Peggy and Rob recently moved from their college town in coastal Washington State to northern New Mexico. Not long afterward, Peggy began to feel dizzy and noticed that she was urinating less than before and didn’t feel quite as sharp mentally. To herself, she blamed these symptoms on the stress of moving and setting up their home in a strange community far from their families. But Peggy did not feel any better as she got established in her new life. In fact, within weeks, she had some near-blackouts when rising from a chair.

Eventually, Rob asked Peggy about her fluid intake. Their new environment was much warmer and drier than their old one, and although he did not notice much extra perspiration, he felt constantly thirsty and was toting a water bottle along on errands. In the middle of the night, he’d even wake up and take a long drink from the bedside water glass. When he thought about it, he noticed that his urine was more colorful than what he remembered from Washington. And he realized that when he wore a backpack, his shirt got soaked in the areas where air could not circulate.

Peggy, however, was not drinking more than usual and had unwittingly pushed herself toward dehydration. By changing her body’s fluid balance, she had opened herself up to systemic symptoms that could even be life-threatening. What organ system is responsible for maintaining fluid balance? How does the body know when to conserve water and when to excrete it? These are the focus of our chapter on the urinary system.
The urinary system filters, transports, and stores waste products.

**Learning Objectives**

- Define the functions of the urinary system.
- Identify the organs of the urinary system.
- Diagram the anatomy of the kidney and the nephron.

The urinary system excretes aqueous waste as it maintains fluid balance and blood volume (Figure 14.1). It also regulates blood composition, helps to maintain blood pressure, monitors and maintains red blood cell levels, and assists in vitamin D synthesis. In addition, the urinary system is responsible for monitoring and adjusting the ionic composition of the blood, regulating the pH of the blood, regulating blood volume, maintaining blood glucose levels, and producing hormones that regulate calcium levels. And it does all this with four organs: pairs of kidneys and ureters, and the urinary bladder and urethra.

Listing all of these functions at once, it becomes obvious that the four organs of the urinary system are responsible for regulating the fluid environment of the body. As a whole, these are such vital functions that if the urinary system fails, the body will shut down within a few days.

**Urine**

Urine is formed as a by-product of the system’s functions. All of the waste materials removed from the blood by the urinary system leaves the body in urine.

**The Kidneys Are Filtering Organs**

The kidneys filter blood and produce hormones. These two fist-sized, bean-shaped organs lie immediately beneath the back musculature, embedded in a protective layer of fat (Figure 14.2). The kidneys are retroperitoneal, meaning they lie posterior to the peritoneal membrane. Because of this relatively unprotected placement, the kidneys are susceptible to injury from an external blow. Consequently, football pads are designed to cover the kidney area, and boxers are not permitted to punch opponents in the back. The right kidney is slightly lower than the left.

The kidneys themselves are covered with a tough outer membrane, the renal capsule (Figure 14.3). A large renal artery enters the kidney at the hilus. One quarter of the blood from every heartbeat gets shunted through the renal arteries to the kidneys. The hilus provides exit for the equally large renal vein and the kidney’s nerves and lymphatic vessels. The ureters are also attached at the hilus.

A sagittal section through a kidney reveals a uniform outer cortex and an irregular inner medulla. The cortex appears grainy and solid, and portions of it dip between the renal pyramids of the medulla. The renal pyramids are cone-shaped structures formed from an accumulation of collecting ducts filled with urine. The area adjacent to the hilus is the renal pelvis, where the formed urine is collected and passed to the next organ, the ureters. The renal pelvis is coated in a protective mucous membrane because the urine it contains is toxic to the cells. Among other substances, this urine contains nitrogenous wastes filtered from the blood.

Nitrogenous wastes

Compounds containing nitrogen, such as urea, that are produced during protein metabolism.

**The Urinary System**

The urinary system lies behind the peritoneum, protected by strong back muscles and fat. The kidneys are the organs responsible for filtering the blood, whereas the other three organs transport and excrete the resulting urine.
The kidneys are composed of millions of nephrons, packed together under the renal capsule (Figure 14.4). The large blood supply that enters the kidneys is diverted through smaller and smaller arteries and arterioles until it winds its way to a knotted vessel at the beginning of each nephron. The blood vessel leaving each nephron then breaks into peritubular capillaries, which wind around the entire nephron before being collected into venules. The venous system of the kidneys follows the same route as the arterial system, eventually leaving the kidney in the large renal veins. At the nephron, the blood is filtered, and the necessary ions and nutrients are returned to the circulatory system. The waste material remains in the fluid within the tubules of the nephron.

Beyond cleaning blood, the kidneys also produce the hormones calcitriol and erythropoietin, which regulate the concentration of calcium and formed elements in blood. Calcitriol, the active form of vitamin D, helps maintain blood calcium levels. Erythropoietin stimulates production of new red blood cells.
MILLIONS OF NEPHRONS DO THE FILTERING WORK

When observing a kidney under a light microscope, it becomes obvious that the organ is in fact a large collection of small nephrons, each responsible for filtering a portion of the blood that passes through the kidney (Figure 14.5). Each nephron is encircled by a separate capillary bed, providing the link between the urinary and cardiovascular systems. This link begins at a glomerulus, or vessel knot. The glomerulus is formed from an incoming arteriole. Leaving the glomerulus, the efferent arteriole leads to a capillary bed surrounding the nephron. The blood from the capillary bed is collected in a renal venule and transferred to larger and larger veins until it leaves the kidney at the renal vein.

The nephron itself is composed of a glomerular capsule surrounding the glomerulus, a proximal convoluted tubule, a loop, and a distal convoluted tubule connected to a collecting duct. Each portion of the tubule has a distinct role in filtering blood, balancing ions and pH, and removing wastes.

The initial portion of the nephron, called Bowman’s capsule, or the glomerular capsule, surrounds the glomerulus. The tubule that extends from the glomerular capsule is the proximal convoluted tubule (PCT). Proximal means “close to,” and convoluted means “having twists or coils.” This tubule is the one closest to the glomerulus, and it does have plenty of twists and turns.

