9.5 The Excretory System

In multicellular organisms, individual cells cannot effectively secrete wastes to the external environment. One of the main functions of the excretory system (aided by osmoregulation) is to concentrate wastes and expel them from the body. The second main function of the excretory system is to regulate fluids and water within the body. Most metabolic wastes and toxins are dissolved in the body's internal environment, so maintenance of the body fluids is essential for keeping the body free of waste products and enabling it to function properly. In this section, you will learn about the functions of the excretory system and examine how the excretory system works in simpler organisms and in more complex organisms, such as humans and other mammals.

Excretion in Invertebrates and Non-mammalian Vertebrates

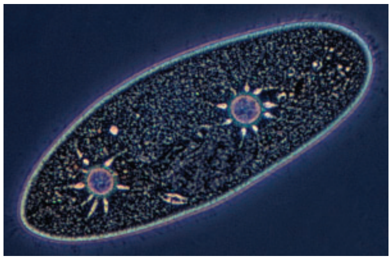

Figure 1 Some single-celled organisms, such as the paramecium, excrete material directly into the external environment via contractile vacuoles.

contractile vacuole a structure in a single-celled organism that maintains osmotic equilibrium by pumping excess fluid out of the cell

metanephridium an excretory organ in some invertebrates that is used to reabsorb and eliminate wastes

Single-celled organisms and simple multicellular organisms produce the same metabolic wastes and toxic compounds as more complex organisms. These waste products must be excreted to maintain homeostasis. Simple organisms have an advantage over more complex organisms because their cells are in constant contact with the external environment. Wastes are excreted directly from their cells, and the water currents in the external environment carry the wastes away. A greater challenge for simple organisms is maintaining a fluid balance with the external environment. Free-living single-celled organisms, such as the paramecium, have an internal environment that is hyperosmotic to their surroundings (**Figure 1**). If they were not able to maintain a fluid balance, they would continuously absorb water from the environment and eventually burst. To expel excess water, these protozoans have **contractile vacuoles**, which pump out water to maintain osmotic balance.

In more complex organisms, the excretory system must take on different forms to meet different challenges. Some invertebrate animals, such as the earthworm, have excretory organs called **metanephridia** (singular: metanephridium) that expel wastes from the body (**Figure 2**). In each segment of the earthworm, hemolymph (a fluid that serves as both interstitial fluid and blood) flows into a pair of metanephridia, which are twisted into convoluted shapes to maximize their surface area. Ions and wastes are reabsorbed from the hemolymph and secreted (along with water) into a saclike organ called a bladder. From there, the excess water and waste products are secreted to the external environment through a pore in the side of the worm's body.

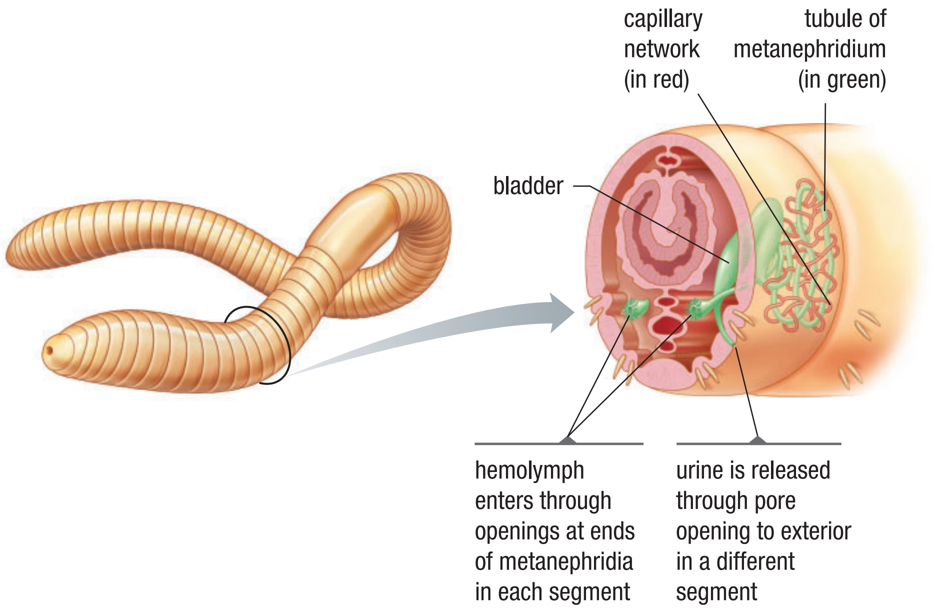

Figure 2 A metanephridium of an earthworm

Insects such as the grasshopper excrete wastes using a set of organs called **Malpighian tubules**. The closed ends of these organs are immersed in the hemolymph. The open ends empty into the intestines (**Figure 3**). Several substances, such as uric acid (the nitrogenous waste product) and potassium and sodium ions, are secreted into the tubules. As the concentration of these substances increases, water moves osmotically from the hemolymph into the tubule to form a dilute waste solution. The waste solution (urine) then travels to the intestines of the insect, where specialized cells reabsorb most of the K^+ and Na^+ back into the hemolymph. This causes water to move from the intestines back into the hemolymph by osmosis—an important water conservation measure. The uric acid that is left behind forms crystals and is expelled with the insect's digestive waste products.

