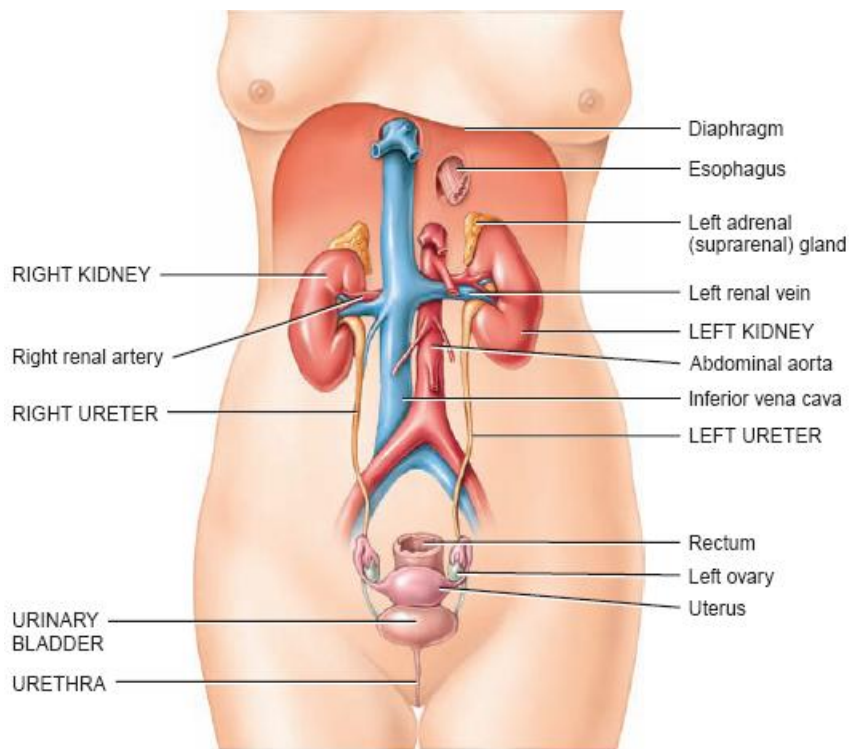# CHAPTER 11: URINARY SYSTEM

At the end of this chapter, student will be able to:

a) Describe the location and general function of each organ of the urinary system.

b) Name the parts of a nephron and the important blood vessels associated with them.

c) Explain how the following are involved in urine formation: glomerular filtration, tubular reabsorption, tubular secretion, and blood flow through the kidney.

d) Describe the mechanisms of tubular reabsorption, and explain the importance of tubular secretion.

e) Describe how the kidneys help maintain normal blood volume and blood pressure.

f) Name and state the functions of the hormones that affect the kidneys.

g) Describe how the kidneys help maintain normal pH of blood and tissue fluid.

h) Describe the urination reflex, and explain how voluntary control is possible.

i) Describe the characteristics of normal urine.

The **urinary system** consists of two kidneys, two ureters, one urinary bladder, and one urethra. After the kidneys filter blood plasma, they return most of the water and solutes to the bloodstream. The remaining water and solutes constitute **urine,** which passes through the ureters and is stored in the urinary bladder until it is excreted from the body through the

urethra.

Diaphragm
Esophagus
Left adrenal (suprarenal) gland
Left renal vein
LEFT KIDNEY
Abdominal aorta
Inferior vena cava
LEFT URETER
Rectum
Left ovary
Uterus

RIGHT KIDNEY
Right renal artery
RIGHT URETER
URINARY BLADDER
URETHRA

Functions of the Urinary System

1. The kidneys regulate blood volume and composition, help regulate blood pressure, synthesize glucose, release erythropoietin, participate in vitamin D synthesis, and excrete wastes by forming urine.
2. The ureters transport urine from the kidneys to the urinary bladder.
3. The urinary bladder stores urine.
4. The urethra discharges urine from the body.

11.1 KIDNEY

The formation of urine is the function of the kidneys, and the rest of the system is responsible for eliminating the urine.

Functions of the kidneys include the following:

Regulation of blood ionic composition. The kidneys help regulate the blood levels of several ions, most importantly sodium ions, potassium ions, calcium ions, chloride ions, and phosphate ions.

Regulation of blood pH. The kidneys excrete a variable amount of hydrogen ions into the urine and conserve bicarbonate ions , which are an important buffer of H- in the blood. Both of these activities help regulate blood pH.

Regulation of blood volume. The kidneys adjust blood volume by conserving or eliminating water in the urine. An increase in blood volume increases blood pressure; a decrease in blood volume decreases blood pressure.

Regulation of blood pressure. The kidneys also help regulate blood pressure by secreting the enzyme renin, which activates the renin–angiotensin–aldosterone pathway.

Increased renin causes an increase in blood pressure.

Maintenance of blood osmolarity. By separately regulating loss of water and loss of solutes in the urine, the kidneys maintain a relatively constant blood osmolarity close to 300 milliosmoles per liter (mOsm/liter).

Production of hormones. The kidneys produce two hormones. **Calcitriol,** the active form of vitamin D, helps regulate calcium homeostasis, and **erythropoietin** which stimulates the production of red blood cells.

Regulation of blood glucose level. Like the liver, the kidneys can use the amino acid glutamine in **gluconeogenesis**, the synthesis of new glucose molecules. They can then release glucose into the blood to help maintain a normal blood glucose level.

