the glomerular capillary. As this pressure rises, filtration decreases. Conversely, conditions that decrease plasma colloid osmotic pressure, such as a decrease in plasma protein concentration, increase the filtration rate.

In *glomerulonephritis,* the glomerular capillaries are inflamed and become more permeable to proteins, which appear in the glomerular filtrate and in urine (proteinuria). At the same time, the protein concentration in blood plasma decreases (hyporoteinemia), and this decreases plasma colloid osmotic pressure. As a result, less tissue fluid moves into the capillaries, and edema develops.

The hydrostatic pressure in the glomerular capsule sometimes changes because of an obstruction, such as a stone in a ureter or an enlarged prostate gland pressing on the urethra. If this occurs, fluids back up into renal tubules and raise the hydrostatic pressure in the glomerular capsule. Because any increase in capsular pressure opposes glomerular filtration, the filtration rate may decrease significantly.

At rest, the kidneys receive about 25% of the cardiac output, and about 20% of the blood plasma is filtered as it flows through the glomerular capillary. This means that in an average adult, the glomerular filtration rate for the nephrons of both kidneys is about 125 milliliters per minute, or 180,000 milliliters (180 liters, or nearly 45 gallons) in 24 hours. Only a small fraction is excreted as urine. Instead, most of the fluid that passes through the renal tubules is reabsorbed and reenters the plasma.

CHECK YOUR RECALL

1. Which processes form urine?
2. Which forces affect net filtration pressure?
3. Which factors influence the rate of glomerular filtration?

Regulation of Filtration Rate

The glomerular filtration rate is usually relatively constant. To help maintain homeostasis, however, the glomerular filtration rate may increase when body fluids are in excess and decrease when the body must conserve fluid.

Sympathetic nervous system reflexes that respond to changes in blood pressure and blood volume can alter the glomerular filtration rate. If blood pressure or volume drops sufficiently, afferent arterioles vasoconstrict, decreasing the glomerular filtration rate. This helps ensure that less urine forms when the body must conserve water. Conversely, vasodilation of afferent

arterioles increases the glomerular filtration rate to counter increased blood volume or blood pressure.

Another mechanism to control filtration rate involves the enzyme *renin*. Juxtaglomerular cells secrete renin in response to three types of stimuli: (1) whenever special cells in the afferent arteriole sense a drop in blood pressure; (2) in response to sympathetic stimulation; and (3) when the macula densa (see fig. 17.7) senses decreased amounts of chloride, potassium, and sodium ions reaching the distal tubule. Once in the bloodstream, renin reacts with the plasma protein *angiotensinogen* to form *angiotensin I*. A second enzyme (*angiotensin converting enzyme,* or ACE) in the lungs and in plasma quickly converts angiotensin I to *angiotensin II*.

Angiotensin II carries out a number of actions that help maintain sodium balance, water balance, and blood pressure (fig. 17.11). Angiotensin II vasoconstricts the efferent arteriole, which causes blood to back up into the glomerulus, thus raising glomerular capillary hydrostatic pressure. This important action helps minimize the decrease in glomerular filtration rate when systemic blood pressure is low. Angiotensin II has a major effect on the kidneys by stimulating secretion of the adrenal hormone aldosterone, which stimulates tubular reabsorption of sodium.

The heart secretes another hormone, atrial natriuretic peptide (ANP), when blood volume increases. ANP increases sodium excretion by a number of mechanisms, including increasing the glomerular filtration rate.

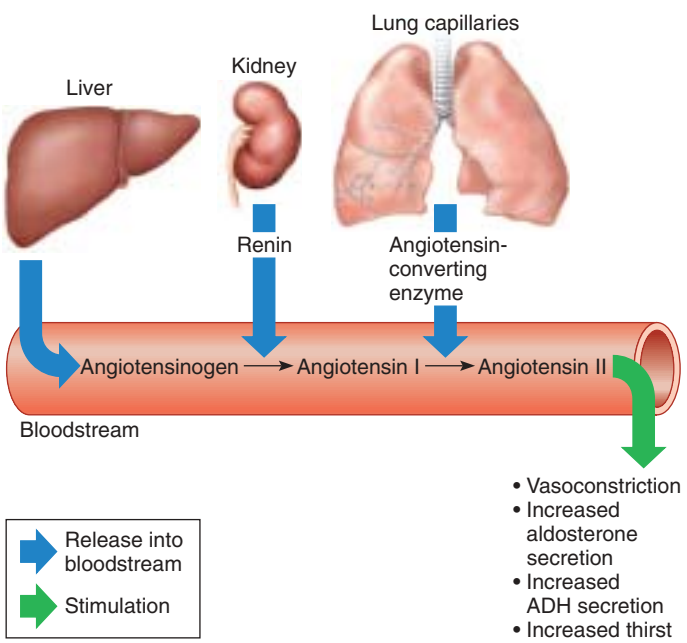


Figure 17.11
The formation of angiotensin II in the bloodstream involves several organs and includes multiple actions that conserve sodium and water.

Elevated blood pressure (hypertension) is sometimes associated with excess release of renin, followed by increased formation of the vasoconstrictor angiotensin II. Patients with this form of high blood pressure often take a drug called an *angiotensin converting enzyme inhibitor* (ACE inhibitor), that prevents the formation of angiotensin II by inhibiting the action of the enzyme that converts angiotensin I into angiotensin II.

CHECK YOUR RECALL

1. What is the function of the macula densa?
2. How does renin help regulate filtration rate?

Tubular Reabsorption

Comparing the composition of glomerular filtrate entering the renal tubule with that of urine leaving the tubule reveals that the fluid changes as it passes through the tubule (see table 17.1). For example, glucose is present in glomerular filtrate but absent in urine. In contrast, urea and uric acid are much more concentrated in urine than in glomerular filtrate. Such changes in fluid composition are largely the result of **tubular reabsorption** (tu´bu-lar re-ab-sorp´shun), the process by which filtered substances are returned to the bloodstream. In this process, substances are transported out of the tubular fluid, through the epithelium of the renal tubule, and into the interstitial fluid. These substances then diffuse into the peritubular capillaries (fig. 17.12*a*).

Tubular reabsorption returns substances to the internal environment. The term *tubular* is used because the epithelial cells that make up the renal tubules control this process. In tubular reabsorption, substances must first cross the cell membrane facing the inside of the tubule and then cross the cell membrane facing the interstitial fluid.

The basic rules for movements across cell membranes apply to tubular reabsorption. Substances moving down a concentration gradient must be lipid-soluble, or there must be a carrier or channel for that substance in the renal tubular cells. Active transport, requiring ATP, may move substances uphill against a concentration gradient.