Malpighian tubule the main organ of excretion in insects, which is used to carry wastes to the intestines

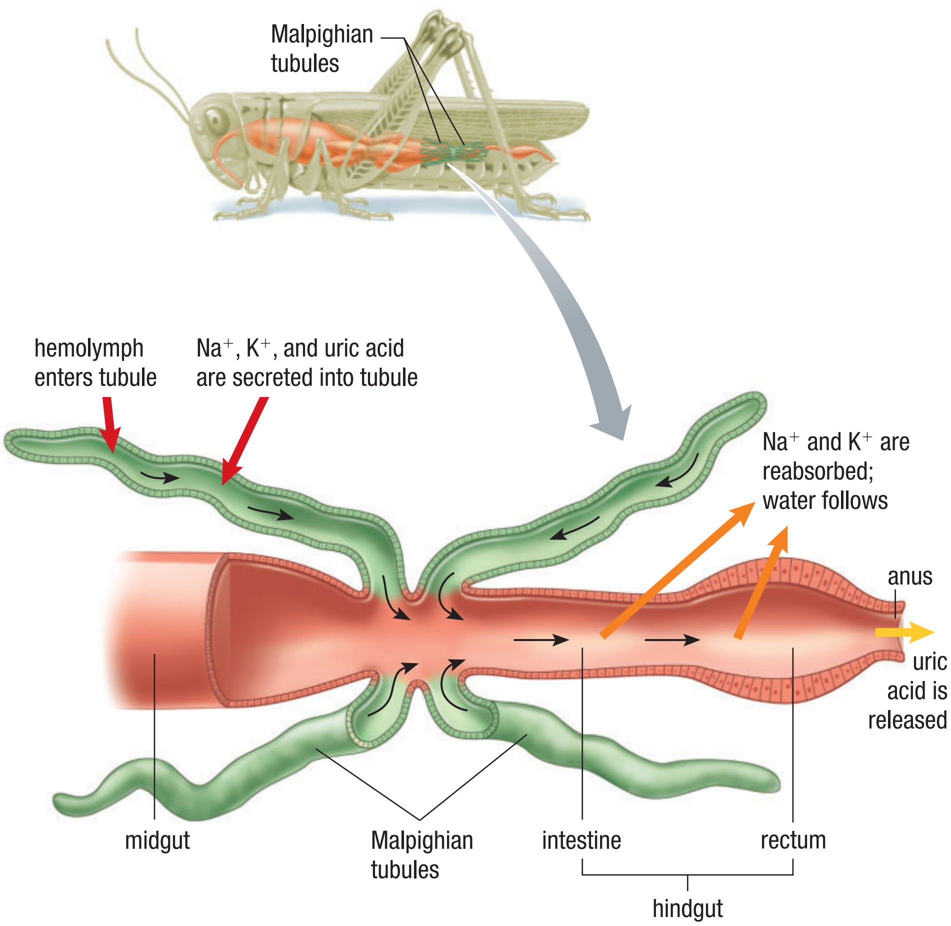

Figure 3 Excretion through Malpighian tubules in a grasshopper

Terrestrial reptiles and most birds conserve water by excreting nitrogenous wastes in the form of an almost water-free paste of uric acid crystals. This is excreted into the cloaca (end of the digestive system) and removed from the body along with the digestive wastes. The white substance in bird droppings is uric acid. The darker substance is feces.

Reptiles and birds that live in or around salt water take in large quantities of salt with their food and rarely or never drink fresh water. These animals usually excrete excess salt through specialized salt glands located in the head (**Figure 4**). The salt glands remove salts from the blood by active transport. The salts are secreted to the environment as a water solution, in which the salts are two to three times more concentrated than in body fluids. The secretion exits through the nostrils of birds and lizards, and as salty tears from the eye sockets of sea turtles and crocodilians.

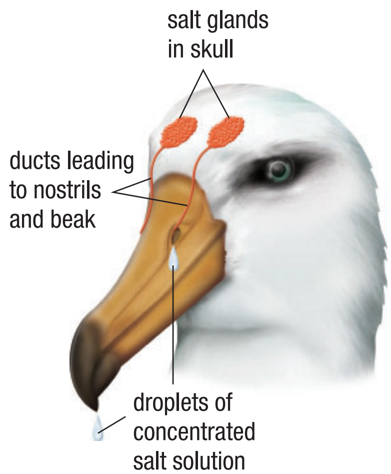

Figure 4 Saltwater birds get rid of excess salt through salt glands in the head.

The Human Excretory System

nephron the tiny functional unit of the kidney that filters wastes from the blood

The excretory systems of all vertebrates, including humans, use specialized tubules, called **nephrons**, which regulate the water balance in the body and conduct excretion (**Figure 5**). These tubules are located in the major organs of the excretory system—the kidneys. The kidneys, ureters, bladder, and urethra together make up the human excretory system.

