Urination and the Nervous System

When the urinary bladder fills with urine to about 250 ml, stretch receptors send sensory nerve impulses to the spinal cord. Subsequently, motor nerve impulses from the spinal cord cause the urinary bladder to contract and the sphincters to relax so that urination is possible. In older children and adults, the brain controls this reflex, delaying urination until a suitable time (Fig. 16.2).

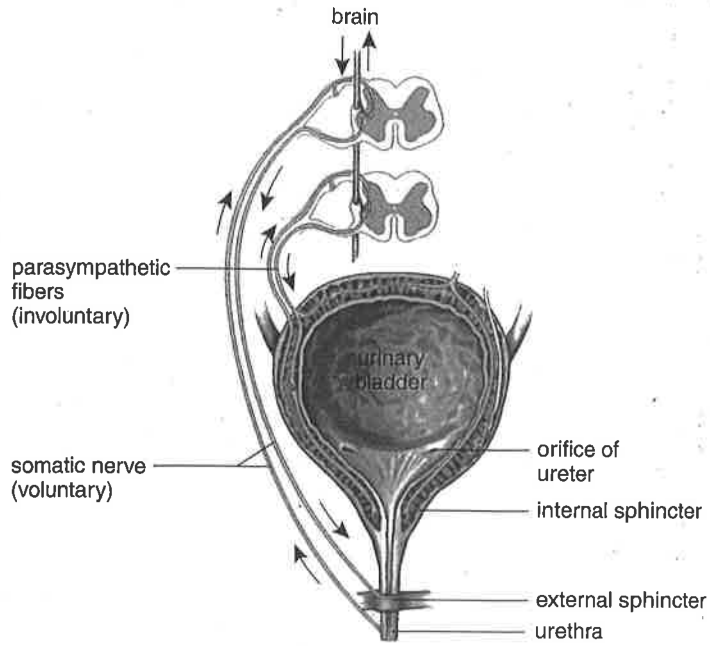

Figure 16.2 Urination.
As the bladder fills with urine, sensory impulses go to the spinal cord and then the brain. The brain can override the urge to urinate. When urination occurs, motor nerve impulses cause the bladder to contract and an internal sphincter to open. Nerve impulses also cause an external sphincter to open.

> Only the urinary system, consisting of the kidneys, the urinary bladder, the ureters, and the urethra, holds urine.

Functions of the Urinary System

The primary functions of the urinary system are carried out by the kidneys. The kidneys are organs of excretion. **Excretion** is the removal of metabolic wastes from the body. The kidneys also maintain the water-salt balance and the acid-base balance of the body. In addition, they have a hormonal function.

Metabolic Wastes

The kidneys are the primary organs for excretion of nitrogenous wastes including urea, creatinine, and uric acid.

Urea is the nitrogenous end product of amino acid metabolism. The breakdown of amino acids in the liver releases ammonia, which the liver combines with carbon dioxide to produce urea. Ammonia is very toxic to cells and urea is much less toxic. Urea is the primary nitrogenous end product of human beings.

Two other nitrogenous end products are excreted by the kidneys. **Creatinine** is the end product of creatine phosphate metabolism. Creatine phosphate is a high-energy phosphate reserve molecule in muscles. The breakdown of nucleotides produces **uric acid,** which is rather insoluble. If too much uric acid is present in blood, it precipitates out. Crystals of uric acid sometimes collect in the joints, producing a painful ailment called gout.

Water-Salt Balance

A principal function of the kidneys is to maintain the appropriate water-salt balance of the body. As we shall see, blood volume is intimately associated with the salt balance of the body. As you know, salts, such as NaCl, have the ability to cause osmosis, the diffusion of water—in this case into the blood. The more salts there are in the blood, the greater the blood volume and the greater the blood pressure. Therefore, the kidneys are also involved in regulating blood pressure.

The kidneys maintain the appropriate level of other ions such as potassium ions (K^+), bicarbonate ions (HCO_3^-), and calcium ions (Ca^{2+}) in the blood.

Acid-Base Balance

The kidneys also regulate the blood acid-base balance. In order for us to remain healthy, the blood pH should be just about 7.4. The kidneys monitor and control blood pH, mainly by excreting hydrogen ions (H^+) and reabsorbing bicarbonate ion (HCO_3^-) as needed. Urine usually has a pH of 6 or lower.

Hormonal Function

The kidneys assist the endocrine system. They secrete the hormone **erythropoietin,** which stimulates red blood cell production. They also modify a precursor molecule from the skin so that it becomes active vitamin D (calcitriol). Vitamin D promotes calcium (Ca^{2+}) reabsorption from the digestive tract.

The kidneys also secrete renin, a substance involved in the secretion of aldosterone from the adrenal cortex. Aldosterone causes the reabsorption of sodium ions (Na^+).

> The kidneys are major organs of homeostasis because they excrete nitrogenous wastes. They also regulate the water-salt balance and the acid-base balance of the blood.

A helicopter lands on the roof of the hospital. Paramedics rush an insulated container from the aircraft to an operating room a few stories below. Brushing aside the ice in the container, a surgeon plucks out a fist-sized reddish mass, a kidney. Within hours, the organ, which has replaced the diseased kidneys inside a young girl's body, is busy producing urine. The transplanted organ, if not rejected, should save the girl from a difficult life of being periodically hooked up to dialysis machines. Rejection is unlikely because it has already been determined that the tissues of the donor are very compatible with those of the recipient.

A kidney is absolutely essential for a healthy life because it helps regulate the pH and the water-salt balance of blood, and it excretes nitrogenous wastes. By regulating the amount of salt and water in the blood, a kidney helps keep blood pressure within a normal range. By excreting nitrogenous wastes, it rids the body of toxic substances. One kidney alone is all we need, and therefore the donor of a kidney will suffer no ill consequences except the trauma of abdominal surgery. This chapter will detail exactly how a kidney performs its life-preserving functions.