Peritubular capillary blood is under relatively low pressure because it has already passed through two arterioles. Also, the walls of the peritubular capillaries are more permeable than other capillaries. Finally, because fluid is lost through glomerular filtration, the plasma protein concentration in the peritubular capillaries is relatively high. All these factors enhance the rate of fluid reabsorption from the renal tubule.

Tubular reabsorption occurs throughout the renal tubule, but most of it takes place in the proximal convoluted portion. The epithelial cells here have many

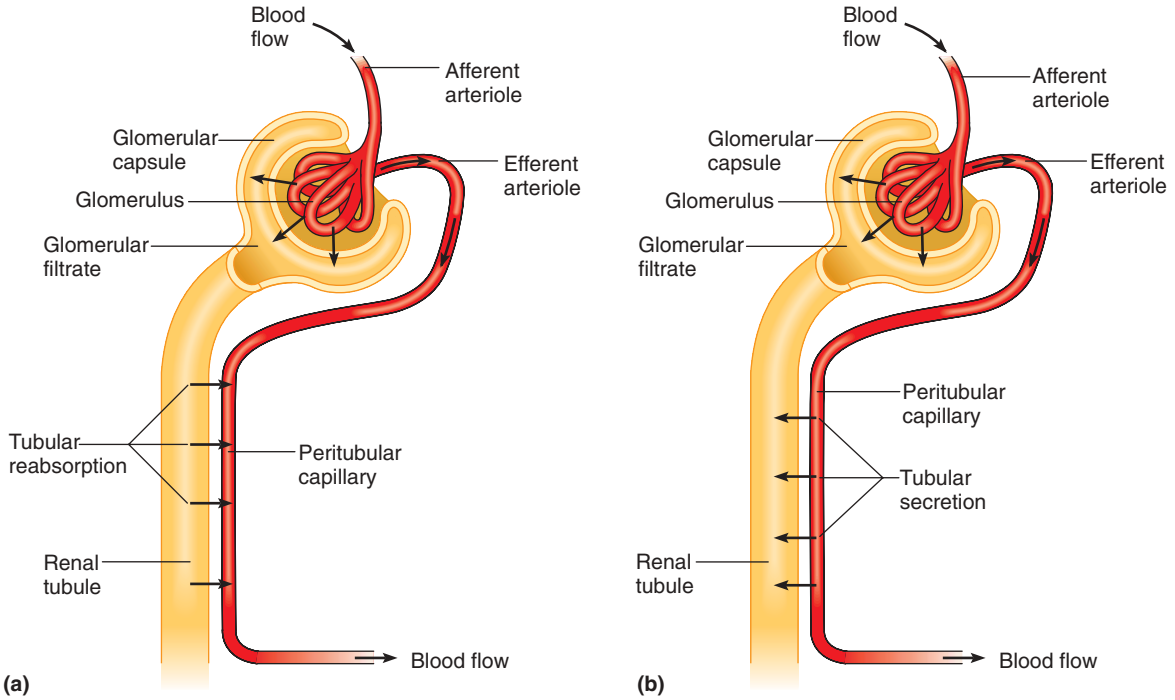


Figure 17.12
Two processes in addition to glomerular filtration contribute to urine formation. (*a*) Reabsorption transports substances from the glomerular filtrate into the blood within the peritubular capillary. (*b*) Secretion transports substances from the blood within the peritubular capillary into the renal tubule.

microscopic projections called *microvilli* that form a "brush border" on their free surfaces. These tiny extensions greatly increase the surface area exposed to glomerular filtrate and enhance reabsorption.

Segments of the renal tubule are adapted to reabsorb specific substances, using particular modes of transport. Active transport, for example, reabsorbs glucose through the walls of the proximal convoluted tubule. Water is then reabsorbed by osmosis through the epithelium of the proximal convoluted tubule. However, portions of the distal convoluted tubule and collecting duct may be almost impermeable to water, a characteristic important in the regulation of urine concentration and volume, as described later in this chapter.

Active transport utilizes carrier molecules in cell membranes (see chapter 3, p. 63). These carriers transport certain molecules across the membrane, release them, and then repeat the process. Such a mechanism, however, has a *limited transport capacity;* that is, it can only transport a certain number of molecules in a given time because the number of carriers is limited.

Usually, carrier molecules are able to transport all of the glucose in glomerular filtrate. But when the plasma glucose concentration increases to a critical level, called the *renal plasma threshold,* more glucose molecules are in the filtrate than can be actively transported. As a result, some glucose remains in the tubular fluid and is excreted in urine.

Glucose in urine, called *glucosuria* (or *glycosuria*), may occur following intravenous administration of glucose. It may also occur in a patient with diabetes mellitus whose blood glucose concentration rises abnormally (see chapter 11, p. 293).

Amino acids enter the glomerular filtrate and are reabsorbed in the proximal convoluted tubule. Three different active transport mechanisms reabsorb different groups of amino acids, whose members have similar structures. Normally, only a trace of amino acids remains in urine.

Glomerular filtrate is nearly free of protein except for traces of albumin, a small protein that is taken up by endocytosis through the brush border of epithelial cells lining the proximal convoluted tubule. Proteins inside epithelial cells are broken down to amino acids, which then move into the blood of the peritubular capillary.

The epithelium of the proximal convoluted tubule reabsorbs other substances, including creatine; lactic, citric, uric, and ascorbic (vitamin C) acids; and phosphate, sulfate, calcium, potassium, and sodium ions. Active transport mechanisms with limited transport capacities reabsorb these chemicals. However, these substances usually do not appear in urine until glomerular filtrate concentration exceeds a particular substance's threshold.

Sodium and Water Reabsorption

Substances that remain in the renal tubule become more concentrated as water is reabsorbed from the filtrate. Water reabsorption occurs passively by osmosis, primarily in the proximal convoluted tubule, and is closely associated with the active reabsorption of sodium ions, increasing if sodium reabsorption increases, and decreasing if sodium reabsorption decreases (fig. 17.13).

Active transport (the sodium pump) reabsorbs about 70% of sodium ions in the proximal segment of the renal tubule. As these positively charged ions (Na^+) move through the tubular wall, negatively charged ions, including chloride ions (Cl^-), phosphate ions (PO_4^{-3}), and bicarbonate ions (HCO_3^-), accompany them. These negatively charged ions move because of the electrochemical attraction between particles of opposite charge, a form of *passive transport* that does not require direct expenditure of cellular energy.

As active transport moves more sodium ions out of the proximal tubule, along with (passively) various negatively charged ions, the concentration of solutes within the peritubular blood increases. Since water moves across cell membranes from regions of lesser solute concentration toward regions of greater solute concentration, water moves by osmosis from the renal tubule into the peritubular capillary. Movement of solutes and water into the peritubular capillary greatly reduces the fluid volume within the renal tubule. The end of the proximal convoluted tubule is in osmotic equilibrium, and the remaining tubular fluid is isotonic.