Excretion of wastes and foreign substances. By forming urine, the kidneys help excrete **wastes**. Some wastes excreted in urine result from metabolic reactions in the body. These include **ammonia** and **urea** from the deamination of amino acids; **bilirubin** from the catabolism of hemoglobin; **creatinine** from the breakdown of creatine phosphate in muscle fibers; and **uric acid** from the catabolism of nucleic acids. Other wastes excreted in urine are foreign substances from the diet, such as **drugs** and **environmental toxins**.

ANATOMY OF THE KIDNEYS

The paired **kidneys** are reddish, kidney-bean-shaped organs located just above the waist between the peritoneum and the posterior wall of the abdomen. Because their position is posterior to the peritoneum of the abdominal cavity, they are said to be **retroperitoneal** organs. The kidneys are located between the levels of the last thoracic and third lumbar vertebrae, a position where they are partially protected by the eleventh and twelfth pairs of ribs. The right kidney is slightly lower than the left because the liver occupies considerable space on the right side superior to the kidney.

External Anatomy of the Kidneys

A typical adult kidney is 10–12 cm (4–5 in.) long, 5–7 cm wide, and 3 cm thick and has a mass of 135–150 g.

The concave medial border of each kidney faces the vertebral column. Near the center of the concave border is an indentation called the **renal hilum**, through which the ureter emerges from the kidney along with blood vessels, lymphatic vessels, and nerves.

Three layers of tissue surround each kidney:

The **deep layer**, the **renal capsule** which serves as a barrier against trauma and helps maintain the shape of the kidney.

The **middle layer**, the **adipose capsule,** is a mass of fatty tissue surrounding the renal capsule. It also protects the kidney from trauma and holds it firmly in place within the abdominal cavity.

The **superficial layer**, the **renal fascia,** is another thin layer of dense irregular connective tissue that anchors the kidney to the surrounding structures and to the abdominal wall. On the anterior surface of the kidneys, the renal fascia is deep to the peritoneum

Internal anatomy

A frontal section through the kidney reveals two distinct regions:

A **superficial**, light red area called the **renal cortex** and a **deep**, darker reddish-brown inner region called the **renal medulla**.

The **renal medulla** consists of several cone-shaped **renal pyramids.** The base (wider end) of each pyramid faces the renal cortex, and its apex (narrower end), called a **renal papilla,** points toward the renal hilum.

The **renal cortex** is the smooth textured area extending from the renal capsule to the bases of the renal pyramids and into the spaces between them. It is divided into an **outer cortical zone** and an **inner juxtamedullary zone**.

Those portions of the renal cortex that extend between renal pyramids are called **renal columns.**

A **renal lobe** consists of a renal pyramid, its overlying area of renal cortex, and one-half of each adjacent renal column.

Together, the renal cortex and renal pyramids of the renal medulla constitute the **parenchyma** (functional portion) of the kidney. Within the parenchyma are the functional units of the kidney about 1 million microscopic structures called **nephrons**.

