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

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

Urine Formation

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

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

▲ Homeostatic Imbalance

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

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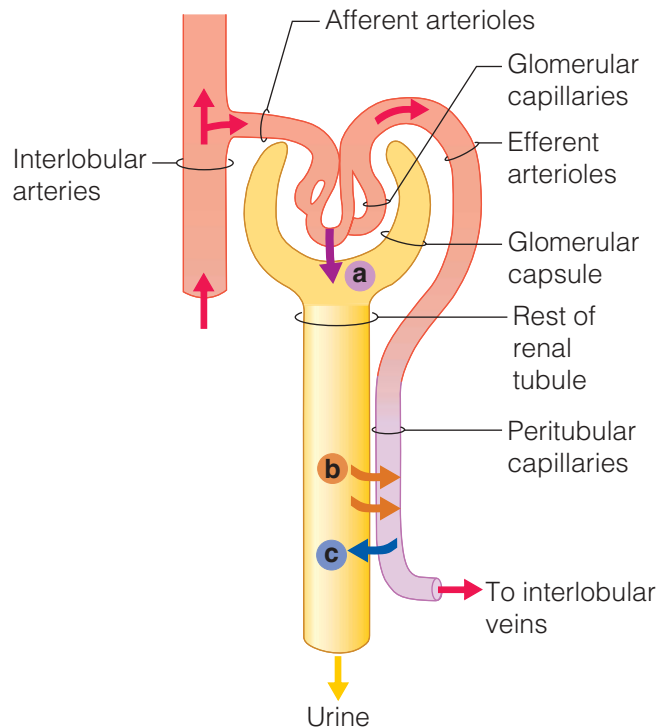
KEY:

a **Filtration:** Water and solutes smaller than proteins are forced through the capillary walls and pores of the glomerular capsule into the renal tubule.

b **Tubular Reabsorption:** Water, glucose, amino acids, and needed ions are transported out of the filtrate into the tubule cells and then enter the capillary blood.

c **Tubular Secretion:** H^+, K^+, creatinine, and drugs are removed from the peritubular blood and secreted by the tubule cells into the filtrate.

FIGURE 15.4   The kidney depicted schematically as a single large, uncoiled nephron. A kidney actually has millions of nephrons acting in parallel. The three processes by which the kidneys adjust the composition of plasma are **(a)** filtration, **(b)** tubular reabsorption, and **(c)** tubular secretion.
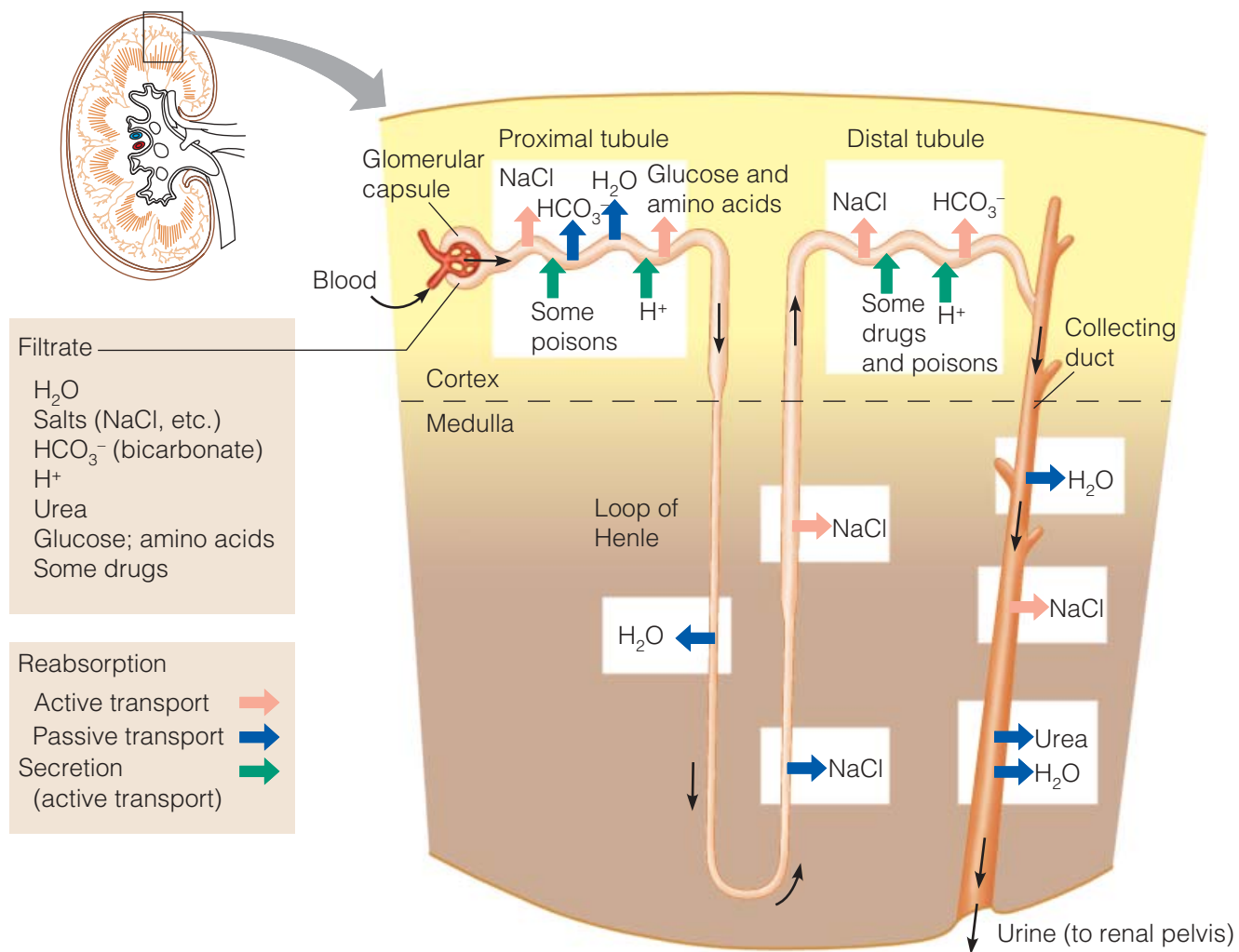
FIGURE 15.5 **Sites of filtration, reabsorption, and secretion in a nephron.**