Active transport continues to reabsorb sodium ions as the tubular fluid moves through the nephron loop, the distal convoluted tubule, and the collecting duct. Water is absorbed passively by osmosis in various segments of the renal tubule. As a result, almost all the sodium ions and water that enter the renal tubule as part of the glomerular filtrate are reabsorbed before urine is excreted.

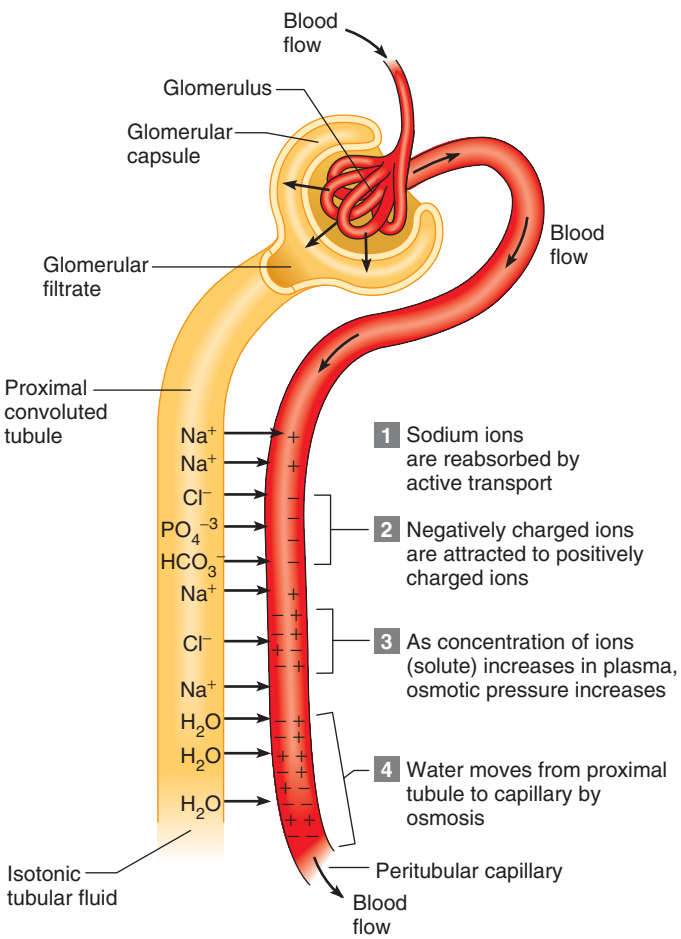


Figure 17.13
In the proximal portion of the renal tubule, osmosis reabsorbs water in response to active transport reabsorbing sodium and other solutes.

CHECK YOUR RECALL

1. Which chemicals are normally present in the glomerular filtrate but not in urine?
2. Which mechanisms reabsorb solutes from the glomerular filtrate?
3. Describe the role of passive transport in urine formation.

Tubular Secretion

Although 20% of the plasma flowing through the kidneys is filtered in the glomeruli, approximately 80% escapes filtration and continues on through the peritubular capillaries. In **tubular secretion** (tu´bu-lar se-kre´shun), certain substances move from the plasma of blood in the peritubular capillary into the fluid of the renal tubule. As a result, the amount of a particular chemical excreted in the urine may exceed the amount filtered from the plasma in the glomerulus (fig. 17.12*b*). As in the case of tubular reabsorption, the term *tubular* refers to control by the epithelial cells that make up the renal tubules.

Active transport mechanisms similar to those that function in reabsorption secrete some substances. Secretory mechanisms, however, transport substances in the opposite direction. For example, the epithelium of the proximal convoluted segment actively secretes certain organic compounds, including penicillin, creatinine, and histamine, into the tubular fluid.

Hydrogen ions are also actively secreted throughout the entire renal tubule. Secretion of hydrogen ions is important in regulating the pH of body fluids, as chapter 18 (p. 484) explains.

Most potassium ions in the glomerular filtrate are actively reabsorbed in the proximal convoluted tubule, but some may be secreted in the distal segment and collecting duct. During this process, active reabsorption of sodium ions from the tubular fluid produces a negative electrical charge within the tubule. Because positively

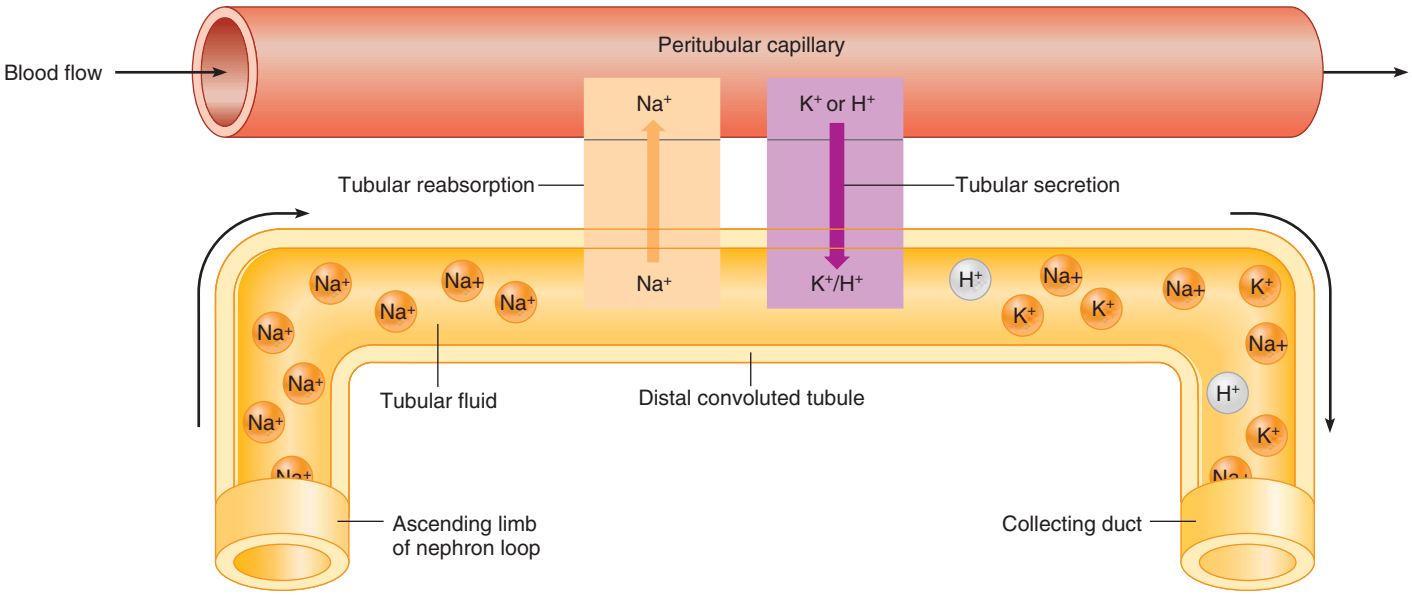


Figure 17.14
In the distal convoluted tubule, potassium ions (or hydrogen ions) may be passively secreted in response to the active reabsorption of sodium ions.

charged potassium ions (K^+) and hydrogen ions (H^+) are attracted to negatively charged regions, these ions move passively through the tubular epithelium and enter the tubular fluid (fig. 17.14). Potassium ions are also secreted by active processes.