16.1 Urinary System

The urinary system includes the kidneys and associated structures, which are illustrated in Figure 16.1. The kidneys produce urine, which passes by way of the ureters to the bladder where it is stored. The urethra carries urine to outside the body.

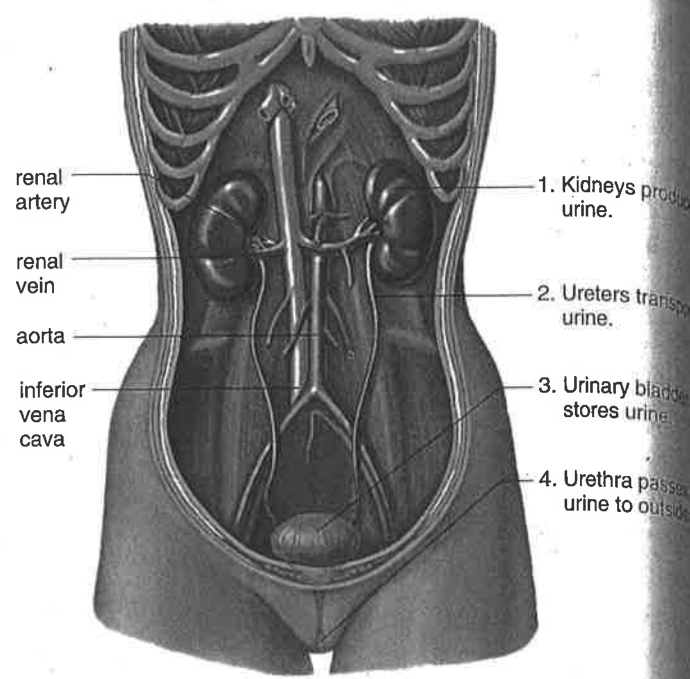

Figure 16.1 The urinary system.
Urine is found only within the kidneys, the ureters, the urinary bladder, and the urethra.

The Urinary Organs

The kidneys are found on either side of the vertebral column, just below the diaphragm. They lie in depressions against the deep muscles of the back beneath the peritoneum, the lining of the abdominal cavity, where they also receive some protection from the lower rib cage. But the kidneys can be damaged by blows on the back—kidney punches are not allowed in boxing. Each kidney is usually held in place by connective tissue, called renal fascia. A sharp blow to the back can dislodge a kidney, which is then called a floating kidney.

The **kidneys** are bean-shaped, reddish brown organs, each about the size of a fist, which produce urine. They are covered by a tough capsule of fibrous connective tissue overlaid by adipose tissue. A depression (the hilum) on the concave side is where the **renal artery** enters and the **renal vein** and ureters exit.

The **ureters**, and indeed the entire urinary tract are lined by a mucosa. The ureters are tubes about 25 cm long that convey the urine from the kidneys toward the bladder by peristalsis. Urine enters the bladder by peristaltic contractions, in jets that occur at the rate of five per minute.

The **urinary bladder**, which can hold up to 600 ml of urine, is a hollow, muscular organ that gradually expands as urine enters. The wall of the bladder consists of connective tissue and smooth muscle. The bladder's outer serosa is continuous with the parietal peritoneum. (You get the urge to void when the bladder fills to about 250 milliliters, and you become uncomfortable at about 500 milliliters. When the bladder becomes overdistended, you may lose the urge to void.)

The **urethra** extends from the urinary bladder to an external opening called the external urethral orifice. The internal urethral sphincter occurs where the urethra leaves the bladder, and an external urethral sphincter is located where the urethra exits the pelvic cavity.

The urethra differs in length in the female and the male. In the female, the urethra is only about 4 cm long. The short length of the female urethra makes bacterial invasion easier and explains why females are more prone to urinary tract infections than males. In the male, the urethra averages 20 cm when the penis is flaccid (limp, nonerect). As the urethra leaves the male urinary bladder, it is encircled by the prostate gland. In older men, enlargement of the prostate gland can restrict urination, a condition that usually can be corrected surgically.

There is no connection between the genital (reproductive) and urinary systems in females; there is a connection in males because the urethra also carries sperm during ejaculation. This double function does not alter the path of urine, and it is important to realize that urine is found only in the structures noted in Figure 16.2.

16.2 The Kidneys

When a kidney is sliced lengthwise, it is possible to see the many branches of the renal artery and vein that reach inside the kidney (Fig. 16.3*a*). If the blood vessels are removed, it is easier to identify three regions of a kidney. The **renal cortex** is an outer granulated layer that dips down in between a radially striated, or lined, inner layer called the renal medulla. The **renal medulla** consists of cone-shaped tissue masses called renal pyramids. The **renal pelvis** is a central space, or cavity, that is continuous with the ureter (Fig. 16.3*b*).

Microscopically, the kidney is composed of over one million **nephrons,** sometimes called renal or kidney tubules (Fig. 16.3*c*). The nephrons produce urine and are positioned so that the urine flows into a collecting duct. Several nephrons enter the same collecting duct; the collecting ducts enter the renal pelvis.

Macroscopically, a kidney has three regions: renal cortex, renal medulla, and a renal pelvis that is continuous with the ureter. Microscopically, a kidney contains over one million nephrons.