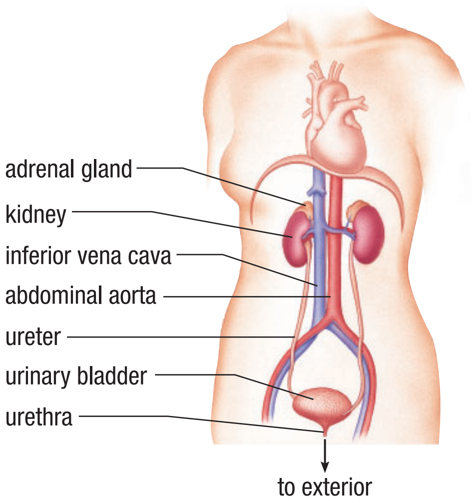

Figure 5 The human excretory system

Kidneys

The kidneys play a critical role in removing wastes, balancing blood pH, and maintaining the body's water balance. Mammals have two kidneys, one on each side of the vertebral column. In humans, the average kidney has a mass of about 150 g and receives about 25 % of the cardiac output (roughly 1.25 L/min). Blood is supplied to the kidney through the renal artery. ("Renal" refers to the kidney.) The kidney filters the wastes from the blood, and the clean blood exits the kidney through the renal veins. **Figure 6** shows the internal structure of a kidney. The outer layer of the kidney is called the renal cortex. An inner layer, called the medulla, is found beneath the cortex. A hollow cavity, called the renal pelvis, connects the kidney to the ureter, through which urine passes to the urinary bladder. Once the bladder is full (with roughly 300 to 400 mL of urine), the urine exits the body through the urethra.

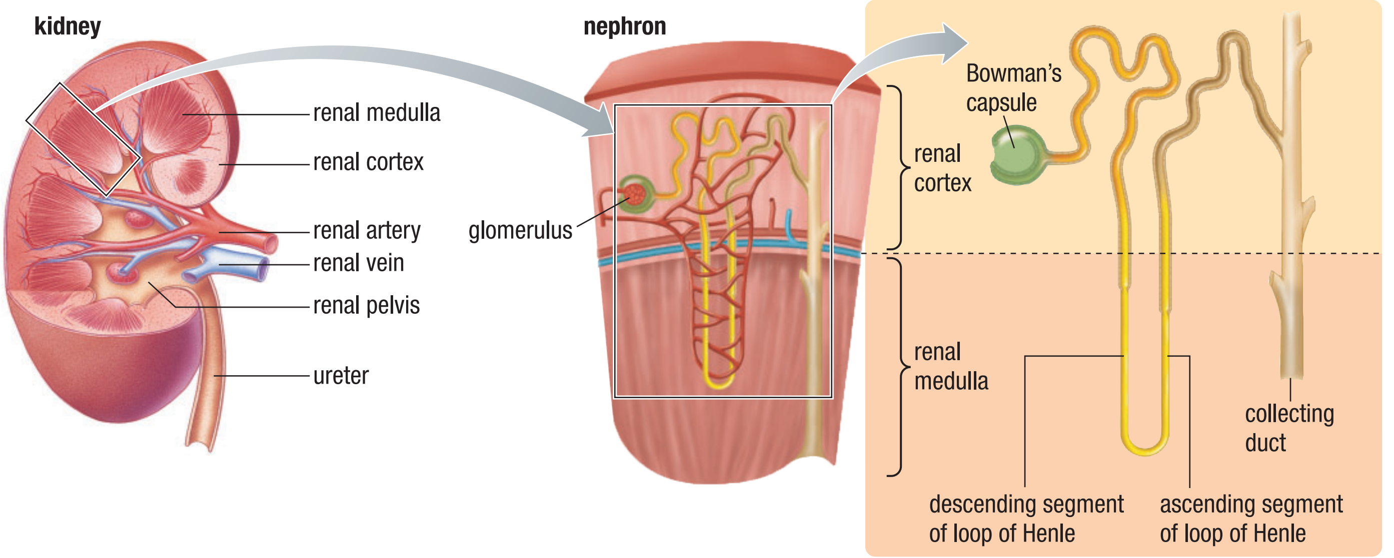

Figure 6 Anatomy of the kidney. Each kidney contains about 1 000 000 nephrons.

NEPHRONS

Each kidney contains about 1 000 000 nephrons, which are the functional unit of the kidney. Nephrons are differentiated into regions, which perform the series of steps that are involved in excretion (**Figure 7**). At one end is the **Bowman's capsule**, a small folded structure that encircles a group of blood capillaries, the **glomerulus**, in the cortex. The glomerulus performs the first steps in the filtration of blood to form urine. Blood is supplied to the glomerulus by the **afferent arteriole** and, after being filtered, exits via the **efferent arteriole** and is carried to a net of capillaries called the **peritubular capillaries**. The peritubular capillaries surround the tubules that carry away the urine and allow for the reabsorption of essential ions and minerals back into the bloodstream.

During the first steps of filtration, components of the unfiltered blood pass from the glomerulus into the Bowman's capsule and enter a **proximal convoluted tubule**, which lies in the renal cortex. This tubule descends into the medulla and forms a U-shaped structure called the **loop of Henle** before rising again to form a **distal convoluted tubule**. The distal tubule drains the urine into a branching system of collecting ducts that lead to the renal pelvis, which then empties through the ureter to the bladder.