To summarize, urine forms as a result of the following:

- Glomerular filtration of materials from blood plasma.
- Reabsorption of substances, including glucose; water; creatine; amino acids; lactic, citric, and uric acids; and phosphate, sulfate, calcium, potassium, and sodium ions.
- Secretion of substances, including penicillin, histamine, phenobarbital, hydrogen ions, ammonia, and potassium ions.

CHECK YOUR RECALL

1. Define *tubular secretion.*
2. Which substances are actively secreted?
3. How does sodium reabsorption affect potassium secretion?

Regulation of Urine Concentration and Volume

The hormones aldosterone and ADH (antidiuretic hormone) may stimulate additional reabsorption of sodium and water, respectively. The changes in sodium and water excretion in response to these hormones are the final adjustments the kidney makes to maintain a constant internal environment.

As discussed in chapter 11 (pp. 290–291), the adrenal gland secretes aldosterone in response to changes in the blood concentrations of sodium and potassium ions. Aldosterone stimulates the distal tubule to reabsorb sodium and secrete potassium. Angiotensin II is another important stimulator of aldosterone secretion.

Neurons in the hypothalamus produce ADH, which the posterior pituitary releases in response to a decreasing water concentration in blood or a decrease in blood volume. When ADH reaches the kidney, it increases the water permeability of the epithelial linings of the distal convoluted tubule and collecting duct, and water moves rapidly out of these segments by osmosis—that is, water is reabsorbed. Consequently, urine volume falls, and soluble wastes and other substances become more concentrated, which minimizes loss of body fluids when dehydration is likely.

If body fluids contain excess water, ADH secretion decreases. As blood levels of ADH drop, the epithelial linings of the distal segment and collecting duct become less permeable to water, less water is reabsorbed, and urine is more dilute, excreting the excess water. Table 17.2 summarizes the role of ADH in urine production.

TABLE 17.2 ROLE OF ADH IN REGULATING URINE CONCENTRATION AND VOLUME

1. Concentration of water in blood decreases.
2. Increase in osmotic pressure of body fluids stimulates osmoreceptors in hypothalamus of brain.
3. Hypothalamus signals posterior pituitary to release ADH.
4. Blood carries ADH to kidneys.
5. ADH causes distal convoluted tubules and collecting ducts to increase water reabsorption by osmosis.
6. Urine becomes concentrated, and urine volume decreases.

Urea and Uric Acid Excretion

Urea is a by-product of amino acid catabolism. Consequently, its plasma concentration reflects the amount of protein in the diet. Urea enters the renal tubule by filtration. About 50% of it is reabsorbed, and the remainder is excreted in urine.

Uric acid is a product of the metabolism of certain organic bases in nucleic acids. Active transport reabsorbs all the uric acid normally present in glomerular filtrate, but a small amount is secreted into the renal tubule and is excreted in urine.

Elevated concentrations of uric acid in the plasma cause *gout*. Because uric acid is relatively insoluble, it precipitates when in excess. In gout, crystals of uric acid are deposited in joints and other tissues, causing inflammation and extreme pain. The joints of the great toes are most often affected, but other hand and foot joints may also be involved. Drugs that inhibit uric acid reabsorption, thus increasing its excretion, are used to treat gout. People once thought gluttony caused gout, but the condition may be inherited.

CHECK YOUR RECALL

1. How does the hypothalamus regulate urine concentration and volume?
2. Explain how urea and uric acid are excreted.

Table 17.3 summarizes some specific functions of the nephron segments and the collecting duct.

Urine Composition

Urine composition reflects the amounts of water and solutes that the kidneys must eliminate from the body or retain in the internal environment to maintain homeostasis. The composition differs considerably from time to time because of variations in dietary intake and physical activity. Urine is about 95% water, and usually contains urea and uric acid. It may also contain a trace of amino acids and a variety of electrolytes, whose concentrations vary directly with amounts in the diet (see table 17.1).

The volume of urine produced is usually between 0.6 and 2.5 liters per day, depending on fluid intake, environmental temperature, relative humidity of the surrounding air, and the person's emotional condition, respiratory rate, and body temperature. Urine output of 50–60 milliliters per hour is normal; output of less than 30 milliliters per hour may indicate kidney failure.

Glucose, proteins, hemoglobin, ketones, and blood cells are not normally in urine, but circumstances may explain their presence. Glucose in urine may follow a large intake of carbohydrates, proteins may appear following vigorous physical exercise, and ketones may appear after a prolonged fast. Pregnant women may have glucose in their urine as birth nears.

CHECK YOUR RECALL

1. List the normal constituents of urine.
2. What factors affect urine volume?

TABLE 17.3 FUNCTIONS OF NEPHRON COMPONENTS

PART	FUNCTION
RENAL CORPUSCLE	
Glomerulus	Filtration of water and dissolved substances from plasma
Glomerular capsule	Receives glomerular filtrate
RENAL TUBULE	
Proximal convoluted tubule	Reabsorption of glucose; amino acids; creatine; lactic, uric, citric, and ascorbic acids; phosphate, sulfate, calcium, potassium, and sodium ions by active transport Reabsorption of water by osmosis Reabsorption of chloride ions and other negatively charged ions by electrochemical attraction Active secretion of substances such as penicillin, histamine, creatinine, and hydrogen ions
Descending limb of nephron loop	Reabsorption of water by osmosis
Ascending limb of nephron loop	Reabsorption of sodium, potassium, and chloride ions by active transport
Distal convoluted tubule	Reabsorption of sodium ions by active transport Reabsorption of water by osmosis Secretion of hydrogen and potassium ions both actively and passively by electrochemical attraction
Collecting duct	Reabsorption of water by osmosis

Note: Although the collecting duct is not anatomically part of the nephron, it is included here because of its functional importance.

17.4 Urine Elimination

After urine forms in the nephrons, it passes from the collecting ducts through openings in the renal papillae and enters the calyces of the kidney (see fig. 17.2). From there, it passes through the renal pelvis, and a ureter conveys it to the urinary bladder (see fig. 17.1 and reference plate 6, p. 28). The urethra excretes urine to the outside.