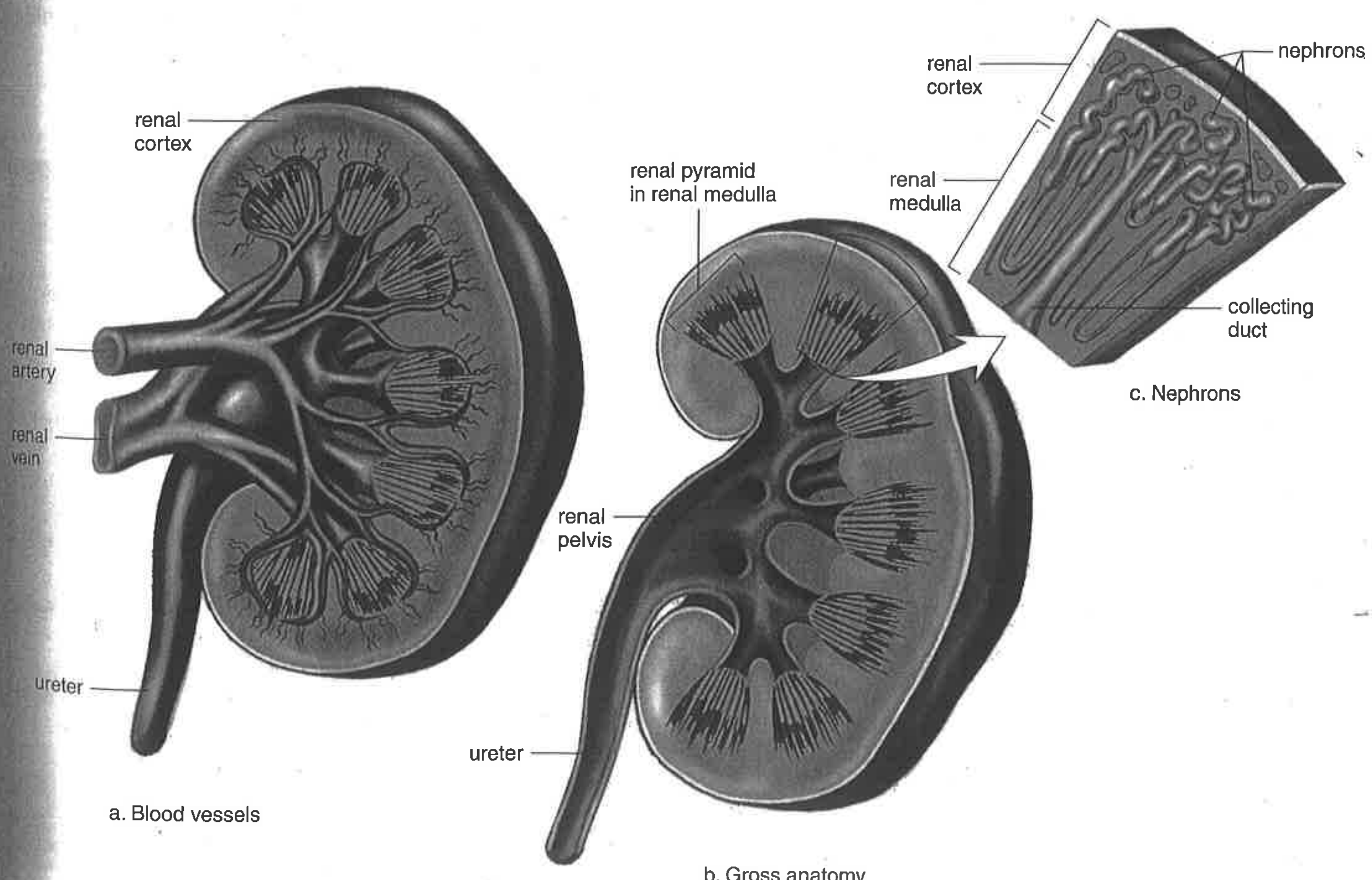

Figure 16.3 Gross anatomy of the kidney.
a. A longitudinal section of the kidney showing the blood supply. Note that the renal artery divides into smaller arteries, and these divide into arterioles. Venules join to form small veins, which join to form the renal vein. **b.** The same section without the blood supply. Now it is easier to distinguish the renal cortex, the renal medulla, and the renal pelvis, which connects with a ureter. The renal medulla consists of the renal pyramids. **c.** An enlargement showing the placement of nephrons.

Anatomy of a Nephron

Each nephron has its own blood supply, including two capillary regions (Fig 16.4). From the renal artery, an afferent arteriole leads to the **glomerulus,** a knot of capillaries inside the glomerular capsule. Blood leaving the glomerulus enters the efferent arteriole and then the **peritubular capillary network,** which surrounds the rest of the nephron. From there the blood goes into a venule that joins the renal vein.