CAREER LINK

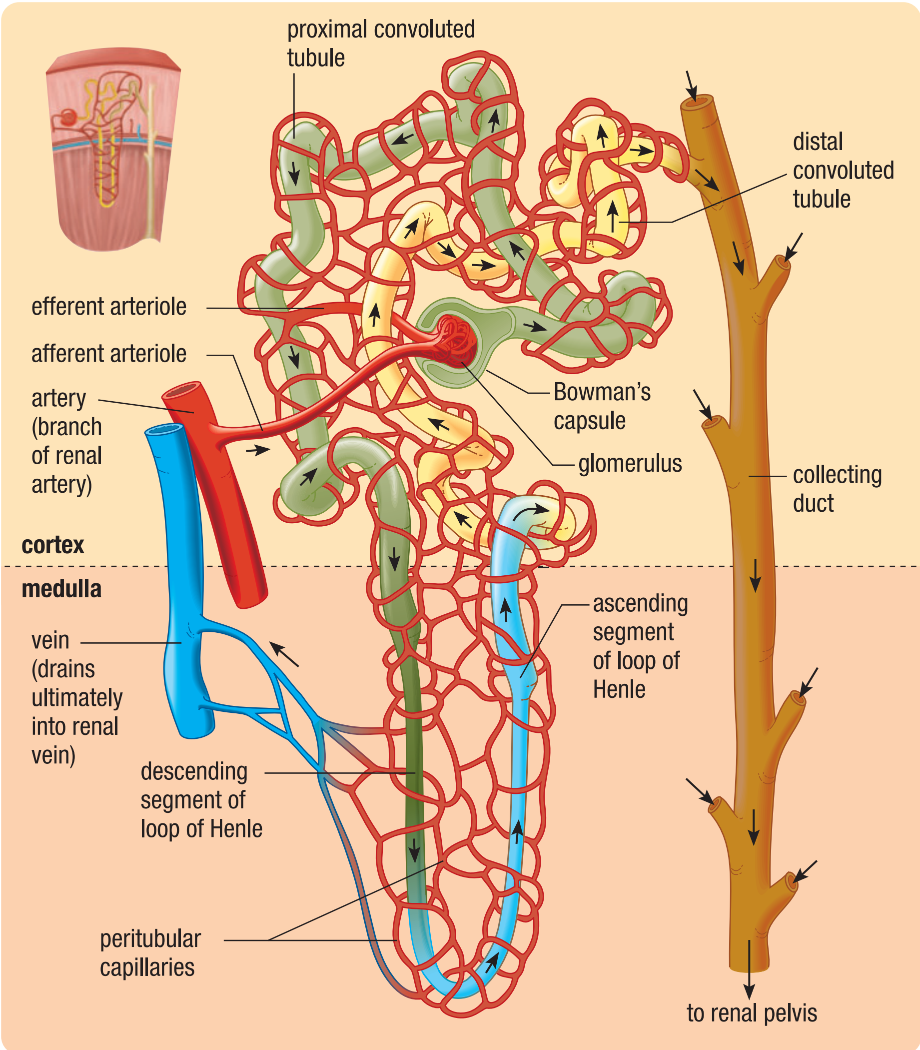

Figure 7 A nephron and its blood circulation

Bowman's capsule a small folded structure in the human kidney that encircles the glomerulus

glomerulus a network of capillaries within the Bowman's capsule that performs the first step in the filtration of blood

afferent arteriole a vessel that supplies blood to the nephrons in the human kidney

efferent arteriole a vessel that carries away filtered blood from the nephrons in the human kidney

peritubular capillaries a net of capillaries in the nephrons that reabsorb essential ions and minerals from filtered blood

proximal convoluted tubule the duct portion of a nephron that connects the Bowman's capsule to the loop of Henle

loop of Henle the U-shaped part of the duct that connects the proximal convoluted tubule to the distal convoluted tubule

distal convoluted tubule the duct portion of a nephron that connects the loop of Henle to the ducts that lead to the renal pelvis

The Formation of Urine

As alluded to previously, the different sections of the nephron have specialized functions in the formation of urine and the conservation of water. In mammals, urine is hypoosmotic to the surrounding body fluids. This means that water tends to move from urine into the body fluids, an adaptation that conserves water. Three features of the nephrons interact to conserve nutrients and water, balance salts, and concentrate wastes for excretion: the arrangement of the loop of Henle, which descends into the medulla and rises back into the cortex; the differences in permeability of successive parts of the nephrons; and the concentration gradient of molecules and ions in the interstitial fluid of the kidney, which gradually increases from the cortex to the deepest levels of the medulla.

Urine formation is the result of three interrelated processes: filtration, reabsorption, and secretion. Filtration occurs as body fluids move from the blood into the Bowman's capsule. Reabsorption transfers essential solutes and water from the nephron back into the blood. Secretion transfers materials from the blood back into the nephron. In this section, you will examine each of these processes, which occur in different parts of the nephron.