Ureters

Each **ureter** is a tube about 25 centimeters long that begins as the funnel-shaped renal pelvis. It extends downward behind the parietal peritoneum and runs parallel to the vertebral column. Within the pelvic cavity, each ureter courses forward and medially, joining the urinary bladder from underneath.

The ureter wall has three layers. The inner layer, or *mucous coat,* is continuous with the linings of the renal tubules and the urinary bladder. The middle layer, or *muscular coat,* consists largely of smooth muscle fibers. The outer layer, or *fibrous coat,* is connective tissue (fig. 17.15).

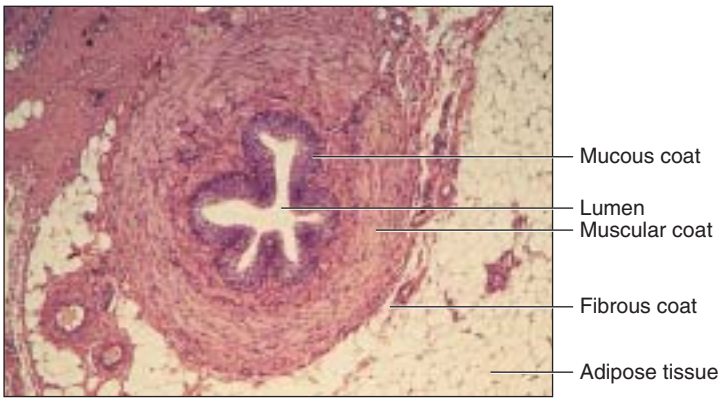


Figure 17.15
Cross section of a ureter (75×).

The muscular walls of the ureters propel the urine. Muscular peristaltic waves, originating in the renal pelvis, force urine along the length of the ureter. When a peristaltic wave reaches the urinary bladder, a jet of urine spurts into the bladder. A flaplike fold of mucous membrane covers the opening through which urine enters the bladder. This fold acts as a valve, allowing

Topic of Interest KIDNEY STONES

Kidney stones, which are usually composed of uric acid, calcium oxalate, calcium phosphate, or magnesium phosphate, can form in the collecting ducts and renal pelvis (fig. 17A). Such a stone passing into a ureter causes sudden, severe pain that begins in the region of the kidney and radiates into the abdomen, pelvis, and lower limbs. It may also cause nausea and vomiting, and blood in the urine

About 60% of kidney stones pass from the body on their own. Other stones were once removed surgically but are now shattered with intense sound waves. In this procedure, called *extracorporeal shock-wave lithotripsy* (*ESWL*), the patient is placed in a stainless steel tub filled with water. A spark-gap electrode produces shock waves underwater, and a reflector concentrates and focuses the shock-wave energy on the stones. The resulting sandlike fragments then leave in urine.

The tendency to form kidney stones is inherited, particularly the stones that contain calcium, which account for more than half of all cases. Eating calcium-rich foods does not increase the risk, but taking calcium supplements can. People who have calcium oxalate stones can reduce the risk of recurrence by avoiding specific foods: chocolate, coffee, wheat bran, cola, strawberries, spinach, nuts and tea. Other causes of kidney stones include excess vitamin D, blockage of the urinary tract, or a complication of a urinary tract infection.

It is very helpful for a physician to analyze the composition of the stones, because certain drugs can prevent recurrence. Stones can be obtained during surgery or by the person, using a special collection device. The best advice to steer clear of kidney stones, however, is simple: drink a lot of water.

Figure 17A
Although small compared to this fingertip, this kidney stone is sufficiently large to cause severe pain.

urine to enter the bladder from the ureter but preventing it from backing up.

CHECK YOUR RECALL

1. Describe the structure of a ureter.
2. How is urine moved from the renal pelvis to the urinary bladder?
3. What prevents urine from backing up from the urinary bladder into the ureters?

Urinary Bladder

The **urinary bladder** is a hollow, distensible, muscular organ that stores urine and forces it into the urethra (see fig. 17.1 and reference plate 6, p. 28). It is within the pelvic cavity, behind the symphysis pubis and beneath the parietal peritoneum.

The pressure of surrounding organs alters the shape of the somewhat spherical bladder. When empty, the inner wall of the bladder forms many folds, but as the bladder fills with urine, the wall becomes smoother. At the same time, the superior surface of the bladder expands upward into a dome.

The internal floor of the bladder includes a triangular area called the *trigone,* which has an opening at each of its three angles (fig. 17.16*a*). Posteriorly, at the base of the trigone, the openings are those of the ureters. Anteriorly, at the apex of the trigone, a short, funnel-shaped extension, called the *neck* of the bladder, contains the opening into the urethra.

The wall of the urinary bladder has four layers. The inner layer, or *mucous coat,* includes several thicknesses of transitional epithelial cells. The thickness of this tissue changes as the bladder expands and contracts. Thus, during distension, the tissue may be only two or three cells thick; during contraction, it may be five or six cells thick (see chapter 5, p. 95).

The second layer of the bladder wall is the *submucous coat.* It consists of connective tissue and contains many elastic fibers. The third layer of the bladder wall, or *muscular coat,* is composed primarily of coarse bundles of smooth muscle fibers. These bundles are interlaced in all directions and at all depths, and together they comprise the **detrusor muscle** (detruz´or mus´l). The portion of the detrusor muscle that surrounds the neck of the bladder forms an *internal urethral sphincter.* Sustained contraction of this muscle prevents the bladder from emptying until pressure within the bladder increases to a certain level. The detrusor muscle is innervated with parasympathetic nerve fibers that function in the micturition reflex, discussed next.

The outer layer of the bladder wall, or *serous coat,* consists of the parietal peritoneum. This layer is only on the bladder's upper surface. Elsewhere, the outer coat is composed of connective tissue.