Most of the nephrons begin in the cortex of the kidneys. The collection of many, many capsules and associated PCTs make up the outer cortex of the kidneys. From the PCT, the newly filtered fluid is transported into the loop of the nephron. This portion of the nephron extends from the cortex into the medulla of the kidneys, making up a portion of the renal pyramid. The loop dives down into the medulla and back up to the cortex, where it joins with the distal convoluted tubule (DCT). Distal means “further from,” indicating that this tubule lies some distance from the glomerulus. The DCT leads directly to the collecting duct. One collecting duct gathers newly formed urine from a series of nephrons and drains it to the renal pelvis. These collecting ducts comprise the majority of the renal pyramids.

The urine that reaches the renal pelvis is almost ready for excretion from the body. As it travels through the rest of the urinary system, it is subjected to small adjustments in composition before it is voided, or released. Owing to the action of the nephron, blood leaving the peritubular capillaries is cleansed, balanced, and ready to be transported to the rest of the body.

Amazingly, the body maintains more nephrons than it needs. This is not characteristic of the human body—usually when there is an excess of proteins, compounds, or structures, the body will break down the excess and retain only the bare minimum needed for survival. Recall that unused muscular tissue atrophies, leaving no sign of its existence. Literally millions of extra nephrons are maintained. We have enough filtering capacity in one kidney to provide all the cleansing and monitoring of fluid balance necessary for life. Having two kidneys allows us to donate a kidney for transplant and not suffer adverse effects on either fluid balance or general well-being.

CONCEPT CHECK

List the organs of the urinary system, in order from urine formation to release from the body.

Describe the functions of the urinary system.

Trace the pathway of fluid through the nephron.
Urine is Formed Through Filtration and Osmosis

LEARNING OBJECTIVES

- Define glomerular filtration
- Explain the functions of the PCT, loop, and DCT

**LIQUID IS FORCED INTO THE LUMEN OF THE GLOMERULUS**

To understand how this filtration occurs, it may help to review the material on osmosis and pressure from Chapter 3. Glomerular blood pressure is higher than systolic blood pressure. This increase is partially caused by the kinking and twisting of the glomerular vessels. You have experienced this in your garden hose if you have ever bent it. The pressure increases because the water must travel past the obstructions. A similar phenomenon occurs in the glomerular vessels. In addition, the incoming (afferent) arterioles have a larger diameter than the outgoing (efferent) glomerular arterioles. This increases pressure in the glomerulus by creating back pressure. The total pressure on the blood forces most of the fluid into the capsule. In order to actually filter the blood, the blood pressure has to overcome the pressure of the fluid already in the capsule (capillary pressure) as well as the osmotic pressure of the blood itself.

Because the glomerular system relies on pressure, there is a lower limit to its functioning (Figure 14.6). If your systolic pressure drops below 60 millimeters Hg, blood in the glomerulus will not be forced through the glomerular wall because glomerular pressure will not rise high enough to force plasma from the blood vessels. This leads to serious complications because the aqueous portion of the blood cannot filter into the nephron and therefore cannot be cleansed.

During filtration, the formed elements and plasma proteins remain in the glomerular vessel because they are too large to pass through the fenestrations of the cells that line the glomerulus (Figure 14.7). The proteins left in the blood of the capillary are essential because they set up the osmotic gradient that later pulls most of the water from the filtrate back into the blood. Every day, approximately 180 liters of fluid are filtered from the blood, but only a small fraction of that is excreted. Imagine how different life would be if we lost 180 liters of fluid every day! That is equal to 60 times the total plasma volume of the body. Not only would we have to drink constantly, but we would most likely also have a different social custom surrounding the need to urinate, because it would occur almost constantly. In the body as in the biosphere, recycling makes a real difference.

---

**Figure 14.6**

Glomerular pressure

1. The force of the blood in the glomerular vessel causes fluid to leak into the nephron.
2. The fluid already in the nephron exerts an opposite force, a back pressure preventing a huge influx of fluids.
3. The now thicker blood pulls water back into it from the more watery filtrate in the nephron. The net filtration pressure is the sum of these three forces: #1 pushing fluid into the nephron, while #2 and 3 pull water back from the nephron.
4. The osmotic pressure of the blood in the peritubular capillaries from the nephron tubule. If these conditions are not met, the nephron cannot filter the blood, and the urinary system will fail.

**Figure 14.7**

Renal corpuscle histology

The blood is forced through the walls of the glomerulus via increased blood pressure. Water, ions, nutrients, and waste materials pass through the fenestrations of the podocytes (specialized cells comprising the glomerular walls).
How much water should I drink?

Water. It's just about the most popular nutrient around, and these days, hydration is almost a personal virtue. Adequate hydration is necessary for the functioning of the kidneys and most other body systems. Water maintains the blood's volume, helping it transport nutrients and remove wastes. When water is scarce, homeostasis is threatened, and especially so during illness or physical exertion.

Hydration, combined with adequate sodium levels in the interstitial fluids, helps keep the osmolarity the same on both sides of the cell membrane. Underhydration, if not corrected by the urinary system through mechanisms discussed in the main text, can cause water to osmose from the cells into interstitial fluid. Overhydration, sometimes called "water intoxication," can cause water to osmose into cells, creating swelling, or edema.

How much water should we drink? Historically, the standard advice was to drink eight 8-ounce glasses of water each day. Oddly, this widely trumpeted health advice did not have a scientific basis. In 2004, the National Academy of Sciences (NAS) came up with some scientifically supported advice. According to the NAS recommendations, a man needs to ingest 3.0 liters of fluids (not counting moisture from food) each day. Oddly, this widely trumpeted health advice did not have a scientific basis. In 2004, the National Academy of Sciences (NAS) came up with some scientifically based recommendations. According to the NAS recommendations, a man needs to ingest 3.0 liters of fluids (not counting moisture from food) each day.

If this recommendation is accurate, the 8 by 8 advice (1.9 liters) seriously understated the need for water. According to the NAS recommendations, a man needs to ingest 3.0 liters of fluids (not counting moisture from food) to stay hydrated.