(Figure 15.5). The tubule cells are "transporters," taking up needed substances from the filtrate and then passing them out their posterior aspect into the extracellular space, from which they are absorbed into peritubular capillary blood. Some reabsorption is done passively (for example, water passes by osmosis), but the reabsorption of most substances depends on active transport processes, which use membrane carriers and are very selective. There is an abundance of carriers for substances that need to be retained, and few or no carriers for substances of no use to the body. Needed substances (for example, glucose and amino acids) are usually entirely removed from the filtrate. **Nitrogenous waste products** are poorly reabsorbed, if at all. These include **urea** (u-re′ah),

formed by the liver as an end product of protein breakdown when amino acids are used to produce energy; **uric acid,** released when nucleic acids are metabolized; and **creatinine** (kre-at′ĭ-nin), associated with creatine (kre′ah-tin) metabolism in muscle tissue. Because tubule cells have few membrane carriers to reabsorb these substances, they tend to remain in the filtrate and are found in high concentrations in urine excreted from the body. Various ions are reabsorbed or allowed to go out in the urine, according to what is needed at a particular time to maintain the proper pH and electrolyte composition of the blood. Most reabsorption occurs in the proximal convoluted tubules, but the distal convoluted tubule and the collecting duct are also active.

ischemia at the shunt site. Hemorrhage is an added risk, because the blood must be heparinized to prevent clotting during hemodialysis. (*Heparin* is an anticoagulant.)

A less efficient but more convenient procedure for patients who are not hospitalized is *continuous ambulatory peritoneal dialysis (CAPD)*. CAPD uses the patient's own peritoneal membrane as the dialyzing membrane. Fluid that is equal in chemical content to normal plasma

and interstitial fluid is introduced into the patient's peritoneal cavity with a catheter and left to equilibrate there for 15 to 60 minutes. Then the dialysis fluid is retrieved from the peritoneal cavity and replaced with fresh dialysis fluid. The procedure is repeated until the patient's blood chemistry reaches normal. Because some ambulatory patients may be inattentive to cloudy or bloody dialysis fluid, infection is more common in CAPD than in hemodialysis.

When renal damage is nonreversible, as in chronic, slowly progressing renal failure, the kidneys become totally unable to process plasma or concentrate urine, and a kidney transplant is the only answer. Unhappily, the signs and symptoms of this life-threatening problem become obvious only after about 75 percent of renal function has been lost. The end-stage of renal failure, *uremia,* occurs when about 90 percent of the nephrons have been lost.