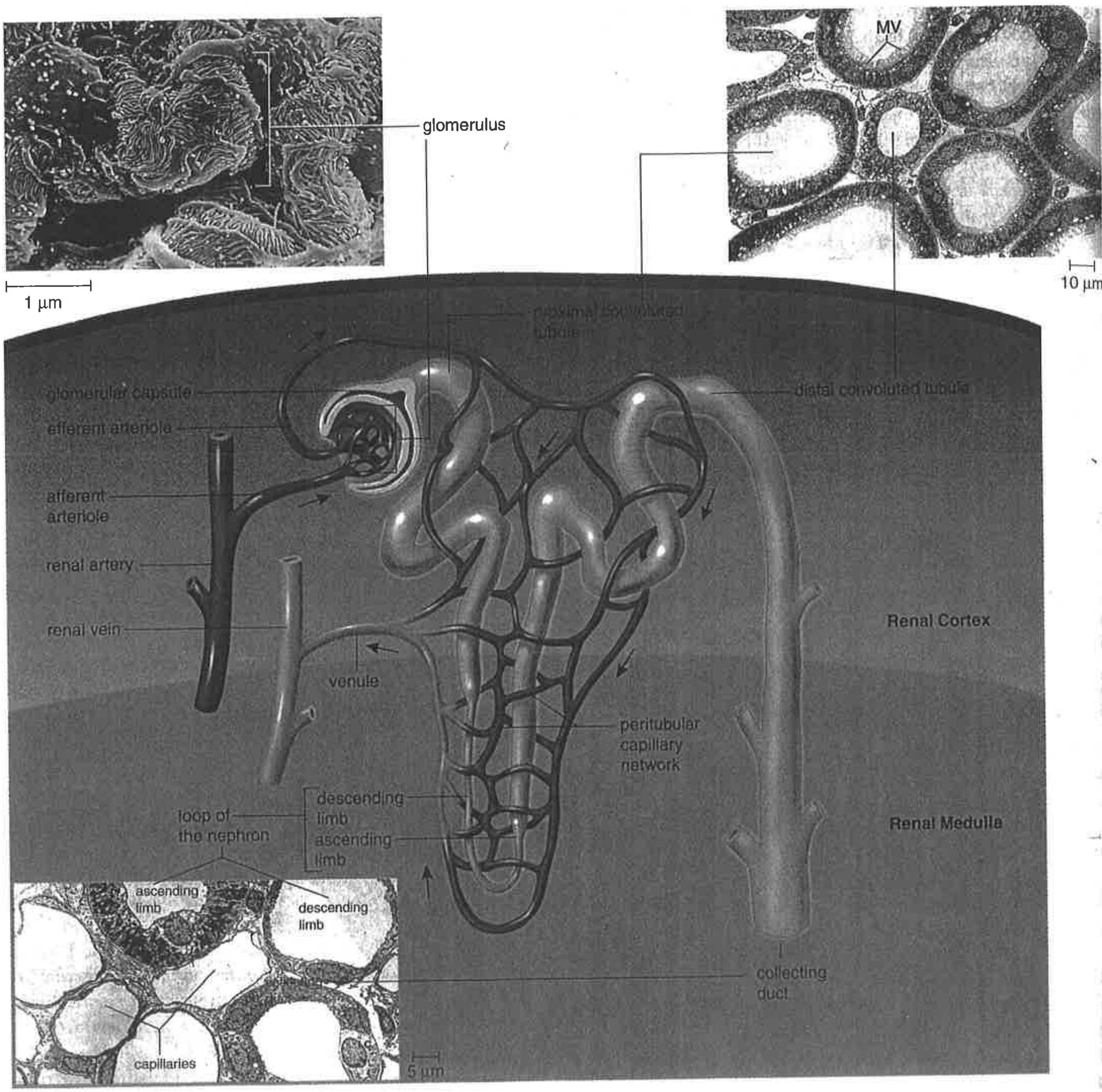

Figure 16.4 Nephron anatomy.
A nephron is made up of a glomerular capsule, the proximal convoluted tubule, the loop of the nephron, the distal convoluted tubule, and the collecting duct. The micrographs show these structures in cross section; MV = microvilli. You can trace the path of blood about the nephron by following the arrows.

Parts of a Nephron

Each nephron is made up of several parts (Fig. 16.4). The structure of each part suits its function.

First, the closed end of the nephron is pushed in on itself to form a cuplike structure called the **glomerular capsule** (Bowman's capsule). The outer layer of the glomerular capsule is composed of squamous epithelial cells; the inner layer is made up of **podocytes** that have long cytoplasmic processes. The podocytes cling to the capillary walls of the glomerulus and leave pores that allow easy passage of small molecules from the glomerulus to the inside of the glomerular capsule. This process, called *glomerular filtration*, produces a filtrate of blood.

Next, there is a **proximal** (meaning near the glomerular capsule) **convoluted tubule.** The cuboidal epithelial cells lining this part of the nephron have numerous microvilli, about 1 μm in length, that are tightly packed and form a brush border (Fig. 16.5). A brush border greatly increases the surface area for the *tubular reabsorption* of filtrate components. Each cell also has many mitochondria, which can supply energy for active transport of molecules from the lumen to the peritubular capillary network.

Simple squamous epithelium appears as the tube narrows and makes a U-turn called the **loop of the nephron** (loop of Henle). Each loop consists of a descending limb that allows water to leave and an ascending limb that extrudes salt (NaCl). Indeed, as we shall see, this activity facilitates the reabsorption of water by the nephron and collecting duct.

The cells of the **distal convoluted tubule** have numerous mitochondria, but they lack microvilli. This is consistent with the active role they play in moving molecules from the blood into the tubule, a process called *tubular secretion.* The distal convoluted tubules of several nephrons enter one collecting duct. A kidney contains many collecting ducts, which carry urine to the renal pelvis.

As shown in Figure 16.4, the glomerular capsule and the convoluted tubules always lie within the renal cortex. The loop of the nephron dips down into the renal medulla; a few nephrons have a very long loop of the nephron, which penetrates deep into the renal medulla. **Collecting ducts** are also located in the renal medulla, and they give the renal pyramids their lined appearance.

Each part of a nephron is anatomically suited to its specific function in urine formation.