In hot, dry conditions, or during strenuous exercise, fluid consumption must increase. And that raises one final question: When is water a cure rather than a cure? In rare situations, athletes have died from hyponatremia, a rare condition in which the blood's sodium concentration is too low. This condition resembles water intoxication: Cells swell and can burst, as water responds to the higher sodium concentration by undergoing osmosis, moving from interstitial fluid into the cells. So instead of guzzling gallons of water during athletic events, it may be better to swill sports drinks, including glucose and amino acids, and important ions such as sodium, calcium, and potassium, occur in the PCT.

The NAS researchers found that each day, healthy women in the United States consume about 2.7 liters of water from food and beverages, whereas men consume about 3.7 liters. About 80 percent of that amount comes from water and other beverages, and the rest from moisture in food. In general, the NAS experts said, hydration is not something to worry about because "thirst provides the body feedback that we are getting dehydrated, so that we can consume more fluids."

If this recommendation is accurate, the 8 by 8 advice (1.9 liters) seriously understated the need for water. According to the NAS recommendations, a man needs to ingest 3.0 liters of fluids (not counting moisture from food) to stay hydrated.

As filtrate passes through the nephron, ions and water are returned to the peritubular capillaries in a process called tubular reabsorption. Approximately 80% of the filtered water is returned to the blood immediately at the PCT. Glucose, amino acids, and salts are also returned to the bloodstream. The walls of the proximal convoluted tubule have a large surface area to accommodate all this reabsorption. The cells that line the PCT are covered with microvilli. These cells are adjacent to the endothelial cells of the peritubular capillaries, creating a thin layer that allows diffusion from the tubule to the blood.

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CHAPTER 14

The Urinary System

Urine formation begins in the glomerulus, where blood plasma is filtered and collected by the renal corpuscle. At the PCT, most of the water and many ions and nutrients are reabsorbed by the blood. The loop serves to remove more water and ions, setting up a salt gradient in the medulla of the kidney. This is referred to as countercurrent multiplication, or CCM, because the ascending and descending loop flow opposite each other. Each current affects the water and salt concentration in the other. The collecting ducts pass right through the salt gradient set up by the CCM, providing one last opportunity to remove water from the urine before sending it on to the ureters. Water is a vital fluid and as such must be carefully monitored. The Health Wellness and Disease box, “How much water should I drink?” takes a look at the role of water in personal health.

This process requires ATP, and provides delicate control over fluid homeostasis. Tubular secretion provides a fine-tuning of the dissolved compounds in the blood. It is this process that provides clues as to the amount and type of drugs that are traveling through the body at any one time. Most of the breakdown products of drugs, both pharmaceutical and recreational, are large and must be secreted into the nephron. The Ethics and Issues box in the last section of the chapter discusses this in detail.

The loop of the nephron and the collecting duct help remove even more water from the filtrate, serving to precisely regulate fluid loss (Figures 14.12 and 14.11). Interestingly, the descending arm of the loop of the nephron is permeable to water, but the ascending limb is not. Therefore, water leaves the filtrate as it moves down the loop of the nephron, and salts leave the filtrate as it flows up the ascending arm, creating a salt gradient in the medulla of the kidney. This is referred to as countercurrent multiplication, or CCM, because the ascending and descending loop flow opposite each other. Each current affects the water and salt concentration in the other. The collecting ducts pass right through the salt gradient set up by the CCM, providing one last opportunity to remove water from the urine before sending it on to the ureters. Water is a vital fluid and as such must be carefully monitored. The Health Wellness and Disease box, “How much water should I drink?” takes a look at the role of water in personal health.

The countercurrent multiplication activity of the nephron loop can be easily seen in this diagram. Because of this action, the medulla of the kidney is a very salty area.

The urinary system is formed through filtration and osmosis.
The urinary bladder is a hollow, variable-sized organ (Figure 14.14). It lies in the pelvic cavity, posterior to the pubic bones and the pubic symphysis. The bladder is lined with transitional epithelium to allow for expansion without tearing. The base of the bladder has a triangular area where the two ureters enter and the urethra exits. This area is called the trigone. The bladder is transported to the bladder for storage through the renal pelvis and the ureter often do the trick, but some stones are too large to pass. These may be broken apart by ultrasound waves, to allow the fragments to be excreted. Because kidney stones often reappear, patients are asked to avoid foods high in calcium, eat less protein (to decrease urine acidity), and drink more fluids, especially water.

**Urine is Transported to the Bladder for Storage**

**LEARNING OBJECTIVES**

- Outline the functions of the bladder and the urethra.
- Understand why females are more susceptible to urinary tract infections.

The filtrate has passed through the nephron and collecting ducts, and reaches the renal pelvis; it is referred to as urine. Most of the fine-tuning of ion concentration and water content is completed by this point (Table 14.1). Water can still be removed as the urine sits in the remainder of the organs of the urinary system, but the salt content is relatively stable. While in the renal pelvis, water can continue to leave the urine, concentrating the salts in the urine. This can lead to the formation of kidney stones. These rock-like masses, usually composed of calcium oxalate, can grow large enough to block renal flow (Figure 14.12). Kidney stones are extremely painful as they move through the urinary pelvis and can become lodged in the kidney or the ureters. Some kidney stones are jagged or pointy, making them even more likely to jam in the system. Removal of kidney stones rarely requires medical assistance. Drinking lots of water and resting as the stone moves through the urinary pelvis and the ureter often do the trick, but some stones are too large to pass. These may be broken apart by ultrasound waves, to allow the fragments to be excreted. Because kidney stones often reappear, patients are asked to avoid foods high in calcium, eat less protein (to decrease urine acidity), and drink more fluids, especially water.