Filtration

The process of urine formation begins at the Bowman's capsule (**Figure 8**). The cells of the Bowman's capsule and the capillaries that it surrounds form a selectively permeable membrane, with spaces just wide enough to admit water, ions, small nutrient molecules (such as glucose and amino acids), and nitrogenous waste molecules (primarily urea). The higher pressure of the blood in the glomerulus drives fluid that contains these molecules and ions into the capsule. Blood cells, platelets, and plasma proteins are too large to pass through and are retained in the capillaries. The fluid that enters the Bowman's capsule, which contains only the smaller molecules (including

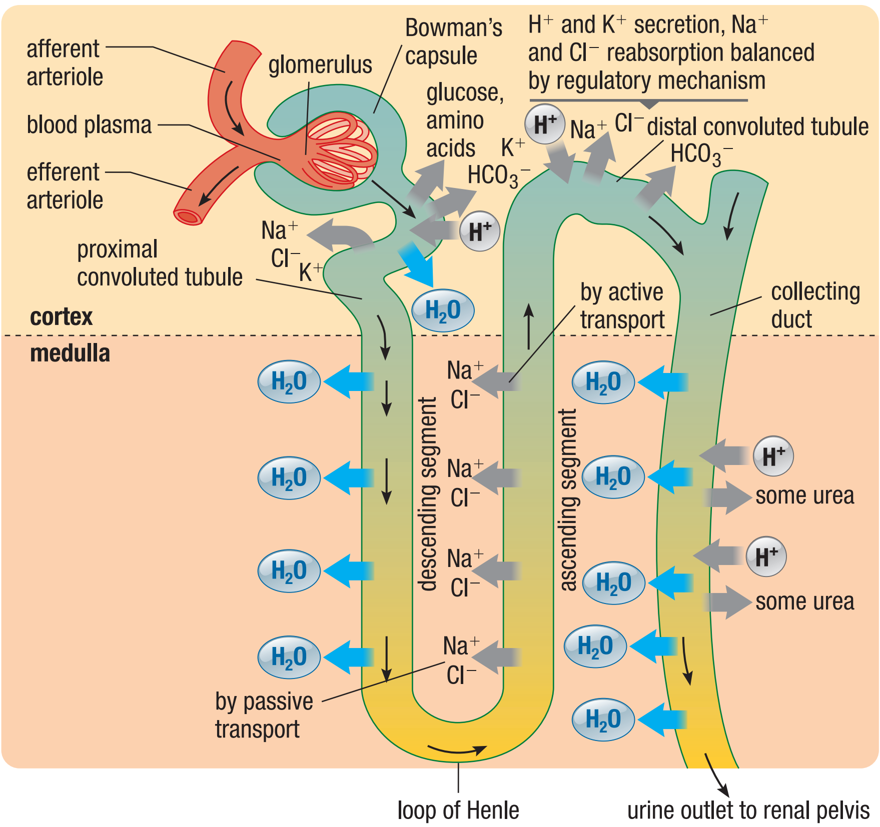

Figure 8 The movement of water, ions, and other molecules through the collecting tubules and nephrons in the kidney

metabolic waste), is an ultrafiltrate of the blood. The process in which fluid and small molecules pass into the Bowman's capsule is known as **filtration** (**Figure 9**).

About 1400 L of blood pass through the kidneys every day, and the Bowman's capsules filter about 180 L of fluid from this blood. The human body contains roughly 2.75 L of blood plasma. This means that the kidneys filter the entire contents of the blood plasma 65 times every day. Only about 1.5 L of the daily filtrate is excreted as urine. The rest consists primarily of water and is reabsorbed into the nephrons.

filtration the process in which blood and fluid pass through a selectively permeable membrane

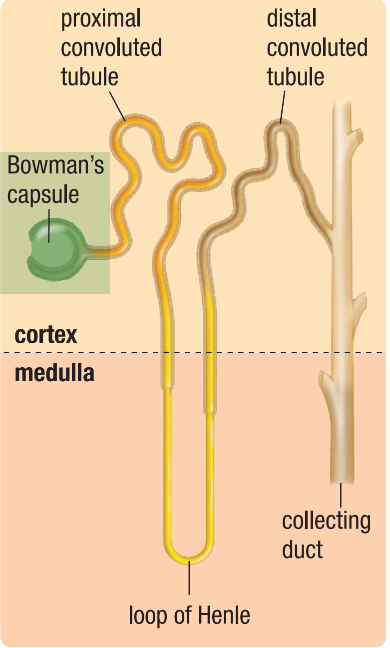

Figure 9 Filtration occurs in the Bowman's capsule.