Tubular Secretion **Tubular secretion** is essentially reabsorption in reverse. Some substances, such as hydrogen and potassium ions and creatinine, also move from the blood of the peritubular capillaries through the tubule cells or from the tubule cells themselves into the filtrate to be eliminated in urine. This process seems to be important for getting rid of substances not already in the filtrate, such as certain drugs, or as an additional means for controlling blood pH (Figure 15.5).

Characteristics of Urine

In 24 hours, the marvelously complex kidneys filter some 150 to 180 liters of blood plasma through their glomeruli into the tubules, which process the filtrate by taking substances out of it (reabsorption)

and adding substances to it (secretion). In the same 24 hours, only about 1.0 to 1.8 liters of urine are produced. Obviously, urine and filtrate are quite different. Filtrate contains everything that blood plasma does (except proteins), but by the time it reaches the collecting ducts, the filtrate has lost most of its water and just about all of its nutrients and necessary ions. What remains, **urine,** contains nitrogenous wastes and unneeded substances. Assuming we are healthy, our kidneys can keep our blood composition fairly constant despite wide variations in diet and cell activity.

Freshly voided urine is generally clear and pale to deep yellow. The normal yellow color is due to *urochrome* (u′ro-krōm), a pigment that results from the body's destruction of hemoglobin. The

TABLE 15.1	Abnormal Urinary Constituents	
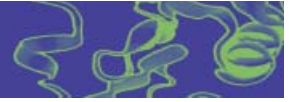
Substance	Name of condition	Possible causes
Glucose	Glycosuria (gli″ko-su′re-ah)	Nonpathological: Excessive intake of sugary foods Pathological: Diabetes mellitus
Proteins	Proteinuria (pro″te-ĭ-nu′re-ah) (also called albuminuria)	Nonpathological: Physical exertion, pregnancy Pathological: Glomerulonephritis, hypertension
Pus (WBCs and bacteria)	Pyuria (pi-u′re-ah)	Urinary tract infection
RBCs	Hematuria (he″mah-tu′re-ah)	Bleeding in the urinary tract (due to trauma, kidney stones, infection)
Hemoglobin	Hemoglobinuria (he″mo-glo-bĭ-nu′re-ah)	Various: Transfusion reaction, hemolytic anemia
Bile pigment	Bilirubinuria (bil″ĭ-roo-bĭ-nu′re-ah)	Liver disease (hepatitis)

more solutes are in the urine, the deeper yellow its color; on the other hand, dilute urine is a pale, straw color. At times, urine may be a color other than yellow. This might be a result of eating certain foods (beets, for example) or the presence of bile or blood in the urine.

When formed, urine is sterile, and its odor is slightly aromatic. If it is allowed to stand, it takes on an ammonia odor caused by the action of bacteria on the urine solutes. Some drugs, vegetables (such as asparagus), and various diseases (such as diabetes mellitus) alter the usual odor of urine.

Urine pH is usually slightly acid (around 6), but changes in body metabolism and certain foods may cause it to be much more acidic or basic. For example, a diet that contains large amounts of protein (eggs and cheese) and whole-wheat products causes urine to become quite acid; thus, such foods are called *acid-ash foods*. Conversely, a vegetarian diet is called an *alkaline-ash diet* because it makes urine quite alkaline as the kidneys excrete the excess bases. Bacterial infection of the urinary tract also may cause the urine to be alkaline.

Since urine is water plus solutes, urine weighs more, or is more dense, than distilled water. The term used to compare how *much* heavier urine is than distilled water is **specific gravity.** Whereas the specific gravity of pure water is 1.0, the specific gravity of urine usually ranges from 1.001 to 1.035 (dilute to concentrated urine, respectively). Urine is generally dilute (that is, it has a low specific gravity) when a person drinks excessive fluids, uses diuretics (drugs that increase urine output), or has chronic renal failure (a condition in which the kidney loses its ability to concentrate urine). Conditions that produce urine with a high specific gravity include inadequate fluid intake, fever, and a kidney inflammation called *pyelonephritis* (pi″ĕ-lo-nĕ-fri′tis).

Solutes normally found in urine include sodium and potassium ions, urea, uric acid, creatinine, ammonia, bicarbonate ions, and various other ions, depending on blood composition. With certain diseases, urine composition can change dramatically, and the presence of abnormal substances in urine is often helpful in diagnosing the problem. This is why a routine urinalysis should always be part of any good physical examination.

Substances *not* normally found in urine are glucose, blood proteins, red blood cells, hemoglobin, white blood cells (pus), and bile. Names and possible causes of conditions in which abnormal urinary constituents and volumes might be seen are given in Table 15.1.