**Substances Filtered, Reabsorbed, and Excreted in Urine per Day**

<table>
<thead>
<tr>
<th>Substance</th>
<th>Filtered* (enters renal tubule)</th>
<th>Reabsorbed (returned to blood)</th>
<th>Excreted in Urine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>180 liters</td>
<td>178–179 liters</td>
<td>1–2 liters</td>
</tr>
<tr>
<td>Chloride ions (Cl⁻)</td>
<td>640 g</td>
<td>607.7 g</td>
<td>32.3 g</td>
</tr>
<tr>
<td>Sodium ions (Na⁺)</td>
<td>579 g</td>
<td>575.1 g</td>
<td>3.9 g</td>
</tr>
<tr>
<td>Bicarbonate ions (HCO₃⁻)</td>
<td>275 g</td>
<td>274.97 g</td>
<td>0.03 g</td>
</tr>
<tr>
<td>Glucose</td>
<td>162 g</td>
<td>162 g</td>
<td>0</td>
</tr>
<tr>
<td>Urea</td>
<td>54 g</td>
<td>54 g</td>
<td>0</td>
</tr>
<tr>
<td>Potassium ions (K⁺)</td>
<td>29.6 g</td>
<td>29.6 g</td>
<td>2.0 g*</td>
</tr>
</tbody>
</table>

* Assuming glomerular filtration is 180 liters per day.
† In addition to being filtered and reabsorbed, water is secreted.
‡ After virtually all filtered K⁺ is reabsorbed in the convoluted tubules and loop of Henle, a variable amount of K⁺ is secreted in the collecting duct.

From the renal pelvis, urine travels down the ureter to the urinary bladder (Figure 14.12). The ureters are approximately 20-centimeter-long, thin muscular tubes lined with mucous. The ureters loop behind the urinary bladder and enter it at the base. This allows the bladder to expand upward without dislodging the ureters. With every heartbeat, blood is pushed into the glomerulus and filtered. The nephrons constantly form urine, so the tubes and ducts of the urinary system are always full of fluid. As more urine is produced, it pushes what is already formed down the ureters and into the bladder, where small contractions move the urine toward the bladder.

**The Urinary Bladder Stores Urine Before Release**

The urinary bladder is a hollow, variable-sized organ (Figure 14.14). It lies in the pelvic cavity, posterior to the pubic bones and the pubic symphysis. The base of the bladder has a triangular area where the two ureters enter and the urethra exits. This area is called the trigone. The bladder is lined with transitional epithelium to allow for expansion without tearing or
destroying the integrity of the inner lining. The empty bladder is the size of a walnut, but can stretch to hold up to 800 ml of fluid in males, and slightly less in females.

Discharging urine from the bladder is called urinating, voiding, or micturition. This reflex involves both smooth and skeletal muscles. Urine is constantly being formed and drained into the bladder. When the bladder contains approximately 300 ml, pressure in the bladder stimulates stretch receptors that send nerve impulses to the micturition center. The micturition reflex causes contraction of the walls of the bladder and relaxation of the internal urethral sphincter muscle. Urine moves down into the urethra, pressing on the external sphincter muscle. At this point, you can consciously control the opening of the external urinary sphincter. Should you choose not to void the contents of the bladder, the urge to urinate will subside until the next 300 ml is collected in the bladder.

As we mature, we learn to anticipate and control this reflex, but we cannot delay micturition indefinitely. The bladder continues to expand, and a second reflex will begin shortly. Just as we are not able to hold our breath until we die, we cannot retain urine until the bladder bursts. When the bladder reaches 700 to 800 ml, micturition occurs despite our best efforts to control the external urethral sphincter.

**THE URETHRA TRANSPORTS URINE OUT OF THE BODY**

When micturition occurs, the urine leaves the body via the urethra, a single tube extending from the trigone of the bladder to the exterior. In females, the urethra is a short 5 centimeters, emptying in front of the vaginal opening. The male urethra is almost four times longer because it runs the length of the penis (Figure 14.15). The urinary and reproductive systems join in the male, sharing the male urethra. In the female, the two systems are separate. The female urethra carries only urine, and the female reproductive tract opens at the vaginal orifice.

Because the distance from the exterior to the bladder is shorter in females, they suffer far more urinary tract infections (UTIs). Bacteria outside the body can travel the short distance up the urethra and colonize the bladder, resulting in painful urination often accompanied by bleeding from the irritated bladder walls. (If the urine contains glucose, the bacteria multiply even faster.) UTIs are serious infections that must be cleared up. If the bacteria are allowed to remain in the bladder, they will eventually travel up the ureters and colonize the pelvis and tubules of the kidney. Kidney infections are painful and serious because they block normal kidney function and can lead to kidney failure.

**Comparison section showing the female urethra**

**Comparison between female and male urethras**

**Figure 14.15**

**INCONTINENCE IS THE LOSS OF CONTROL OVER VOIDING**

As we age, many things change, including our ability to control micturition when the urge arises. Incontinence can and does occur in all age brackets, genders, and social levels, but it is far more common in elderly women. Perhaps the stress of bearing children weakens the muscles of the pelvic floor, leading to greater difficulty controlling these muscles in later years.

An estimated 12 million Americans suffer incontinence, and most do not require surgery. Incontinence can be a symptom of many different pathologies but is not a pathology in its own right. Causes include chronic urinary tract infections, side effects of medication, muscular weakness, an enlarged prostate gland in males, constipation, or neuromuscular disease. There are three types of incontinence determined by the underlying cause of the problem, each with the same result. Stress incontinence is the leaking of urine during physical exertion. Urge incontinence is the inability to quell the urge to urinate. Overflow incontinence is the overflowing of the urinary bladder caused by waiting too long before urinating, as happens in young children who are learning to control their sphincter muscles. Treatment for incontinence is tailored to the cause. Muscular strengthening exercises or behavioral modification may be recommended.
A key function of the kidneys is to maintain the body’s water and salt balance. Excreted urine usually has a much different osmolarity than the blood. When it is originally filtered from the blood, the fluid in the nephrons has the same water-to-solute ratio as the blood. As it moves through the nephron, this ratio changes to produce concentrated or dilute urine, depending on the body’s demands. Dilute urine is produced by removing solutes from the forming urine leaving the nephron. Water cannot pass back across the walls of the DCT or the collecting tubule. As the ion concentration drops in the urine, the water proportion increases, so fluid reaching the collecting duct is far less concentrated than blood plasma, resulting in dilute urine (Figure 14.16).

Concentrated urine is produced by the reabsorption of water at the loop of the nephron and the collecting duct (Figure 14.17). The cells of the DCT can be hormonally controlled to reabsorb water when the proper hormones are present. Water can also be reabsorbed across the walls of the urinary bladder. This reabsorption explains why the first morning urination is more concentrated than urine produced and passed later in the day.

Osmolarity
Osmotic pressure of a solution.

Solutes
Substances dissolved in the solvent.