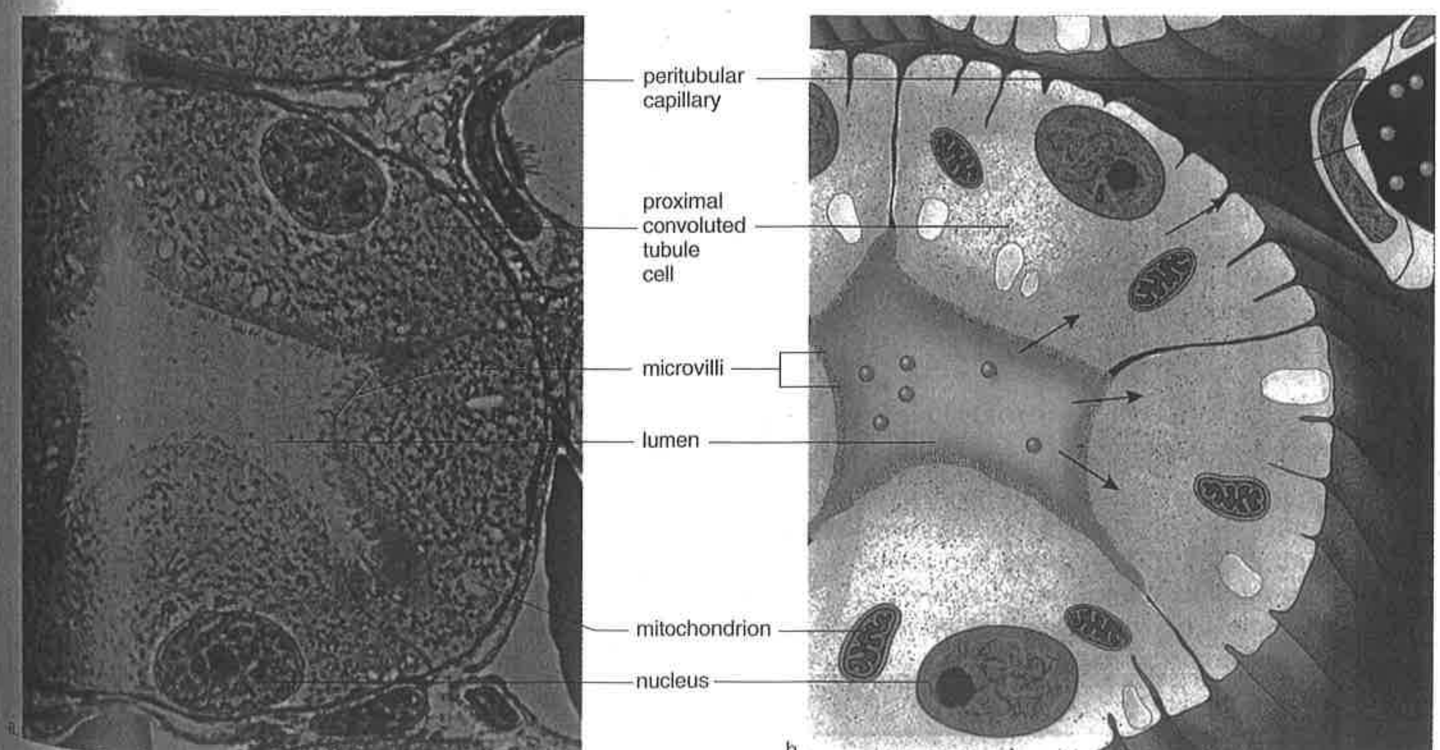

Figure 16.5 Proximal convoluted tubule.
a. This photomicrograph shows that the cells lining the proximal convoluted tubule have a brushlike border composed of microvilli, which greatly increases the surface area exposed to the lumen. The peritubular capillary network surrounds the cells. **b.** Diagrammatic representation of **(a)** shows that each cell has many mitochondria, which supply the energy needed for active transport, the process that moves molecules (green) from the lumen of the tubule to the capillary, as indicated by the arrows.

16.4 Maintaining Water-Salt Balance

The kidneys regulate the water-salt balance of the blood. In this way, they also maintain the blood volume and blood pressure. Most of the water and salt (NaCl) present in the filtrate is reabsorbed across the wall of the proximal convoluted tubule. Reabsorption also occurs along the remainder of the nephron.

Reabsorption of Water

The excretion of a hypertonic urine (one that is more concentrated than blood) is dependent upon the reabsorption of water from the loop of the nephron (loop of Henle) and the collecting duct.

A long loop of the nephron, which typically penetrates deep into the renal medulla, is made up of a *descending* (going down) *limb* and an *ascending* (going up) *limb*. Salt (NaCl) passively diffuses out of the lower portion of the ascending limb, but the upper, thick portion of the limb actively extrudes salt out into the tissue of the outer renal medulla (Fig. 16.7). Less and less salt is available for transport as fluid moves up the thick portion of the ascending limb. Because of these circumstances, the loop of the nephron establishes an *osmotic gradient* within the tissues of the renal medulla: the concentration of salt is greater in the direction of the inner medulla. (Note that water cannot leave the ascending limb because the limb is impermeable to water.)

Also, if you examine Figure 16.7 carefully, you can see that the innermost portion of the inner medulla has the highest concentration of solutes. This cannot be due to salt because active transport of salt does not start until the thick portion of the ascending limb. Urea is believed to leak from the lower portion of the collecting duct, and it is this molecule that contributes to the high solute concentration of the inner medulla.

Because of the osmotic gradient within the renal medulla, water leaves the descending limb of the loop of the nephron along its length. This is a countercurrent mechanism: as water diffuses out of the descending limb, the remaining solution within the limb encounters an even greater osmotic concentration of solute; therefore, water will continue to leave the descending limb from the top to the bottom.

Fluid entering a collecting duct comes from the distal convoluted tubule. This fluid is now isotonic to the cells of the cortex. This means that to this point, the net effect of reabsorption of water and salt is the production of a fluid that has the same tonicity as blood. However, the filtrate within the collecting duct also encounters the same osmotic gradient mentioned earlier (Fig. 16.7). Therefore, water diffuses out of the collecting duct into the renal medulla, and the urine within the collecting duct becomes hypertonic to blood plasma.