Because the linings of the ureters and the urinary bladder are continuous, infectious agents, such as bacteria, may ascend from the urinary bladder into the ureters. Inflammation of the urinary bladder, called *cystitis,* is more common in women than in men because the female urethral pathway is shorter. Inflammation of the ureter is called *ureteritis.*

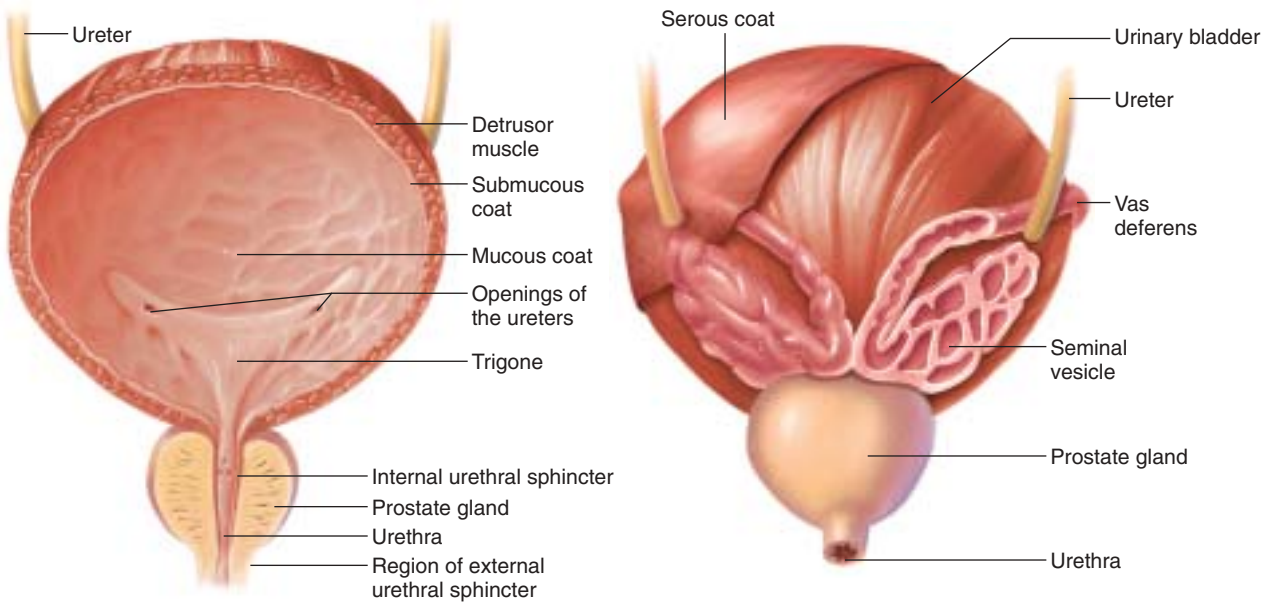


Figure 17.16
A male urinary bladder. (*a*) Longitudinal section. (*b*) Posterior view.

CHECK YOUR RECALL

1. Describe the trigone of the urinary bladder.
2. Describe the structure of the bladder wall.
3. What kind of nerve fibers supply the detrusor muscle?

Micturition

Micturition (mik´´tu-rish´un), or urination, is the process that expels urine from the urinary bladder. In micturition, the detrusor muscle contracts, as do muscles in the abdominal wall and pelvic floor. At the same time, muscles in the thoracic wall and diaphragm do not contract. Micturition also requires relaxation of the *external urethral sphincter.* This muscle, which is part of the urogenital diaphragm described in chapter 8 (pp. 191–193), surrounds the urethra about 3 centimeters from the bladder and is composed of voluntary skeletal muscle tissue.

Distension of the bladder wall as it fills with urine stimulates stretch receptors, triggering the micturition reflex. The *micturition reflex center* is in the spinal cord. When sensory impulses from the stretch receptors signal the reflex center, parasympathetic motor impulses travel to the detrusor muscle, which contracts rhythmically in response. A sensation of urgency accompanies this action.

The urinary bladder may hold as much as 600 milliliters of urine before stimulating pain receptors, but the urge to urinate usually begins when it contains about 150 milliliters. As urine volume increases to 300 milliliters or more, the sensation of fullness intensifies, and contractions of the bladder wall become more powerful. When these contractions are strong enough to force the internal urethral sphincter open, another reflex signals the external urethral sphincter to relax, and the bladder can empty.

Because the external urethral sphincter is composed of skeletal muscle, it is under conscious control, and is typically contracted until a person decides to urinate. Nerve centers in the brainstem and cerebral cortex that can partially inhibit the micturition reflex aid this control. When a person decides to urinate, the external urethral sphincter relaxes, and the micturition reflex is no longer inhibited. Nerve centers within the pons and the hypothalamus of the brain heighten the micturition reflex. Then the detrusor muscle contracts, and urine is excreted through the urethra. Within a few moments, the neurons of the micturition reflex fatigue, the detrusor muscle relaxes, and the bladder begins to fill with urine again.

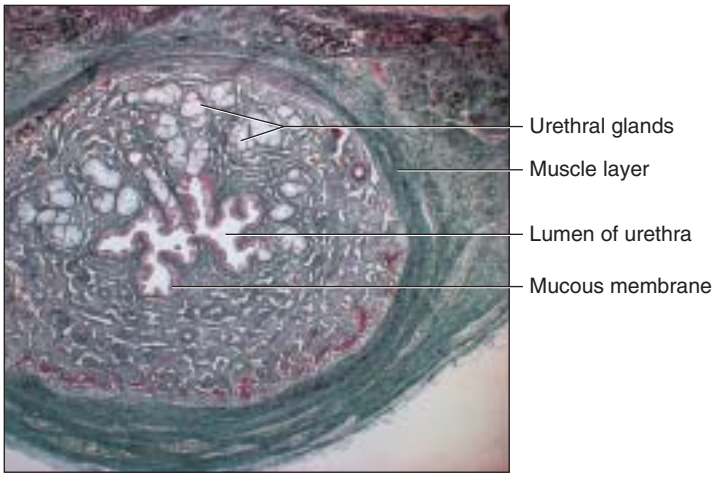


Figure 17.17
Cross section through the urethra (10×).

Damage to the spinal cord above the sacral region destroys voluntary control of urination. However, if the micturition reflex center and its sensory and motor fibers are uninjured, micturition may continue to occur reflexly. In this case, the bladder collects urine until its walls stretch enough to trigger a micturition reflex, and the detrusor muscle contracts in response. This condition is called an *automatic bladder.*

Urethra

The **urethra** is a tube that conveys urine from the urinary bladder to the outside (see fig. 17.1 and reference plate 7, p. 29). Its wall is lined with mucous membrane and contains a thick layer of smooth muscle tissue, whose fibers are generally directed longitudinally. The urethral wall also contains numerous mucous glands, called *urethral glands,* which secrete mucus into the urethral canal (fig. 17.17).

CHECK YOUR RECALL

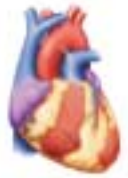
1. Describe micturition.
2. How is it possible to consciously inhibit the micturition reflex?
3. Describe the structure of the urethra.

URINARY SYSTEM

Integumentary System

The urinary system compensates for water loss due to sweating. The kidneys and skin both play a role in vitamin D production.

Cardiovascular System



The urinary system controls blood volume. Blood volume and blood pressure play a role in determining water and solute excretion.