The numbers seen in this image represent the osmolarity of the filtered fluid in milliosmoles per liter. The brown lines surrounding the ascending loop of the kidney and the DCT are areas where water cannot leave the tubule. The blue lines indicate areas of the collecting duct that are impermeable to water only when ADH is not present. If ADH is absent, urine osmolarity can be as low as 65 mOsm/liter, which is very dilute.

Formation of concentrated urine

The area of the nephron that is outlined in green indicates the area where ions are reabsorbed into the interstitial fluid. The nephron here is also relatively impermeable to water, creating a salty area in the medulla of the kidney through which the collecting ducts travel. As fluid moves through this salty area, water is pulled from the collecting ducts, resulting in concentrated urine. All numbers are again in milliosmoles per liter.
I WONDER . . .

Why do they keep telling me to cut down on salt?

Table salt is sodium chloride, and sodium is about as essential as electrolytes get because it helps control osmosis throughout the body. But eating a lot of salt can raise the blood pressure by causing a subtle swelling of the tissues. Over long periods, hypertension can cause deadly or disabling strokes, heart attacks, heart failure, or kidney failure. For years, we’ve been told to cut down on the salt. But that is easier said than done. As mentioned in the text, the kidney is built to recycle salt, enabling some people to survive on less than 1 gram per day. Salt improves the taste of food, and evolution has forced us to crave salt. Sodium chloride is so vital that in the hot, dry Sahara desert bordering the Southwestern desert, salt sells for 25 cents per gram—for gold. You can certainly live without salt, but you will die without salt.

Today, the National Academy of Sciences weighed into the salt debate by suggesting that people aged 19 to 50 ingest at least 1.5 grams of sodium per day. This intake, the group’s experts said, would replace losses due to sweating and help ensure an adequate supply of other nutrients.

At the other end of the spectrum, the National Academy recommended a maximum of 2.3 grams of sodium per day. This intake, the group’s experts said, would replace losses due to sweating and help ensure an adequate supply of other nutrients.

Water can be reabsorbed into the bloodstream at the DCT and collecting duct with help from the hormone ADH (antidiuretic hormone) (Figure 14.18). A diuretic increases the volume of urine produced, whereas an antidiuretic decreases the volume of urine produced. ADH will therefore decrease urine volume. ADH is secreted by the posterior lobe of the pituitary gland, located on the undersurface of the brain, in response to blood volume. ADH in the blood causes the cells surrounding the collecting duct and the DCT to remove more water from the urine, returning it to the depleteded bloodstream.

Surprisingly, sodium is conserved almost as stringly as water. It is important to remember that where sodium goes, water follows. If you live in a humid area, you already know this. In the Deep South, the Midwest in summer, the southern shorelines of the East and West Coasts, and on Pacific islands, humidity can clog salt shakers because sodium chloride draws water molecules from the air, causing clumps in the salt shaker. If you add a few grams of uncooked rice to the salt shaker, they will absorb the water from the salt, preventing the salt crystals from sticking together.

In the nephron, this attraction between water and sodium is used to good advantage. More than 99 percent of the sodium filtered from the blood at the glomerulus is returned before the urine leaves the nephron. Two-thirds of this reabsorption occurs at the PCT. Another 25 percent of the filtered sodium is removed from the forming urine at the ascending limb of the loop of the nephron. This loop sets up a sodium gradient in the medulla of the kidney by removing sodium from the filtrate. Sodium is also reabsorbed from the DCT and the collecting duct, so sodium levels are strictly maintained. (For more on salt consumption, see The Wonder Box.)

Several hormones are involved in salt regulation. Aldosterone, atrial natriuretic peptide (ANP), and brain natriuretic peptide (BNP) all regulate sodium reabsorption at the distal convoluted tubule. Aldosterone causes the excretion of potassium ions and the reabsorption of sodium ions, so water will leave the filtrate with the sodium ions rather than leave with the potassium ions. ANP and BNP both oppose ADH. When either is present, the kidneys produce lots of dilute urine.

Ingested chemicals can also affect nephron function. Caffeine and alcohol both increase urine production, apparently through decreased ADH production. When caffeine is ingested in quantities below 350 mg, we experience central nervous system stimulation, decreased sleepiness, and possible increases in athletic performance. But the side effects include a potential headache and drowsiness as the caffeine wears off, and insomnia. The diuretic effects of caffeine are not particularly helpful. Dehydrated muscle cramps more easily and are less likely to be re-paired after injury. Your body cannot achieve peak function without good hydration.

The Urinary System Maintains the Body’s Water-Salt Balance
The Kidneys Help Maintain the Blood’s Acid-Base Balance

**LEARNING OBJECTIVES**
- Define the carbonate buffering system of the blood.
- Explain the role of the kidneys in maintaining blood pH.

**Body pH**

Body pH must be held within a narrow range (7.35 to 7.45). This is done primarily through the bicarbonate buffer system of the respiratory system, with help from the urinary system. This pH stability is achieved through the maintenance of chemical equilibrium. In the body, all three compartments are equal (blood, returning the reaction to a point where all three bicarbonate ions (HCO₃⁻) actions are “pushed to the right.” In order to maintain homeostasis, we say it is “pushing the reaction to the left.” As the reactions return to equilibrium, when this happens, we say it is “pushing the reaction to the left.”

\[ H^+ + HCO_3^- \rightarrow H_2CO_3 \rightarrow H_2O + CO_2 \]

When carbon dioxide is exhaled, the above reactions are “pushed to the right.” In order to maintain an equal concentration of reactants on either side of the arrows, more hydrogen ions are picked up by the bicarbonate ion (HCO₃⁻) and removed from the blood, returning the reaction to a point where all three compartments are equal (Figure 14.11). This homeostatic function is so vital that the rate and depth of breathing respond to the level of carbon dioxide in the blood. The breathing rate is controlled by the level of bicarbonate ion in the blood. This in turn maintains the buffering capacity of the blood, so that the entire fluid balance of the body is in homeostasis. As the breathing rate increases, carbon dioxide is washed out of the blood, decreasing the bicarbonate ion level. This in turn causes dizziness as the body responds to the loss of buffering capacity. The kidneys must work harder to maintain fluid homeostasis and ion concentrations when this happens. There is a time lag in rectifying the situation because the alteration of the body’s fluid composition by the kidneys is a bit slower than the breathing rate.