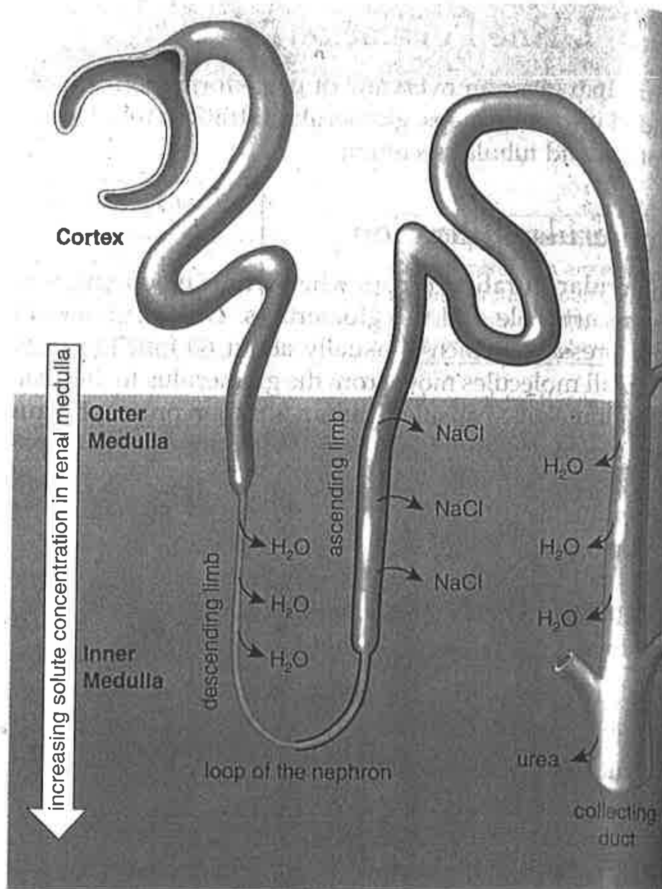

Figure 16.7 Reabsorption of water at the loop of the nephron and the collecting duct.
Salt (NaCl) diffuses and is actively transported out of the ascending limb of the loop of the nephron into the renal medulla; also, urea is believed to leak from the collecting duct and to enter the tissues of the renal medulla. This creates a hypertonic environment, which draws water out of the descending limb and the collecting duct. This water is returned to the cardiovascular system. (The thick line means the ascending limb is impermeable to water.)

Antidiuretic hormone (ADH) released by the posterior lobe of the pituitary plays a role in water reabsorption at the collecting duct. In order to understand the action of this hormone, consider its name. Diuresis means increased amount of urine, and antidiuresis means decreased amount of urine. When ADH is present, more water is reabsorbed (blood volume and pressure rise), and a decreased amount of urine results. In practical terms, if an individual does not drink much water on a certain day, the posterior lobe of the pituitary releases ADH, causing more water to be reabsorbed and less urine to form. On the other hand, if an individual drinks a large amount of water and does not perspire much, ADH is not released. Now more water is excreted, and more urine forms.

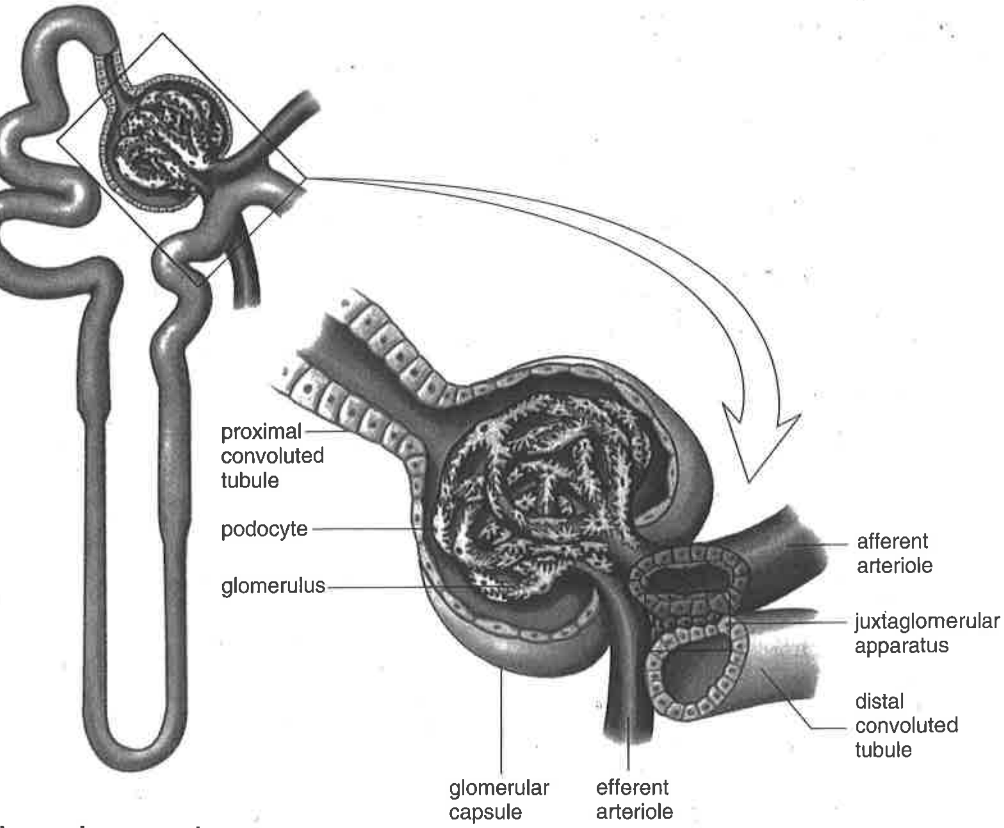

Figure 16.8 Juxtaglomerular apparatus.
This drawing shows that the afferent arteriole and the distal convoluted tubule usually lie next to each other. The juxtaglomerular apparatus occurs where they touch.