Reabsorption

The fluid that is filtered into the Bowman's capsule contains urea, water, ions, and other molecules that are in the same concentrations as they are in the blood plasma. The fluid enters the proximal convoluted tubule, where **reabsorption** occurs (**Figure 10**). Water, ions, and nutrients are transferred back into the interstitial fluid via both passive and active methods. Specialized ion pumps transport potassium, K^+; sodium, Na^+; and chlorine, Cl^-, from the filtrate into the fluid surrounding the tubule. Active transport proteins, embedded in the walls of the tubule, reabsorb the amino acids, glucose, and other nutrients out of the filtrate. Urea and other unwanted compounds are not reabsorbed. The inner walls of the tubule are covered with microscopic extensions called microvilli. These extensions greatly increase the total surface area that is available for the reabsorption of solutes. All of the reabsorption processes make the filtrate hypoosmotic to the interstitial fluid, and this causes water to flow out of the tubule and into the interstitial fluid by osmosis. The movement of water is further facilitated by membrane proteins called **aquaporins**, or water channels, which form passages for additional water molecules to flow out of the tubule. The aquaporins ensure that the maximum amount of water is removed from the tubule during the reabsorption process. The proximal convoluted tubule reabsorbs 67 % of the Na^+, K^+ , and Cl^-; 65 % of the water; 50 % of the urea; and nearly all of the amino acids, glucose, and other nutrients. This highly efficient process saves energy and allows the body to maximize the use of these nutrients.

reabsorption the transfer of water, ions, and nutrients back to the interstitial fluid via passive and active transport

The nutrients and water that are reabsorbed in the proximal convoluted tubule enter the peritubular capillaries. The remaining fluid, which has a high concentration of urea and other wastes that are not reabsorbed, moves through the proximal convoluted tubule into the descending portion of the loop of Henle. There, additional water is reabsorbed by osmosis and the aquaporins. The outward movement of water concentrates the molecules and ions inside the tubule. As the fluid moves into the ascending portion of the loop of Henle, Na^+ and Cl^- are reabsorbed into the interstitial fluid. In the first part of the ascending segment, the concentrations are high enough to move Na^+ and Cl^- out of the tubule by passive diffusion. Toward the top of the ascending segment, these ions are moved out by active transport. Thus, as the fluid flows through the entire loop of Henle, water, nutrients, and ions have been conserved and returned to the body fluids, and urea and other nitrogenous wastes have become concentrated in the filtrate so the total volume of the filtrate in the nephron has been greatly reduced.

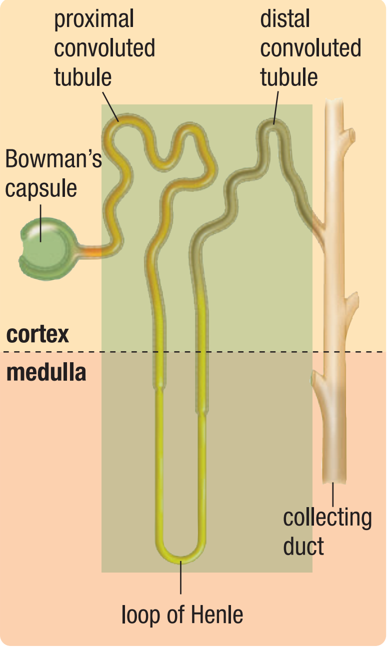

Figure 10 Reabsorption occurs in the proximal convoluted tubule, the loop of Henle, and the distal convoluted tubule.

As the fluid continues along its path, it enters the distal convoluted tubule, where additional water and salts are removed. More ions and solutes move out of the fluid than into it; this causes the further transport of water out of the tubule by osmosis through the aquaporins. The amounts of urea and other nitrogenous wastes remain the same.

The concentrated urea and other wastes flow into the collecting ducts, which further concentrate the urine. The collecting ducts descend from the cortex of the kidney and through the medulla. They are permeable to water, but not to salt ions. The concentration of solutes increases with depth as the fluid descends into the medulla. This causes further removal of water through the ducts, greatly increasing the concentration of the urine. Near the bottom of the medulla, the walls of the collecting ducts contain passive urea transporters, which allow some of the nitrogenous wastes to pass from the duct into the interstitial fluid. This urea adds significantly to the concentration gradient of solutes in the medulla.

aquaporin a membrane protein that passively transports water molecules

Secretion

secretion the removal of waste materials from the blood and intercellular fluid

Secretion is the removal of waste products from the blood and interstitial fluid (**Figure 11**). During the process of urine formation, wastes are secreted at several points in the nephron. Some wastes are secreted from the interstitial fluid into the proximal convoluted tubule. H^+ ions are actively secreted, and the products of detoxified poisons (from the liver) are passively secreted. (Many water-soluble drugs, such as penicillin and other medications, and their metabolites are also secreted into the nephron and excreted in the urine.) Small amounts of ammonia are secreted into the tubule. The secretion of H^+ ions into the filtrate helps to balance the acidity that is constantly generated in the body by metabolic reactions. H^+ secretion is coupled with HCO_3^- reabsorption from the filtrate to the plasma in the peritubular capillaries.

In response to hormones triggered by changes in the salt concentrations in the body, varying amounts of K^+ and H^+ are secreted into the filtrate in the distal convoluted tubule. Additional active secretion of H^+ occurs in the collecting ducts. The balance of ions established in the blood, urine, and interstitial fluid is essential for regulating the pH level of the blood and body fluids. In this way, the kidney acts as a "safety valve." If the acidity of the body fluid rises beyond the levels that can be controlled by the blood's buffer system, the excess H^+ ions are secreted into the collecting ducts and excreted in the urine.