**Respiratory system regulation of blood pH**

The breathing rate is controlled by the level of bicarbonate ion in the blood. This in turn maintains the buffering capacity of the blood, so that the entire fluid balance of the body is in homeostasis. As the breathing rate increases, carbon dioxide is washed out of the blood, decreasing the bicarbonate ion level. This in turn causes dizziness as the body responds to the loss of buffering capacity. The kidneys must work harder to maintain fluid homeostasis and ion concentrations when this happens. There is a time lag in rectifying the situation because the alteration of the blood’s fluid composition by the kidneys is a bit slower than the breathing rate.

**Urineary system regulation of blood pH**

The urinary system is the main regulator of blood pH. When blood pH increases (H⁺ concentration decreases), the kidneys also play a role (Figure 14.20). Whereas the bicarbonate system uses an equilibrium reaction, the urinary system removes acidic and basic substances from the fluid and literally flushes them out. If the blood is too acidic, the kidneys can excrete hydrogen ions and send bicarbonate ions back to the blood. Conversely, if the blood is too basic, the kidneys will return hydrogen ions to the blood and excrete bicarbonate ions. This may adjust pH more slowly than the respiratory system, but the results are permanent.

**CONCEPT CHECK**

- **What** is the usual pH of urine? **Why?**
- **How** does the urinary system help maintain fluid pH in the body?
Casts Small structures formed by mineral or fat deposits on the walls of the renal tubules.

**WARNING SIGNALS FROM URINALYSIS**

Abnormal components in urine can include albumin, hemoglobin, red blood cells, white blood cells, glucose, and casts. Each can indicate a specific problem. See Table 14.2 for a listing of the normal and abnormal constituents of urine:

- **Albumin** is a small protein that must be entering the nephrons at the glomeruli. This could reflect high blood pressure in the glomerulus that forces proteins through the podocyte walls, or tears in glomerular arterioles. Normally, albumin remains in the blood to provide an osmotic force to draw excess water back from the filtrate to the blood. Albumin or other less common proteins in the urine are diagnosed as proteinuria.

- **Hemoglobin** indicates bleeding in the upper urinary tract because the red blood cells have been present in the urine long enough to break open and release hemoglobin. Intact red blood cells would indicate bleeding closer to the lower end of the urinary tract, perhaps in the urethra.

- **White blood cells** in the urine indicate that an immune system response is occurring, usually in response to an infection of the urinary tract, or occasionally the kidney.

### Normal and Abnormal Constituents of Urine

<table>
<thead>
<tr>
<th>Normal Constituent</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>One to two liters in 24 hours but varies considerably.</td>
</tr>
<tr>
<td>Color</td>
<td>Yellow or amber but varies with urine concentration and diet. Color is due to urine pigments. Opaque urine is from large concentrations of blood derivatives. Concentrated urine is darker in color. Dull reddish color from hemoglobin, certain disease conditions, or disease conditions that affect color. Kidney stones may produce blood in urine.</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Transparent when freshly voided but becomes hazy (cloudy) upon standing.</td>
</tr>
<tr>
<td>Odor</td>
<td>Mildly aromatic but becomes ammoniacal upon standing. Some people inherit the ability to form odorless trimethylamine from digested ammonia that gives urine a characteristic odor. Urine of diabetics has a fruity odor due to presence of ketones.</td>
</tr>
<tr>
<td>pH</td>
<td>Ranges between 4.6 and 8; average 6.0; varies considerably with diet. High-protein diets increase acidity; vegetarian diets increase alkalinity.</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>Specific gravity (density) is the ratio of the weight of a volume of substance to the weight of an equal volume of distilled water. In urine, it ranges from 1.001 to 1.035. The higher the concentration of solutes, the higher the specific gravity.</td>
</tr>
</tbody>
</table>

**Table 14.2a**

**How does a urine test prove drug abuse?**

Urine analysis (UA) is a noninvasive way to get a holistic picture of the immediate physiological events occurring in the body. In a sense, urine tells us about the chemical processes in the body. As we examine the chemicals in a river tells us about events in the river’s watershed. If a person has been taking illicit drugs, prescribed medications, or even diet supplements, those compounds, or their breakdown products, will show up in the urine.

Urine testing is often used as a screening and diagnostic tool. UA’s are performed when people complain of abdominal pain, back pain, frequent or painful urination, blood in the urine, or other symptoms of a urinary tract infection, which may show up as elevated levels of white blood cells. It is also a routine part of regular physical examinations.

The test detects substances in the urine associated with many metabolic and kidney disorders. An abnormal UA can be an early warning of trouble, because substances like protein or glucose will begin to appear in the urine before a person is aware of a problem. The health care provider must correlate the urinalysis results with physical complaints and clinical findings to make a diagnosis.

Have you ever wondered what happens to your urine sample? The medical professional first examines its physical characteristics, such as clarity, color, odor, and specific gravity. The next step is a chemical analysis, usually with a "dipstick" test that includes many pads soaked with indicator substances. The strip is dipped into the sample, so the urine can interact with the chemicals in each pad. After a specific time (usually 30 seconds) the color of each pad is compared to a reference chart. This comparison is now automated for greater accuracy.

Urine usually contains urocromes, which gives it that yellow color; nitrogenous wastes like ammonia and urea from metabolic processes; water; ions; and casts-off cells from the epithelial lining of the bladder and urethra. In addition, many large molecules enter the urine when blood in the peritubular capillaries passes the distal convoluted tubule. These molecules can include breakdown products of legal and illegal drugs, vitamin and mineral supplements, or even various environmental contaminants.

The pH of urine should be between 4.6 and 8.2, and the specific gravity between 1.002 and 1.028. For reference, distilled water has a specific gravity of 1.000, and the Pacific Ocean has an average specific gravity of 1.025.

When urinalysis is being used to test for the presence of drugs, the sample is first put through a fast, inexpensive, and inaccurate screening test. Samples that test positive are then put into an analytical machine called the gas chromatograph-mass spectrometer (GC/MS). The GCMS first separates compounds based on their mass, and then uses detector chemicals to identify certain compounds. The machine is expensive but is so sensitive that it can easily detect traces of compounds in concentrations of 1 part per billion, or even less.