Reabsorption of Salt

Usually, more than 99% of sodium (Na^+) filtered at the glomerulus is returned to the blood. Most sodium (67%) is reabsorbed at the proximal tubule, and a sizable amount (25%) is extruded by the ascending limb of the loop of the nephron. The rest is reabsorbed from the distal convoluted tubule and collecting duct.

Hormones regulate the reabsorption of sodium at the distal convoluted tubule. **Aldosterone** is a hormone secreted by the adrenal cortex, the outer portion of the adrenal glands, which lie atop the kidneys. Aldosterone promotes the excretion of potassium ions (K^+) and the reabsorption of sodium ions (Na^+). The release of aldosterone is set in motion by the kidneys themselves. The **juxtaglomerular apparatus** is a region of contact between the afferent arteriole and the distal convoluted tubule (Fig. 16.8). When blood volume, and therefore blood pressure, is not sufficient to promote glomerular filtration, the juxtaglomerular apparatus secretes renin. **Renin** is an enzyme that changes angiotensinogen (a large plasma protein produced by the liver) into angiotensin I. Later, angiotensin I is converted to angiotensin II, a powerful vasoconstrictor that also stimulates the adrenal cortex to release aldosterone. The reabsorption of sodium ions is followed by the reabsorption of water. Therefore, blood volume and blood pressure increase.

Atrial natriuretic hormone (ANH) is a hormone secreted by the atria of the heart when cardiac cells are stretched due to increased blood volume. ANH inhibits the secretion of renin by the juxtaglomerular apparatus and the secretion of aldosterone by the adrenal cortex. Its effect, therefore, is to promote the excretion of Na^+, that is, natriuresis. When Na^+ is excreted, so is water, and therefore blood volume and blood pressure decrease.

These examples show that the kidneys regulate the salt balance in blood by controlling the excretion and the reabsorption of various ions. Sodium (Na^+) is an important ion in plasma that must be regulated, but the kidneys also excrete or reabsorb other ions, such as potassium ions (K^+), bicarbonate ions (HCO_3^-), and magnesium ions (Mg^{2+}), as needed.

Diuretics

Diuretics are agents that increase the flow of urine. Drinking alcohol causes diuresis because it inhibits the secretion of ADH. The dehydration that follows is believed to contribute to the symptoms of a hangover. Caffeine is a diuretic because it increases the glomerular filtration rate and decreases the tubular reabsorption of Na^+. Diuretic drugs developed to counteract high blood pressure in patients inhibit active transport of Na^+ at the loop of the nephron or at the distal convoluted tubule. A decrease in water reabsorption and a decrease in blood volume follow.