Skeletal System

The kidneys and bone tissue work together to control plasma calcium levels.

Lymphatic System

The kidneys control extracellular fluid volume and composition (including lymph).

Muscular System

Muscle tissue controls urine elimination from the bladder.

Digestive System

The kidneys compensate for fluids lost by the digestive system.

Nervous System

The nervous system influences urine production and elimination.

Respiratory System

The kidneys and the lungs work together to control the pH of the internal environment.

Endocrine System

The endocrine system influences urine production.

Reproductive System

The urinary system in males shares organs with the reproductive system. The kidneys compensate for fluids lost from the male and female reproductive systems.

The urinary system controls the composition of the internal environment.

Clinical Terms Related to the Urinary System

anuria (ah-nu´re-ah) Absence of urine due to failure of kidney function or to an obstruction in a urinary pathway.
bacteriuria (bak-te´´re-u´re-ah) Bacteria in urine.
cystectomy (sis-tek´to-me) Surgical removal of the urinary bladder.
cystitis (sis-ti´tis) Inflammation of the urinary bladder.
cystoscope (sis´to-skōp) Instrument used to visually examine the interior of the urinary bladder.
cystotomy (sis-tot´o-me) Incision of the urinary bladder wall.
diuresis (di´´u-re´sis) Increased urine excretion.
diuretic (di´´u-ret´ik) Substance that increases urine production.
dysuria (dis-u´re-ah) Painful or difficult urination.
hematuria (hem´´ah-tu´re-ah) Blood in urine.
incontinence (in-kon´ti-nens) Inability to control urination and/or defecation reflexes.
nephrectomy (nĕ-frek´to-me) Surgical removal of a kidney.
nephrolithiasis (nef´´ro-lĭ-thi´ah-sis) Kidney stones.
nephroptosis (nef´´rop-to´sis) Movable or displaced kidney.
oliguria (ol´´ĭ-gu´re-ah) Scanty urine output.
polyuria (pol´´ĕ-u´re-ah) Excessive urine output.
pyelolithotomy (pi´´ĕ-lo-lĭ-thot´o-me) Removal of a stone from the renal pelvis.
pyelonephritis (pi´´ĕ-lo-ne-fri´tis) Inflammation of the renal pelvis.
pyelotomy (pi´´ĕ-lot´o-me) Incision into the renal pelvis.
pyuria (pi-u´re-ah) Pus (white blood cells) in urine.
uremia (u-re´me-ah) Accumulation in blood of substances ordinarily excreted in urine.
ureteritis (u-re´´ter-i´tis) Inflammation of the ureter.
urethritis (u´´re-thri´tis) Inflammation of the urethra.

Clinical Connection

A twenty-five-year-old man arrived at the hospital in acute renal failure following three days of malaise. He claimed to have taken only cough medicine, and then slept thirty-six hours. A urinalysis revealed blood and protein, but it was the renal biopsy that alarmed the emergency room physician—the kidney tubules were damaged, with telltale crystals of calcium oxalate obstructing their lumens. The physician knew that these crystals result from drinking ethylene glycol, a component of antifreeze, but the patient denied such activity. He was sent home and continued to undergo hemodialysis as an outpatient. A week later, he returned with new symptoms—seizures and other signs of neurological impairment. Over the next two months, with aggressive treatment, his kidney function returned to normal. It was then that he admitted to having drunk the colorless, odorless, sweet-tasting antifreeze, in a suicide attempt. Because the dose that he took was not large enough to damage his kidneys to the extent seen, physicians suspected that an ingredient in the cough medicine increased the toxicity of the antifreeze.

SUMMARY OUTLINE

17.1 Introduction (p. 454)

The urinary system consists of the kidneys, ureters, urinary bladder, and urethra.

17.2 Kidneys (p. 454)

1. Location of the kidneys
   a. The kidneys are high on the posterior wall of the abdominal cavity.
   b. They are behind the parietal peritoneum.
2. Kidney structure
   a. A kidney contains a hollow renal sinus.
   b. The ureter expands into the renal pelvis.
   c. Renal papillae project into the renal sinus.
   d. Each kidney divides into a medulla and a cortex.
3. Kidney functions
   a. The kidneys maintain homeostasis by removing metabolic wastes from blood and excreting them.
   b. They also help regulate red blood cell production; blood volume and blood pressure; and the volume, composition, and pH of body fluids.
4. Renal blood vessels
   a. Arterial blood flows through the renal artery, interlobar arteries, arcuate arteries, interlobular arteries, afferent arterioles, glomerular capillaries, efferent arterioles, and peritubular capillaries.
   b. Venous blood returns through a series of vessels that correspond to the arterial pathways.
5. Nephrons
   a. Nephron structure
      (1) A nephron is the functional unit of the kidney.
      (2) It consists of a renal corpuscle and a renal tubule.
         (a) The corpuscle consists of a glomerulus and a glomerular capsule.
         (b) Segments of the renal tubule include the proximal convoluted tubule, nephron loop (ascending and descending limbs), and distal convoluted tubule, which empties into a collecting duct.
      (3) The collecting duct empties into the minor calyx of the renal pelvis.
   b. Blood supply of a nephron
      (1) The glomerular capillary receives blood from the afferent arteriole and passes it to the efferent arteriole.
      (2) The efferent arteriole gives rise to the peritubular capillary system, which surrounds the renal tubule.

c. Juxtaglomerular apparatus
   (1) The juxtaglomerular apparatus is at the point of contact between the distal convoluted tubule and the afferent and efferent arterioles.
   (2) It consists of the macula densa and juxtaglomerular cells.

17.3 Urine Formation (p. 459)

Nephrons remove wastes from blood and regulate water and electrolyte concentrations. Urine is the end product.