Urine formed by the nephrons drains into large **papillary ducts,** which extend through the renal papillae of the pyramids. The papillary ducts drain into cuplike structures called **minor** and **major calyces**. Each kidney has 8 to 18 minor calyces and 2 or 3 major calyces. A minor calyx receives urine from the papillary ducts of one renal papilla and delivers it to a major calyx. From the major calyces, urine drains into a single large cavity called the **renal pelvis** (pelv- basin) and then out through the **ureter** to the **urinary bladder**.
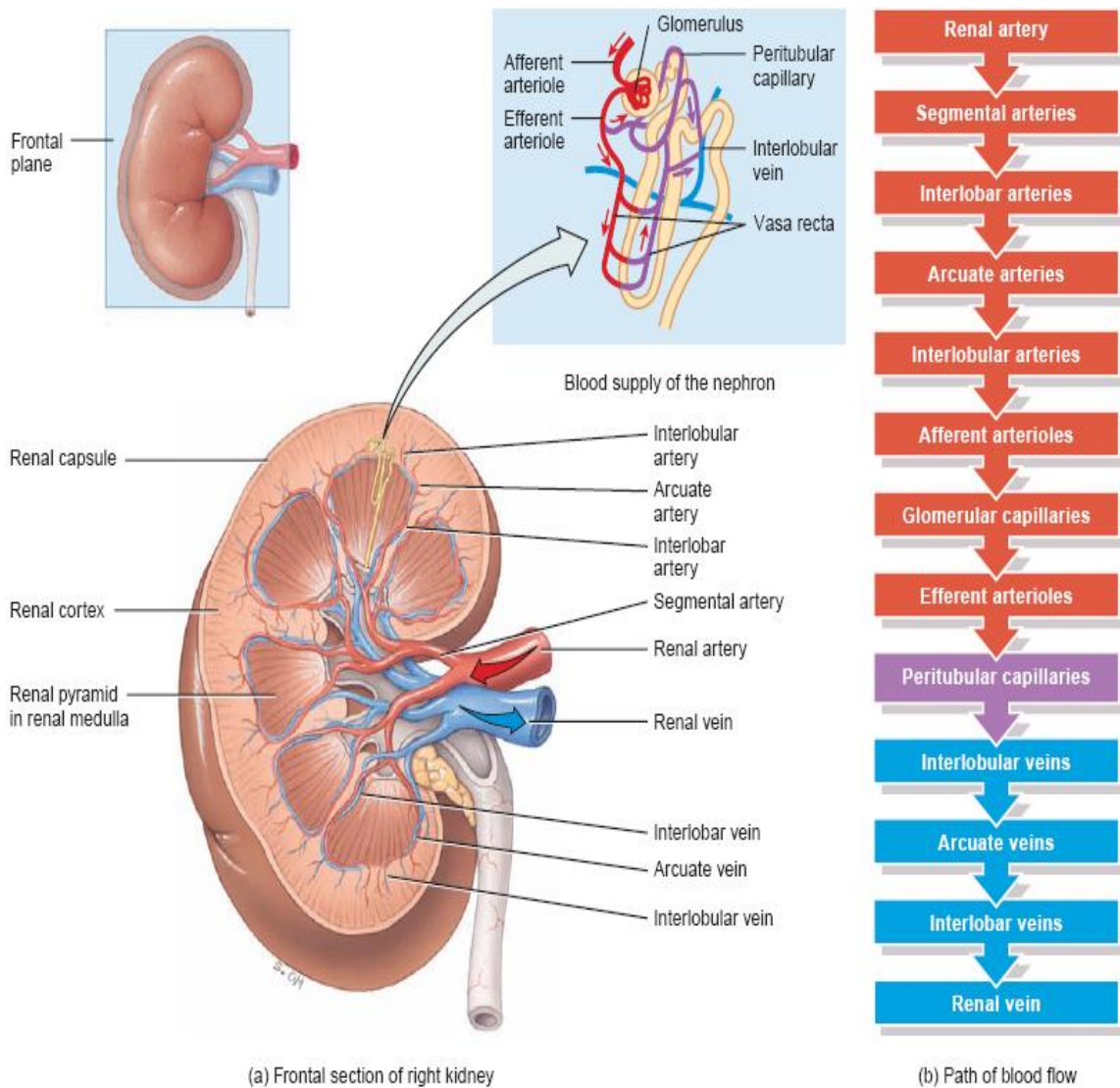
The hilum expands into a cavity within the kidney called the **renal sinus,** which contains part of the renal pelvis, the calyces, and branches of the renal blood vessels and nerves. Adipose tissue helps stabilize the position of these structures in the renal sinus.
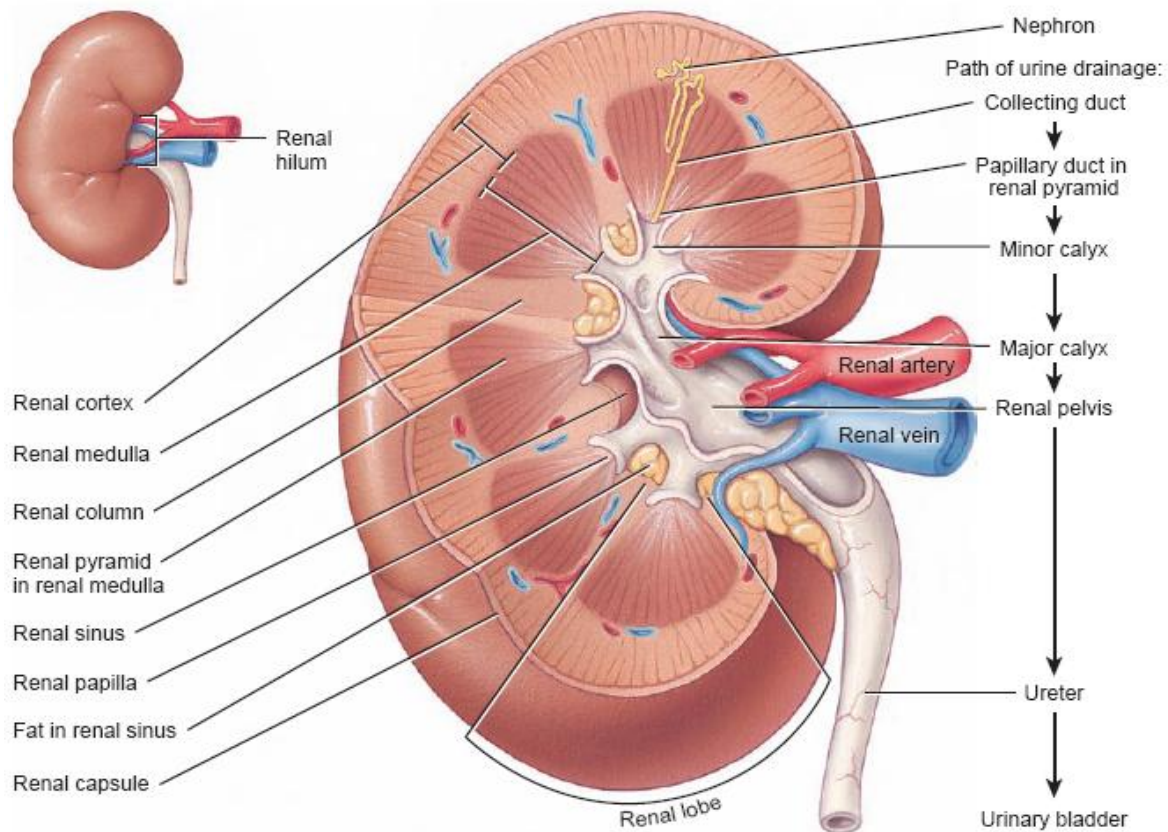
(a) Frontal section of right kidney

Blood and nerve supply of the kidney

Because the kidneys remove wastes from the blood and regulate its volume and ionic composition, it is not surprising that they are abundantly supplied with blood vessels. Although the kidneys constitute less than 0.5% of total body mass, they receive 20–25% of the resting cardiac output via **the right and left renal arteries** .

Blood supply of the nephron

(a) Frontal section of right kidney

Renal artery → Segmental arteries → Interlobar arteries → Arcuate arteries → Interlobular arteries → Afferent arterioles → Glomerular capillaries → Efferent arterioles → Peritubular capillaries → Interlobular veins → Arcuate veins → Interlobar veins → Renal vein

(b) Path of blood flow

In adults, **renal blood flow,** the blood flow through both kidneys, is about 1200 mL per minute.