When urine reaches the bottom of the collecting ducts, it is roughly four times as concentrated with waste molecules as the extracellular fluid. From the collecting ducts, urine flows into the renal pelvis, through the ureters, and into the urinary bladder. From the bladder, the urine exits through the urethra into the external environment.

Table 1 provides a summary of the functions of the different parts of the kidney as wastes are removed from the blood and urine is produced.

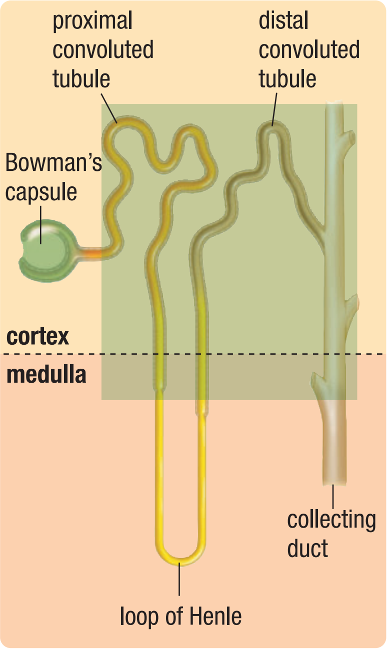

Figure 11 Secretion occurs in the proximal and distal convoluted tubules, and the collecting duct.

Table 1 Functions and Roles of Different Parts of the Nephron and Collecting Ducts

Segment	Location	Primary function	Comparison to interstitial fluid	Result of passage
glomerulus and Bowman's capsule	cortex	Ions (Na^+, Cl^-, and H^+), small nutrients (glucose), nitrogenous wastes (amino acids, urea, and uric acid), vitamins, and minerals are filtered into the Bowman's capsule.	isoosmotic	Water and small substances, but no proteins, pass into the nephrons.
proximal convoluted tubule	cortex	Ions are actively reabsorbed, water leaves through the aquaporins, and H^+ ions are actively secreted. Glucose, amino acids, and other nutrients are actively absorbed.	isoosmotic	Some of the ions, water, and urea, and all of the nutrients return to the interstitial fluid. The pH balance is maintained.
descending portion of loop of Henle	cortex into medulla	Water leaves through the aquaporins.	isoosmotic at top to hyperosmotic at bottom	Additional water is returned to the interstitial fluid.
ascending portion of loop of Henle	medulla into cortex	Na^+ and Cl^- are actively transported out. There is no entry of water and no movement of urea.	hyperosmotic at bottom to isoosmotic at top	Additional ions are returned to the interstitial fluid.
distal convoluted tubule	cortex	K^+ and Na^+ are secreted via active transport into the urine. Na^+ and Cl^- are reabsorbed. Water moves into the urine through the aquaporins.	hypoosmotic at beginning to isoosmotic at junction with collecting ducts	The ionic and pH balance are maintained.
collecting ducts	cortex through medulla, into renal pelvis	Water moves out via the aquaporins. There is no movement of ions. Some urea leaves at the bottom of the collecting ducts.	isoosmotic at junction to hyperosmotic at junction with renal pelvis	More water and some urea are returned to the interstitial fluid. Some H^+ ions are added to the urine.

Mini Investigation

Treating Lead Poisoning

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A1, A2.1

The standard treatment for lead poisoning is the ingestion of a chelating agent. The chelating agent binds with the lead and allows it to dissolve and be secreted with the urine. In this investigation, you will model the process that enables lead to be removed from the body through the kidneys. You will use sodium bicarbonate solution to simulate the blood, and calcium to simulate the actions of the lead in the body. The calcium ions will bind with carbonate ions in the simulated blood just as lead ions settle into red blood cells and interfere with the production of hemoglobin, the oxygen-carrying compound. The calcium in the calcium chloride will act like lead in the body and bind with the carbonate. EDTA is the chelating agent.

Equipment and Materials: safety goggles; 2 medicine droppers; 3 beakers (50 mL); 3 labels: lead (calcium chloride), blood (sodium bicarbonate solution), chelating agent (EDTA); 3 spatulas or plastic knives; balance; 100 mL graduated cylinder; 3 stirring rods; 0.6 g sodium bicarbonate; 0.6 g calcium chloride; water; 0.5 g EDTA

Calcium chloride and EDTA are irritants. Be careful not to get them on your skin or inhale the powder.

1. Put on your safety goggles, and observe all the appropriate safety guidelines.
2. Label a beaker for each of the chemicals.
3. Measure out each chemical, and place each in the appropriate beaker.
4. Add 20 mL of water to each beaker, and stir using a clean glass stirring rod for each solution. Stir until all of the chemicals have dissolved.
5. Use the medicine dropper to slowly add 25 drops of the "lead" solution into the "blood" solution. Record your observations.
6. Pour all of the EDTA solution into the "blood" beaker. Record your observations.

A. What did you observe in Step 5? Explain your answer. T/I
B. What did you observe in Step 6? Explain your answer. T/I
C. What is the role of the excretory system in the treatment of lead poisoning? T/I
D. Based on what you know about excretion, which process do you think is involved? In what part of the nephron will the lead be removed? T/I

Kidney Disease

The kidneys must function properly to maintain water balance and homeostasis. Because the kidneys are in contact with all of the blood and wastes in the body, they are affected by disease or injury in other parts of the body. Conversely, any breakdown of kidney function has an impact on many other organ systems. Many kidney disorders can be diagnosed through urinalysis. In urinalysis, the contents of the urine are analyzed for traces of metabolites and molecules that result from disease.