Visual Focus

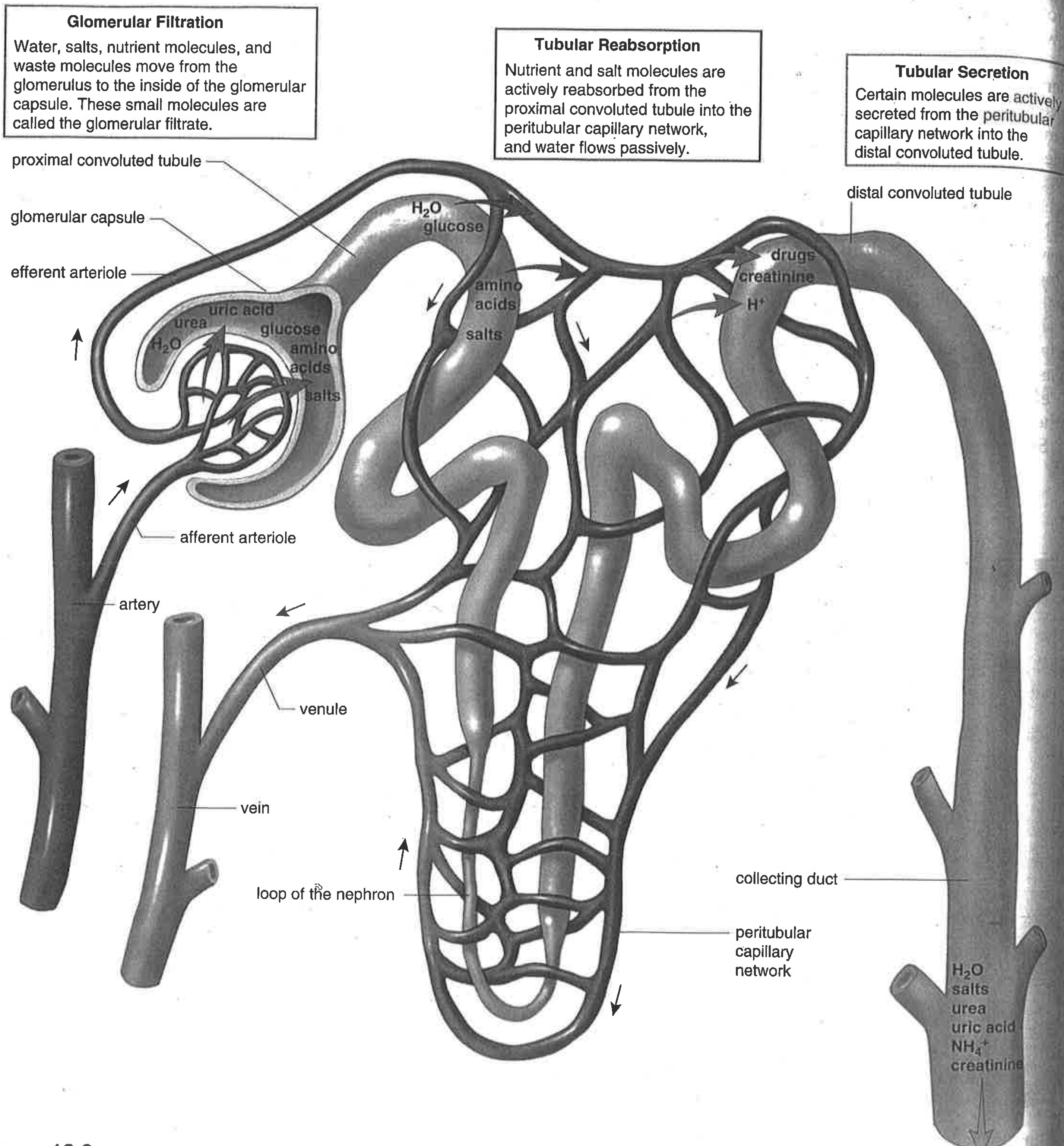

Figure 16.6 Urine formation.
The three steps in urine formation are numbered. Reabsorption of water is not an individual step because it occurs along the length of the nephron and also at the loop of the nephron and collecting duct. Excretion is not a step because it is the end result.

16-12

16.5 Maintaining Acid-Base Balance

The bicarbonate (HCO_3^-) buffer system and breathing work together to maintain the pH of the blood. Central to the mechanism is this reaction, which you have seen before:

$$H^+ + HCO_3^- \rightleftharpoons H_2CO_3 \rightleftharpoons H_2O + CO_2$$

The excretion of carbon dioxide (CO_2) by the lungs helps keep the pH within normal limits, because when carbon dioxide is exhaled this reaction is pushed to the right and hydrogen ions (H^+) are tied up in water. Indeed, when blood pH decreases, chemoreceptors in the carotid bodies (located in the carotid arteries) and in aortic bodies (located in the aorta) stimulate the respiratory center, and the rate and depth of breathing increases. On the other hand, when blood pH begins to rise, the respiratory center is depressed and the bicarbonate ion increases in the blood.

As powerful as this system is, only the kidneys can rid the body of a wide range of acidic and basic substances. The kidneys are slower acting than the buffer/breathing mechanism, but they have a more powerful effect on pH. For the sake of simplicity, we can think of the kidneys as reabsorbing bicarbonate ions and excreting hydrogen ions as needed to maintain the normal pH of the blood. If the blood is acidic, hydrogen ions are excreted and bicarbonate ions are reabsorbed. If the blood is basic, hydrogen ions are not excreted and bicarbonate ions are not reabsorbed. Since the urine is usually acidic, it shows that usually an excess of hydrogen ions are excreted. Ammonia (NH_3) provides a means for buffering these hydrogen ions in urine: ($NH_3 + H^+ \rightarrow NH_4^+$). Ammonia (whose presence is quite obvious in the diaper pail or kitty litter box) is produced in tubule cells by the deamination of amino acids. Phosphate provides another means of buffering hydrogen ions in urine.

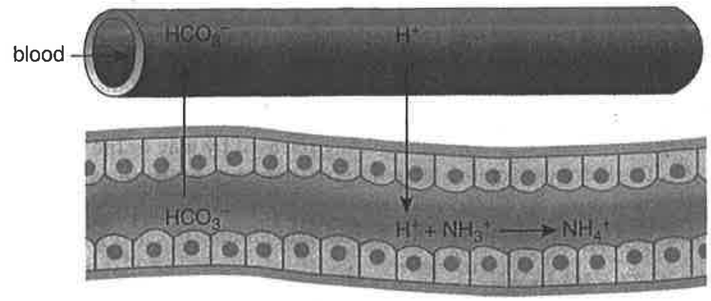

Figure 16.9 **Acid-base balance.**
In the kidneys, bicarbonate ions are reabsorbed and the hydrogen ions are excreted as needed to maintain the pH of the blood. Excess hydrogen ions are buffered, for example, by ammonia (NH_3), which is produced in tubule cells by the deamination of amino acids.

The acid-base balance of the blood is adjusted by the reabsorption of the bicarbonate ions (HCO_3^-) and the secretion of hydrogen ions (H^+) as appropriate.

Bioethical Issue

As a society we are accustomed to thinking that as we grow older, diseases like urinary disorders will begin to occur. Almost everyone is aware that most males are subject to enlargement of the prostate as they age, and that cancer of the prostate is not uncommon among elderly men. However, like many illnesses associated with aging, medical science now knows how to treat or even cure prostate problems. Because of these successes, medical science has lengthened our life span. A child born in the United States in 1900 lived to, say, 47 years. If that same child were born today, it would probably live to at least 76. Even more exciting is the probability that scientists will improve the life span. People could live beyond 100 years and have the same vigor and vitality they had when they were young.

Most people are appreciative of living longer, especially if they can expect to be free of the illnesses and inconveniences associated with aging. But have we examined how we feel about longevity as a society? Whereas we are accustomed to considering that if the birthrate increases so does the size of a population, what about the death rate? If the birthrate stays constant and the death rate decreases, obviously population size also increases. Most experts agree that population growth depletes resources and increases environmental degradation. An older population can also put a strain on the economy if they are unable to meet their financial, including medical, needs without governmental assistance.

What is the ethical solution to this problem? Should we just allow the population to increase due to older people living longer? Should we decrease the birthrate? Should we reduce governmental assistance to older people so they realize that they must be able to take care of themselves? Should we call a halt to increasing the life span through advancements in medical science?

Questions

1. Do you feel that older people make a significant contribution to or a drain on society? Explain.
2. Would you be willing to have fewer children in order to hold the population in check if more people live longer? Why or why not?
3. Should the elderly expect governmental or family assistance as they age? Why or why not?