Within the kidney, the renal artery divides into several **segmental arteries,** which supply different segments (areas) of the kidney. Each segmental artery gives off **several branches** that enter the parenchyma and pass through the renal columns between the renal pyramids as the **interlobar arteries.** At the bases of the renal pyramids, the interlobar arteries arch between the renal medulla and cortex; here they are known as the **arcuate arteries**. Divisions of the arcuate arteries produce a series of **interlobular arteries.** Interlobular arteries enter the renal cortex and give off branches called **afferent arterioles** (af- toward; -ferrent-to carry).

Each nephron receives one afferent arteriole, which divides into capillary network called the **glomerulus** (little ball). The glomerular capillaries then reunite to form an **efferent arteriole** (ef- out) that carries blood out of the glomerulus.

Because they are capillary networks and they also play an important role in urine formation, the glomeruli are considered part of both the cardiovascular and the urinary systems.

The efferent arterioles divide to form the **peritubular capillaries** (peri- around), which surround tubular parts of the nephron in the renal cortex. Extending from some efferent arterioles are long loop-shaped capillaries called **vasa recta** that supply tubular portions of the nephron in the renal medulla.

The peritubular capillaries eventually reunite to form **peritubular venules** and then **interlobular veins,** which also receive blood from the vasa recta. Then the blood drains through the **arcuate veins** to the **interlobar veins** running between the renal pyramids. Blood leaves the kidney through a single **renal vein** that exits at the renal hilum and carries venous blood to the inferior vena cava.

Many renal nerves originate in the **renal ganglion** and pass through the **renal plexus** into the kidneys along with the renal arteries. Renal nerves are part of the sympathetic division of the autonomic nervous system. Most are vasomotor nerves that regulate the flow of blood through the kidney by causing vasodilation or vasoconstriction of renal arterioles.

NEPHRON

Parts of a Nephron

Nephrons are the functional units of the kidneys. Each nephron consists of two parts: a **renal corpuscle**, where blood plasma is filtered, and a **renal tubule** into which the filtered fluid passes.

The **two components** of a renal corpuscle are the **glomerulus** (capillary network) and the **glomerular (Bowman's) capsule,** a double-walled epithelial cup that surrounds the glomerular capillaries.

Blood plasma is filtered in the glomerular capsule, and then the filtered fluid passes into the renal tubule, which has three main sections.

In the order that fluid passes through them, the renal tubule consists of a:

(1) **proximal convoluted tubule,**

(2) **loop of Henle (nephron loop),** and

(3) **distal convoluted tubule.**

The renal corpuscle and both convoluted tubules lie within the **renal cortex**; the loop of Henle extends into the **renal medulla**.

The distal convoluted tubules of several nephrons empty into a single **collecting duct.** Collecting ducts then unite and converge into several hundred large **papillary ducts,** which drain into the minor calyces. The collecting ducts and papillary ducts extend from the renal cortex through the renal medulla to the renal pelvis. So one kidney has about 1 million nephrons, but a much smaller number of collecting ducts and even fewer papillary ducts.

In a nephron, the loop of Henle connects the proximal and distal convoluted tubules. The first part of the loop of Henle dips into the renal medulla, where it is called the **descending limb of the loop of Henle**. It then makes that hairpin turn and returns to the renal cortex as the **ascending limb of the loop of Henle.**
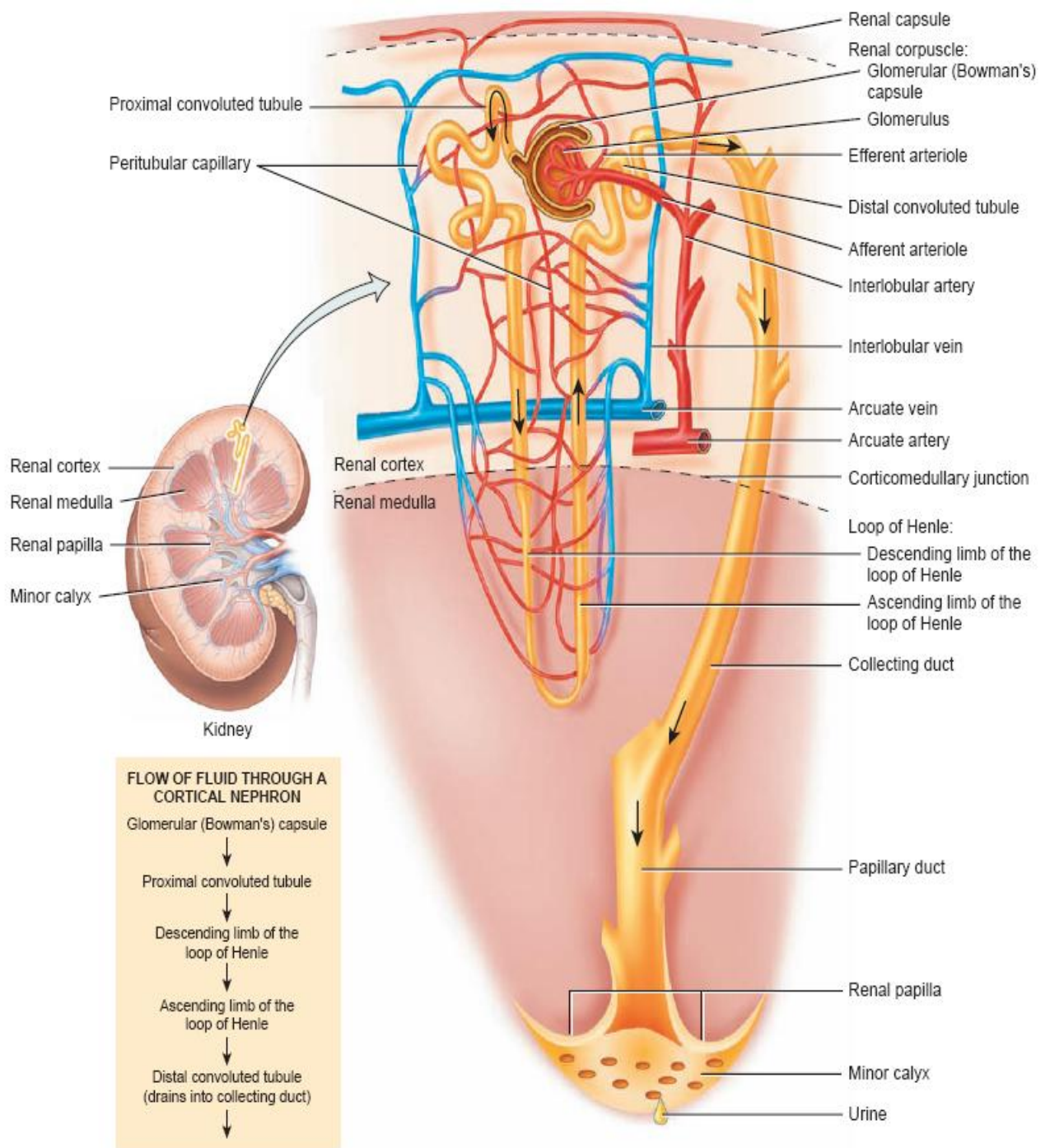
About 80–85% of the nephrons are **cortical nephrons.** Their renal corpuscles lie in the outer portion of the renal cortex, and they have **short** loops of Henle that lie mainly in the cortex and penetrate only into the outer region of the renal medulla. The short loops of Henle receive their blood supply from peritubular capillaries that arise from efferent arterioles.