CAREER LINK

Diabetes mellitus, which is caused by the insufficient secretion of insulin, causes the blood sugar level to rise. Most of the excess sugar remains in the nephrons, opposing the usual osmotic pressure maintained by active transport. The result is the retention of water, so patients with diabetes need to urinate more frequently. While some of the glucose can be excreted in the urine and can be detected by urinalysis, most of the excess glucose is reabsorbed in the proximal tubules of the nephrons.

Kidney stones are an affliction of the excretory system that is caused by the buildup of mineral solutes, such as oxalates, phosphates, and carbonates (**Figure 12**). These solutes can combine with calcium to produce crystals that accumulate and form stones. The sharp stones lodge in the renal pelvis or ureters and can cause considerable pain. Kidney stones are often broken up by high-energy sound waves in a process called extracorporeal shock wave lithotripsy (ESWL). They may also be removed with a uteroscope or by surgery.

The near total loss of kidney function requires the use of dialysis. In dialysis, the blood is run through a filtering machine, which acts as an artificial kidney. Total loss of kidney function leads to the need for a kidney transplant.

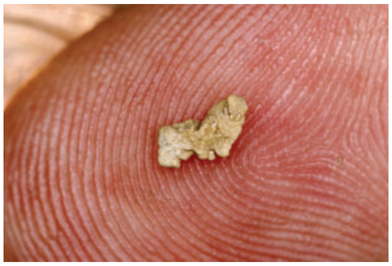

Figure 12 Buildup of minerals can form large deposits like this kidney stone.

Investigation 9.5.1

Diagnosing Kidney Dysfunction (p. 457)

You have learned about some of the diseases that affect the kidneys and how they can be diagnosed by urine analysis. In this investigation, you will test simulated urine samples for physical or chemical properties that may indicate kidney dysfunction.

9.5 Review

Summary

- Single-celled organisms excrete waste directly to the environment. Most invertebrates have specialized structures to process and excrete waste.
- In mammals and other vertebrates, excretory tubules are found in the kidneys. The nephrons filter bodily fluids, reabsorb nutrients, and secrete urine.
- The Bowman's capsule and the glomerulus filter the blood. The fluid then moves through the proximal convoluted tubule, which actively reabsorbs ions and nutrients. Additional water is removed passively.
- The filtered blood reabsorbs water, ions, and other molecules, which are then absorbed in the peritubular capillaries.
- In the descending portion of the loop of Henle, water is reabsorbed by osmosis. In the ascending portion of the loop, ions are removed via active transport. In the distal convoluted tubule, the salt concentrations of the filtrate and the interstitial fluid are balanced.
- In the collecting duct, additional water is reabsorbed. The urine is collected in the renal pelvis. From there, it flows into the bladder, where it is stored until it is excreted.
- There are many diseases and disorders that can interfere with the proper functioning of the kidneys in excreting wastes and maintaining water balance.

Questions

1. (a) What are the similarities between the excretory organs of insects and the kidneys?
   (b) What are some of the differences? K/U
2. Victims of accidents and diseases are able to live healthy lives with just one kidney. With this in mind, what may be the reasons that the body normally uses two kidneys? T/I
3. Describe the flow of blood into and out of the kidneys. Compare the contents of the blood when entering and exiting the kidneys. K/U
4. Describe the flow of fluid through a nephron and to the external environment. Include a simple labelled sketch with your description. K/U C
5. Why is it beneficial for the nephrons to be so folded? K/U
6. You learned that 50 % of the urea is reabsorbed in the proximal convoluted tubes. Why does this not greatly concentrate the nitrogenous waste in the body? K/U
7. Using the Internet and other sources, research some ways to prevent the buildup of calcium. T/I
8. Using the Internet and other sources, research the relationship between diabetes and kidney function. What effect does diabetes have on the proper functioning of the excretory system? T/I
9. What would be the result on the body if Na^+, K^+, and Cl^- were not reabsorbed in the kidneys? K/U
10. How would running in hot temperatures, like Ray Zahab did, affect urine production? T/I
11. Use the Internet and other sources to research the condition known as proteinuria. In a brief summary, describe the causes, symptoms, and risks associated with this condition. T/I C
12. Using reputable sources, research the various causes of chronic kidney disease. Use your findings to answer the questions below. T/I
    (a) What are the causes and stages of chronic kidney disease?
    (b) What are the two types of dialysis, and what are the advantages and disadvantages of each?
    (c) What criteria must a patient meet to become a candidate for an organ transplant?
    (d) What are the issues involved in transplanting organs from a live donor versus a cadaveric donor? What are the risks involved with transplants?
13. Camels and kangaroo rats are just two examples of mammals that live in extremely arid environments. Use the Internet and other sources to find out more about the excretory systems of desert mammals. How are they able to conserve water and maintain proper kidney function? Report your findings back to the class. T/I C

WEB LINK