The GCMS produces a graph showing all chemical compounds detected in the sample. It peaks on the graph indicates the presence of illicit drugs or their metabolites, the test is said to be positive and the person is considered a user of illicit drugs. Drug testing is often sold as a cure-all for detecting drug use, especially among students, athletes, or potential employees. But urinalysis is not perfect. A test result can indicate metabolites of over-the-counter or prescription drugs for those of illicit drugs, forcing test administrators to interpret results carefully. Poppy seeds, found on bagels and pastries, can break down into compounds that resemble metabolites from opiate drugs, because opiates and poppy seeds both come from the opium poppy. Urinalysis is more effective at detecting some drugs than others. Marijuana and other drugs are detectable in the urine for long periods, whereas alcohol and cocaine are cleared quickly from the body. Finally, drug testing is expensive, and some studies suggest that the knowledge that urinalysis will be performed on a regular basis has little effect on employee performance.

The most common "street" advice for fooling a urinalysis, or passing as "clean" despite having recently introduced illicit drugs into your system, is to dilute the urine by drinking massive quantities of water before filling the sample cup. But the GCMS is so sensitive that it can usually pick up traces of drug metabolites in very dilute urine. Deliberately ingesting compounds that will interfere with drug tests also raises medical questions. And these "interferences" are identified in the test, raising a red flag. The best, most surefire way to test drug-free is to live drug-free.
Glomerulonephritis is a general term for blockage of the glomeruli, the functional units of the kidney responsible for filtering blood. Glomerulonephritis can be caused by various conditions, including infections, autoimmune diseases, and medications. It often leads to kidney failure, where the kidneys are no longer able to filter blood effectively, leading to retention of waste products and toxins in the body. Treatment may include medications, dialysis, or kidney transplantation.

Glomerulonephritis may occur due to:
- Allergic reactions to certain medications or foods
- Infections, such as strep throat
- Systemic lupus erythematosus
- Diabetes
- Systemic sclerosis
- Systemic vasculitis
- Amyloidosis
- Sjögren syndrome
- Drug-induced

### Table 14.2b: Normal and Abnormal Constituents of Urine

<table>
<thead>
<tr>
<th>Abnormal Constituent</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>The presence of glucose in urine is called glucosuria. It may be due to diabetes mellitus or renal disease.</td>
</tr>
<tr>
<td>Bilirubin</td>
<td>The presence of bilirubin in urine is called bilirubinuria. It may be due to liver disease or jaundice.</td>
</tr>
<tr>
<td>Casts</td>
<td>Casts are tiny masses of material that have hardened and assumed the shape of the lumen of the tubule in the kidney.</td>
</tr>
</tbody>
</table>

### Normal Constituents

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albumin</td>
<td>Albumin is a protein that is produced in the liver and is filtered by the glomerulus. It is a marker for albuminuria.</td>
</tr>
</tbody>
</table>

### Figure 14.21: Hemodialysis

Hemodialysis is a procedure used to filter and purify blood when the kidneys are unable to do so. It involves passing blood through a dialyzer, a machine that removes waste products and excess water from the blood. Hemodialysis is typically done several times a week and is a life-saving procedure for those with end-stage renal disease. The procedure is usually performed in a hospital or dialysis center and requires a temporary or permanent access to the bloodstream. Patients undergoing hemodialysis may experience symptoms such as fatigue, nausea, and muscle cramps. With proper care and management, patients can lead relatively normal lives despite their condition.
CHAPTER SUMMARY

1 The Urinary System Filters, Transports, and Stores Waste Products

The urinary system is responsible for maintaining fluid homeostasis, ion balance, and blood calcium concentration and for removing fluid waste from the body. The system includes the paired kidneys, the paired ureters, the urinary bladder, and the urethra. The renal pelvis consists of a glomerular capsule surrounded by the renal cortex, an outer convolution, and a loop, and a distal convoluted tubule connected to a collecting duct. Each portion of the tubule has a distinct role in filtering blood, balancing ions and pH, and removing wastes.

2 Urine Is Formed Through Filtration and Osmosis

The nephron is the functional unit of the urinary system. It is made up of 100 liters of fluid are filtered and maintained per day. Glomerular filtration depends on blood pressure, capillary hydrostatic pressure, and osmotic pressure of the blood. The filtrate is captured in Bowman’s capsule and passed to the PCT, where most of the necessary nutrients and water are reabsorbed. The loop of the nephron extends into the middle of the kidney, and assists in removal of salts and water. The OCT is involved in secretion from the blood to the forming urine. The collecting ducts remove urine from the kidney.

3 Urine Is Transported to the Bladder for Storage

Urine is stored in the bladder until voided. After 200 ml of urine fills the bladder, the micturition reflex is stimulated. The voluntary, external urinary sphincter determines when voiding takes place. Incontinence is the loss of this control. The female urethra is shorter than the male urethra, leading to a higher incidence of urinary tract infection in females.

4 The Urinary System Maintains the Body’s Water–Salt Balance

Hormones regulate the amount of water and ions excreted with the urine. Aldosterone regulates sodium reabsorption, effectively preventing the loss of water, causing the production of concentrated urine. ADH regulates sodium reabsorption, effectively removing water and sodium from the body. ANP and BNP work in opposition to ADH, causing the formation of dilute urine.

5 The Kidneys Help Maintain the Blood’s Acid–Base Balance

The kidneys and respiratory system combine to control blood pH. The urinary system can remove acidic and basic substances from the fluid and flush them from the body, with permanent results. If the blood is too acidic, the kidneys can excrete hydrogen ions and send bicarbonate ions back to the blood. If the blood is too basic, the kidneys will return hydrogen ions to the blood, and excrete bicarbonate ions.

6 Life-Threatening Diseases Affect the Urinary System

Dialysis is the exchange of aqueous substances between two solutions through a membrane. In effect, the entire nephron performs dialysis with the peritubular capillaries on a continuous basis. When the kidney shut down, dialysis must continue somehow, or the blood will become toxic to the cells of the body. Dialysis machines permit dialysis to occur outside the body.