The other 15–20% of the nephrons are **juxtamedullary nephrons** (juxta- near to). Their renal corpuscles lie deep in the cortex, close to the medulla, and they have a **long** loop of Henle that extends into the deepest region of the medulla. Long loops of Henle receive their blood supply from peritubular capillaries and from the vasa recta that arise from efferent arterioles.

In addition, the ascending limb of the loop of Henle of juxtamedullary nephrons consists of two portions: a **thin ascending limb** followed by a **thick ascending limb.**
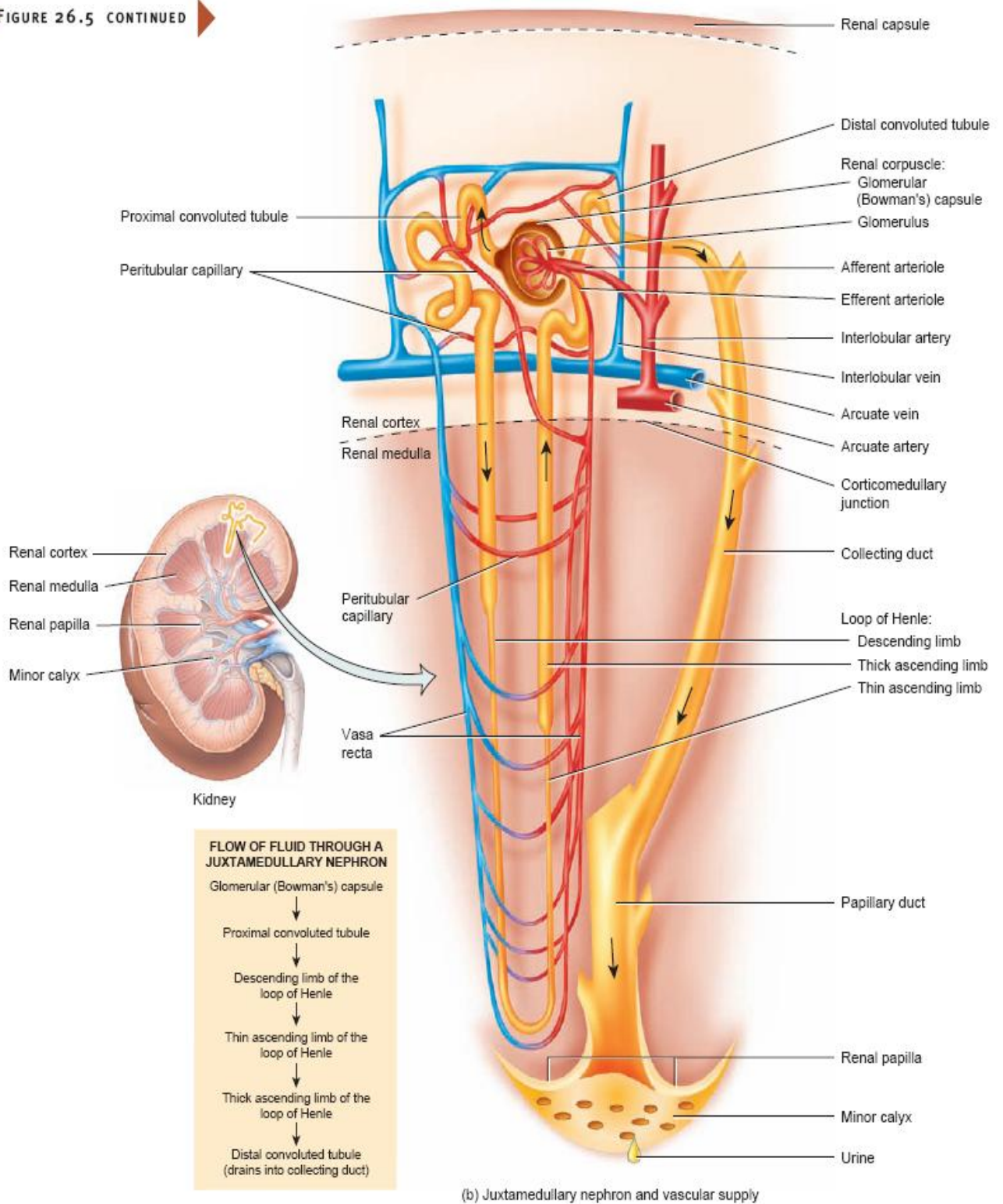
Nephrons with long loops of Henle enable the kidneys to excrete very dilute or very concentrated urine
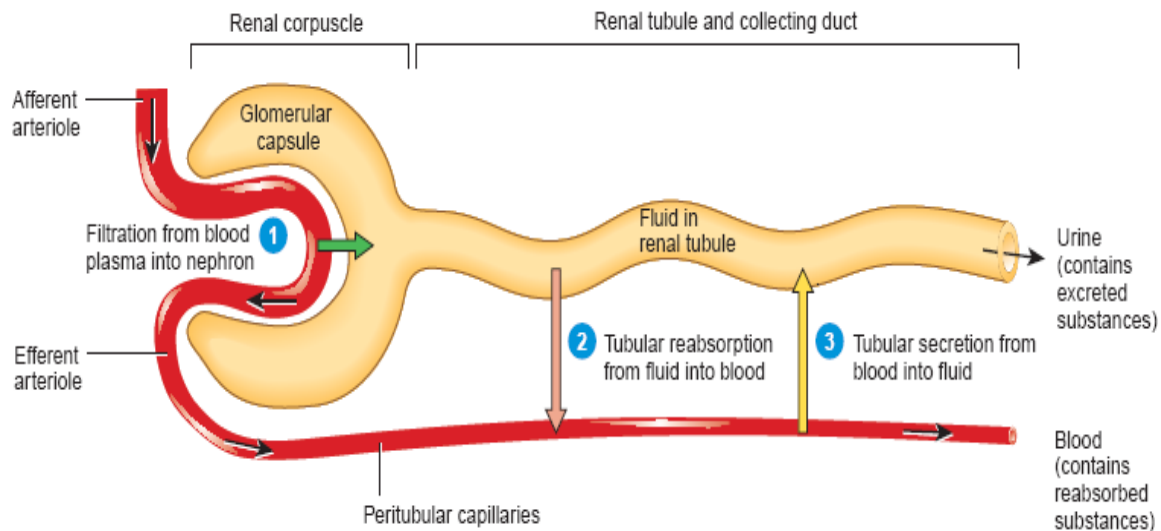
Proximal convoluted tubule