1. Glomerular filtration
   a. Urine formation begins when water and dissolved materials filter out of glomerular capillaries.
   b. Glomerular capillaries are much more permeable than the capillaries in other tissues.
   c. The composition of the filtrate is similar to that of tissue fluid.
2. Filtration pressure
   a. Filtration is due mainly to hydrostatic pressure inside glomerular capillaries.
   b. The osmotic pressure of plasma and the hydrostatic pressure in the glomerular capsule also affect filtration.
   c. Filtration pressure is the net force moving material out of the glomerulus and into the glomerular capsule.
3. Filtration rate
   a. Rate of filtration varies with filtration pressure.
   b. Filtration pressure changes with the diameters of the afferent and efferent arterioles.
   c. As colloid osmotic pressure in the glomerulus increases, filtration rate decreases.
   d. As hydrostatic pressure in a glomerular capsule increases, filtration rate decreases.
   e. The kidneys produce about 125 milliliters of glomerular fluid per minute, most of which is reabsorbed.
4. Regulation of filtration rate
   a. Glomerular filtration rate remains relatively constant, but may increase or decrease as required.
   b. Increased sympathetic nerve activity can decrease glomerular filtration rate.
   c. When the macula densa senses decreased amounts of chloride, potassium, and sodium ions in the distal tubule, it causes juxtaglomerular cells to release renin.
   d. This triggers a series of changes leading to vasoconstriction of afferent and efferent arterioles, which may affect glomerular filtration rate, and aldosterone secretion, which stimulates tubular sodium reabsorption.
5. Tubular reabsorption
   a. Substances are selectively reabsorbed from glomerular filtrate.
   b. The peritubular capillary's permeability adapts it for reabsorption.
   c. Most reabsorption occurs in the proximal tubule, where epithelial cells have microvilli.
   d. Different modes of transport reabsorb various substances in particular segments of the renal tubule.
      (1) Active transport reabsorbs glucose and amino acids.
      (2) Osmosis reabsorbs water.
   e. Active transport mechanisms have limited transport capacities.
6. Sodium and water reabsorption
   a. Substances that remain in the filtrate are concentrated as water is reabsorbed.
   b. Active transport reabsorbs sodium ions.
   c. As positively charged sodium ions move out of the filtrate, negatively charged ions follow them.
   d. Water is passively reabsorbed by osmosis.
7. Tubular secretion
   a. Secretion transports substances from plasma to the tubular fluid.
   b. Various organic compounds are secreted actively.
   c. Potassium and hydrogen ions are secreted both actively and passively.
8. Regulation of urine concentration and volume
   a. Most sodium is reabsorbed before urine is excreted.
   b. Antidiuretic hormone increases the permeability of the distal convoluted tubule and collecting duct, promoting water reabsorption.
9. Urea and uric acid excretion
   a. Diffusion passively reabsorbs urea. About 50% of the urea is excreted in urine.
   b. Active transport reabsorbs uric acid. Some uric acid is secreted into the renal tubule.
10. Urine composition
    a. Urine is about 95% water, and it also usually contains urea and uric acid.
    b. Urine contains varying amounts of electrolytes and may contain a trace of amino acids.
    c. Urine volume varies with fluid intake and with certain environmental factors.

17.4 Urine Elimination (p. 467)

1. Ureters
   a. The ureter extends from the kidney to the urinary bladder.
   b. Peristaltic waves in the ureter force urine to the urinary bladder.
2. Urinary bladder
   a. The urinary bladder stores urine and forces it through the urethra during micturition.
   b. The openings for the ureters and urethra are at the three angles of the trigone.
   c. A portion of the detrusor muscle forms an internal urethral sphincter.
3. Micturition
   a. Micturition expels urine.
   b. Micturition contracts the detrusor muscle and relaxes the external urethral sphincter.
   c. Micturition reflex
      (1) Distension stimulates stretch receptors in the bladder wall.
      (2) The micturition reflex center in the spinal cord sends parasympathetic motor impulses to the detrusor muscle.
      (3) As the bladder fills, its internal pressure increases, forcing the internal urethral sphincter open.
      (4) A second reflex relaxes the external urethral sphincter unless voluntary control maintains its contraction.
      (5) Nerve centers in the cerebral cortex and brainstem aid control of urination.
4. Urethra
   The urethra conveys urine from the urinary bladder to the outside.

REVIEW EXERCISES

1. Name and list the general functions of the organs of the urinary system. (p. 454)
2. Describe the external and internal structure of a kidney. (p. 454)
3. List the functions of the kidneys. (p. 454)
4. Name the vessels through which blood passes as it travels from the renal artery to the renal vein. (p. 455)

5. Distinguish between a renal corpuscle and a renal tubule. (p. 455)
6. Name the parts through which fluid passes from the glomerulus to the collecting duct. (p. 455)
7. Describe the location and structure of the juxtaglomerular apparatus. (p. 458)
8. Define *filtration pressure*. (p. 460)
9. Compare the composition of glomerular filtrate with that of blood plasma. (p. 460)
10. Explain how the diameters of the afferent and efferent arterioles affect the rate of glomerular filtration. (p. 461)
11. Explain how changes in the osmotic pressure of blood plasma affect the glomerular filtration rate. (p. 461)
12. Explain how the hydrostatic pressure of a glomerular capsule affects the rate of glomerular filtration. (p. 461)
13. Describe two mechanisms by which the body regulates filtration rate. (p. 461)
14. Discuss how tubular reabsorption is selective. (p. 462)
15. Explain how the peritubular capillary is adapted for reabsorption. (p. 462)
16. Explain how epithelial cells of the proximal convoluted tubule are adapted for reabsorption. (p. 462)
17. Explain why active transport mechanisms have limited transport capacities. (p. 463)
18. Define *renal plasma threshold*. (p. 463)
19. Explain how amino acids and proteins are reabsorbed. (p. 463)
20. Describe the effect of sodium reabsorption on the reabsorption of negatively charged ions. (p. 464)
21. Explain how sodium reabsorption affects water reabsorption. (p. 464)
22. Explain how potassium ions may be secreted passively. (p. 464)
23. Describe the function of ADH. (p. 465)
24. Compare the processes that reabsorb urea and uric acid. (p. 466)
25. List the common constituents of urine and their sources. (p. 466)
26. List some of the factors that affect the urine volume produced daily. (p. 466)
27. Describe the structure and function of a ureter. (p. 467)
28. Explain how the muscular wall of the ureter helps move urine. (p. 467)
29. Describe the structure and location of the urinary bladder. (p. 468)
30. Define *detrusor muscle*. (p. 468)
31. Distinguish between the internal and external urethral sphincters. (p. 468)
32. Describe the micturition reflex. (p. 469)
33. Explain how the micturition reflex can be voluntarily controlled. (p. 469)

CRITICAL THINKING

1. Imagine you are adrift at sea. Why will you dehydrate more quickly if you drink seawater instead of fresh water to quench your thirst?
2. Why do urinary tract infections frequently accompany sexually transmitted diseases?
3. Would an excess or a deficiency of renin be likely to cause hypertension (high blood pressure)? Cite a reason for your answer.
4. Why may protein in the urine be a sign of kidney damage? What structures in the kidney are probably affected?
5. Why are people following high-protein diets advised to drink large quantities of water?
6. How might very low blood pressure impair kidney function?
7. An infant is born with narrowed renal arteries. What effect will this condition have on urine volume?
8. If a patient who has had major abdominal surgery receives intravenous fluids equal to the blood volume lost during surgery, would you expect urine volume to be greater or less than normal? Why?
9. If blood pressure plummets in a patient in shock as a result of a severe injury, how would you expect urine volume to change? Why?

WEB CONNECTIONS

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