KEY TERMS

- arteriole
- calcium oxalate
- casts
- capillarization
- countercurrent multiplication
- dialysis
- external sphincter muscle
- facilitated diffusion
- fenestrations
- H+ ions
- incontinence
- internal-urethral sphincter
- microvilli
- nephron
- nitrogenuous wastes
- vasomotor
- peritubular capillaries
- secretion
- solutes
- specific gravity

CRITICAL THINKING QUESTIONS

1. Imagine that you contracted a urinary tract infection and did not treat it. Trace the pathway of the bacteria as it moves up the urinary system. What structures would you expect to be damaged by the bacteria once they reached the kidneys?

2. Many home pregnancy tests look for a specific protein in the urine. This compound is present only in pregnant women. Why do the tests recommend using first morning urine? How is it different from urine produced and excreted at midday?

3. Coffee and alcohol both block the secretion of ADH from the posterior pituitary gland. Explain what this does to fluid balance. Does it make sense to drink caffeine before an athletic event? Explain why a cold beer may not be such a great idea on a hot afternoon.

4. What are the differences between hemodialysis and peritoneal dialysis? What are the benefits of each? What are the drawbacks?

5. Assume you were given the following results from a series of urinalysis tests. What would each test indicate?

- Cloudy urine, above-normal specific gravity, high white blood cell count, many transitional epithelial cells. Presence of protein, casts, and hemoglobin. Presence of glucose and ketones (ketones are a by-product of the digestion of body proteins)
- Pale-yellow color, pH 6.8, specific gravity 1.015, no RBCs, no proteins.

6. Why might the female urethra be shorter than the male urethra, leading to a higher incidence of urinary tract infection in females?
SELF TEST

1. Which of the following is NOT a specific function of the urinary system?
   a. Production of urine
   b. Maintenance of blood pH
   c. Maintenance of blood volume
   d. Maintenance of red blood cell levels

2. The function of the structure indicated as C is
   a. Filtration of blood
   b. Transport of urine within the body
   c. Transport of urine from the body
   d. Storage of produced urine

3. In the above diagram, the urethra is indicated by label
   a. A
   b. B
   c. C
   d. D

4. The renal pyramids are composed of
   a. Glomeruli
   b. Peritubular capillaries
   c. Collecting ducts
   d. Renal capsules

5. The correct sequence of blood vessels through the kidney is
   a. Renal artery → interlobar artery → afferent arteriole → peritubular capillaries → renal vein
   b. Renal vein → renal artery → peritubular capillaries → arculate artery → interlobar veins
   c. Renal artery → peritubular capillaries → efferent arteriole → peritubular capillaries → renal vein
   d. Renal artery → efferent arteriole → peritubular capillaries → interlobar artery → renal vein

6. The function of the structure indicated as B is to
   a. Filter blood
   b. Collect filtrate
   c. Reabsorb necessary nutrients
   d. Secret unwanted large waste products

7. In the above figure, label E indicates the
   a. PCT
   b. Loop of Henle
   c. DCT
   d. Glomerulus

8. The portion(s) of the nephron that are usually found in the cortex of the kidney are
   a. PCT, capsule, and loop of Henle
   b. PCT and DCT
   c. Loop of Henle and collecting duct
   d. PCT, capsule, and DCT
   e. Capsule only

9. When blood is filtered through the glomerulus, the two forces opposing movement into the nephron are
   a. A and B
   b. B and C
   c. A and C
   d. All of these forces oppose movement into the capsule

10. Most of the filtered water, and hopefully all of the filtered glucose is returned to the bloodstream at the
    a. PCT
    b. DCT
    c. Loop of Henle
    d. Collecting duct

11. The portion of the nephron that sets up the salt gradient in the medulla of the kidney is the
    a. PCT
    b. DCT
    c. Loop of Henle
    d. Collecting duct

12. The structure shown below is formed when
    a. Overly dilute urine is produced
    b. Overly concentrated urine is produced
    c. Kidney failure is experienced
    d. Too many calcium-rich foods are consumed

13. True or false: The urethra in the image below carries both urine and reproductive fluids.

14. Dilute urine is produced when
    a. ADH is present
    b. ADH is absent
    c. Solutes are added to the forming urine
    d. Water is removed from the collecting duct

15. If you drink more water than you need, you will
    a. Excrete and you will lose water through the urinary system
    b. ADH
    c. Aldosterone
    d. Both b and c will be secreted

16. True or false: Both caffeine and alcohol serve as diuretics, causing the production of copious dilute urine.

17. The compound most important in driving respiration rates and depth of breathing shown in the feedback loop in this figure is
    a. Oxygen
    b. Bicarbonate ions
    c. Carbon dioxide
    d. Hydrogen ions

18. Urinary analysis is able to detect all of the following EXCEPT:
    a. Vitamin supplementation
    b. Illegal drug use
    c. Viral infection
    d. Metabolic kidney disorders

19. White blood cells in the urine indicate
    a. Normal urinary tract functioning
    b. A possible UTI
    c. Bleeding in the kidneys or ureters
    d. Diabetes mellitus

20. During this procedure, if a physician wants to remove excess potassium from the blood, she or he must include
    a. Normal urinary tract functioning
    b. A possible UTI
    c. Bleeding in the kidneys or ureters
    d. Diabetes mellitus

21. True or false: Both caffeine and alcohol serve as diuretics, causing the production of copious dilute urine.

22. The compound most important in driving respiration rates and depth of breathing shown in the feedback loop in this figure is
    a. Oxygen
    b. Bicarbonate ions
    c. Carbon dioxide
    d. Hydrogen ions

23. Urinary analysis is able to detect all of the following EXCEPT:
    a. Vitamin supplementation
    b. Illegal drug use
    c. Viral infection
    d. Metabolic kidney disorders

24. White blood cells in the urine indicate
    a. Normal urinary tract functioning
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    c. Bleeding in the kidneys or ureters
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25. During this procedure, if a physician wants to remove excess potassium from the blood, she or he must include
    a. Normal urinary tract functioning
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    c. Bleeding in the kidneys or ureters
    d. Diabetes mellitus