Peritubular capillary

Renal cortex
Renal medulla
Renal papilla
Minor calyx

Kidney

Renal cortex
Renal medulla

FLOW OF FLUID THROUGH A CORTICAL NEPHRON

Glomerular (Bowman's) capsule
↓
Proximal convoluted tubule
↓
Descending limb of the loop of Henle
↓
Ascending limb of the loop of Henle
↓
Distal convoluted tubule (drains into collecting duct)
↓

Renal capsule

Renal corpuscle:
- Glomerular (Bowman's) capsule
- Glomerulus

Efferent arteriole

Distal convoluted tubule

Afferent arteriole

Interlobular artery

Interlobular vein

Arcuate vein

Arcuate artery

Corticomedullary junction

Loop of Henle:
- Descending limb of the loop of Henle
- Ascending limb of the loop of Henle

Collecting duct

Papillary duct

Renal papilla

Minor calyx

Urine

(a) Cortical nephron and vascular supply

FIGURE 26.5 CONTINUED ▶

Renal capsule

Distal convoluted tubule

Renal corpuscle:
Glomerular (Bowman's) capsule
Glomerulus

Proximal convoluted tubule

Afferent arteriole

Peritubular capillary

Efferent arteriole

Interlobular artery

Interlobular vein

Arcuate vein

Renal cortex

Arcuate artery

Renal medulla

Corticomedullary junction

Collecting duct

Peritubular capillary

Loop of Henle:
Descending limb
Thick ascending limb
Thin ascending limb

Renal cortex
Renal medulla
Renal papilla
Minor calyx

Kidney

Vasa recta

FLOW OF FLUID THROUGH A JUXTAMEDULLARY NEPHRON

Glomerular (Bowman's) capsule
↓
Proximal convoluted tubule
↓
Descending limb of the loop of Henle
↓
Thin ascending limb of the loop of Henle
↓
Thick ascending limb of the loop of Henle
↓
Distal convoluted tubule (drains into collecting duct)

Papillary duct

Renal papilla

Minor calyx

Urine

(b) Juxtamedullary nephron and vascular supply

URINARY PHYSIOLOGY

Figure: Relation of a nephron's structure to its three basic functions: glomerular filtration, tubular reabsorption, and tubular secretion. Excreted substances remain in the urine and subsequently leave the body. For any substance S, excretion rate of S = filtration rate of S - reabsorption rate of S + secretion rate of S.

To produce urine, nephrons and collecting ducts perform **three basic processes: glomerular filtration, tubular reabsorption, and tubular secretion:**

Glomerular filtration. In the first step of urine production, water and most solutes in blood plasma move across the wall of glomerular capillaries into the glomerular capsule and then into the renal tubule.

Tubular reabsorption. As filtered fluid flows along the renal tubule and through the collecting duct, tubule cells reabsorb about 99% of the filtered water and many useful solutes. The water and solutes return to the blood as it flows through the peritubular capillaries and vasa recta.

Tubular secretion. As fluid flows along the renal tubule and through the collecting duct, the tubule and duct cells secrete other materials, such as wastes, drugs, and excess ions, into the fluid.

By filtering, reabsorbing, and secreting, nephrons help maintain homeostasis of the blood's volume and composition.

GROMERULAL FILTRATION

The fluid that enters the capsular space is called the **glomerular filtrate.** The fraction of blood plasma in the afferent arterioles of the kidneys that becomes glomerular filtrate is the

filtration fraction. On average, the daily volume of glomerular filtrate in adults is 150 liters in females and 180 liters in males. More than 99% of the glomerular filtrate returns to the bloodstream via tubular reabsorption, so only 1–2 liters are excreted as urine.

The filtration membrane

Together, the endothelial cells of glomerular capillaries and **the podocytes**, which completely encircle the capillaries, form a leaky barrier known as the **filtration membrane.** This permits filtration of water and small solutes but **prevents** filtration of most **plasma proteins, blood cells, and platelets.**

Substances filtered from the blood cross **three barriers** a **glomerular endothelial cell, the basal lamina, and a filtration slit formed by a podocyte:**

Glomerular endothelial cells are quite permeable because they have large **fenestrations** (pores) This permit all solutes in blood plasma to exit glomerular capillaries but prevents filtration of blood cells and platelets. Located among the glomerular capillaries and in the cleft between afferent and efferent arterioles are **mesangial cells** These contractile cells help regulate glomerular filtration.
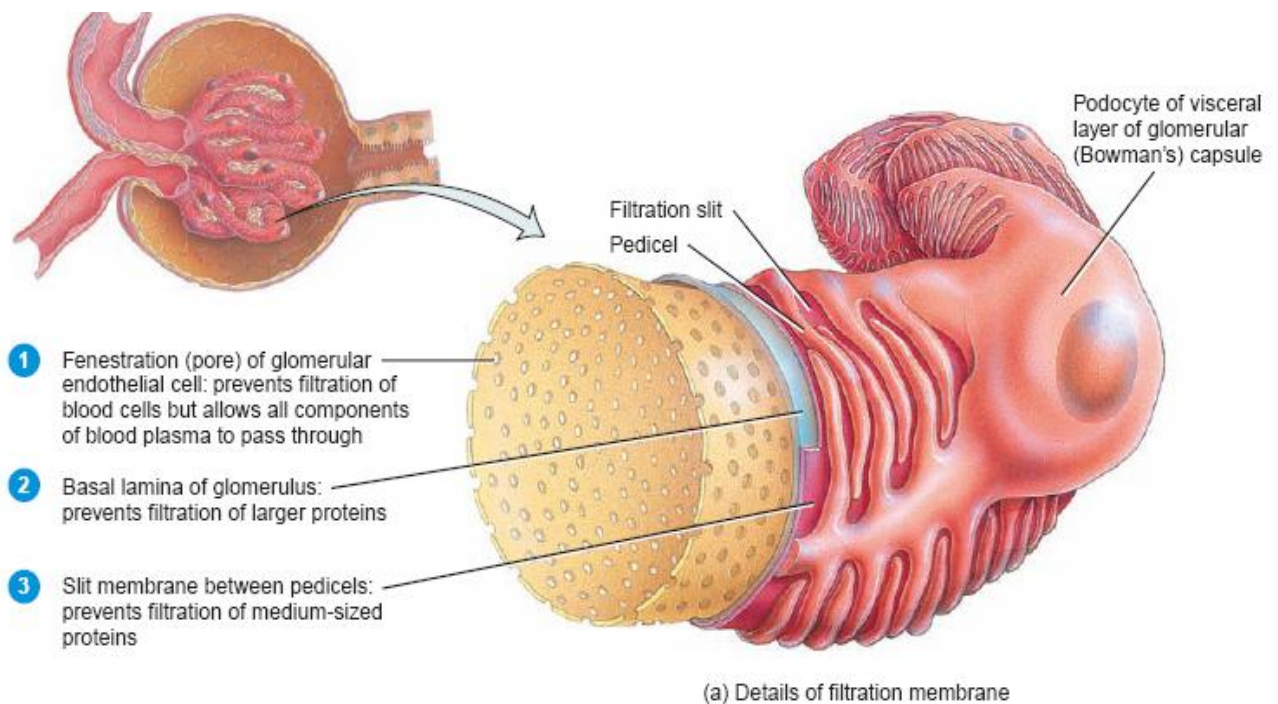
The basal lamina, it prevents filtration of larger plasma proteins.

Extending from each podocyte are thousands of footlike processes termed **pedicels** that cover glomerular capillaries. The spaces between pedicels are the **filtration slits.** A thin membrane, the **slit membrane,** extends across each filtration slit; it permits the passage of molecules having a diameter smaller than 0.006–0.007 micrometer, including water, glucose, vitamins, amino acids, very small plasma proteins, ammonia, urea, and ions.

The principle of filtration the use of pressure to force fluids and solutes through a membrane is the same in glomerular capillaries as in capillaries elsewhere in the body. However, the volume of fluid filtered by the renal corpuscle is much larger than in other capillaries of the body for three reasons:

1. Glomerular capillaries present a large surface area for filtration because they are long and extensive. The mesangial cells regulate how much of this surface area is available for filtration. When mesangial cells are relaxed, surface area is maximal, and glomerular filtration is very high. Contraction of mesangial cells reduces the available surface area, and glomerular filtration decreases.

2. The filtration membrane is thin and porous. Glomerular capillaries also are about 50 times leakier than capillaries in most other tissues, mainly because of their large fenestrations.

3. Glomerular capillary blood pressure is high. Because the efferent arteriole is smaller in diameter than the afferent arteriole, resistance to the outflow of blood from the glomerulus is high. As a result, blood pressure in glomerular capillaries is considerably higher than in capillaries elsewhere in the body.

Podocyte of visceral layer of glomerular (Bowman's) capsule

Filtration slit
Pedicel

1 Fenestration (pore) of glomerular endothelial cell: prevents filtration of blood cells but allows all components of blood plasma to pass through

2 Basal lamina of glomerulus: prevents filtration of larger proteins

3 Slit membrane between pedicels: prevents filtration of medium-sized proteins

(a) Details of filtration membrane

Figure: The filtration membrane

Net filtration pressure

Glomerular filtration depends on **three main pressures**. One pressure **promotes** filtration and two pressures **oppose** filtration.

Glomerular blood hydrostatic pressure (GBHP) is the blood pressure in glomerular capillaries. Generally, GBHP is about 55 mmHg. It promotes filtration by forcing water and solutes in blood plasma through the filtration membrane.

Capsular hydrostatic pressure (CHP) is the hydrostatic pressure exerted against the filtration membrane by fluid already in the capsular space and renal tubule. CHP opposes filtration and represents a "back pressure" of about 15 mmHg.

Blood colloid osmotic pressure (BCOP), which is due to the presence of proteins such as albumin, globulins, and fibrinogen in blood plasma, also opposes filtration. The average BCOP in glomerular capillaries is 30 mmHg.

Net filtration pressure (NFP), the total pressure that promotes filtration, is determined as follows:

Net Filtration Pressure (NFP) = GBHP - CHP -BCOP

By substituting the values just given, normal NFP may be calculated:

NFP =55 mmHg - 15 mmHg - 30 mmHg= 10 mmHg
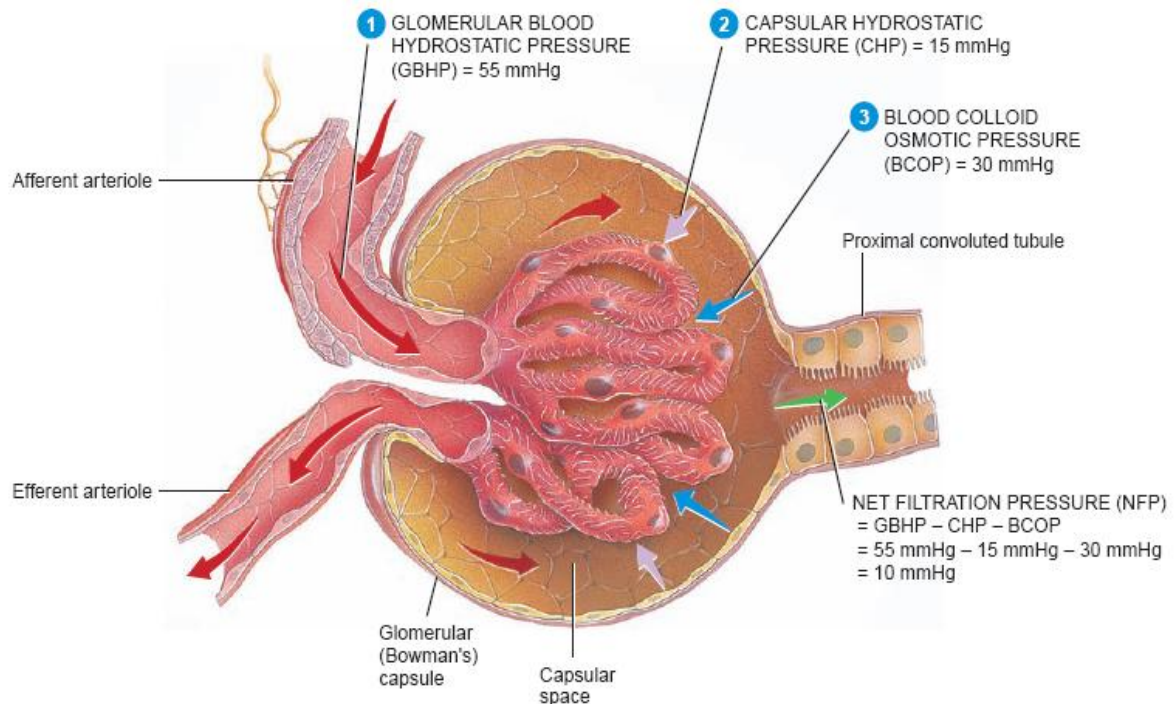
Figure: The pressures that drive glomerular filtration

Thus, a pressure of only 10 mmHg causes a normal amount of blood plasma (minus plasma proteins) to filter from the glomerulus into the capsular space.

Gromerular filtration rate

The amount of filtrate formed in all the renal corpuscles of both kidneys each minute is the **glomerular filtration rate (GFR).** In adults, the GFR averages 125 mL/min in males and 105 mL/min in females. Homeostasis of body fluids requires that the kidneys maintain a relatively constant GFR. If the GFR is too high, needed substances may pass so quickly through the renal tubules that some are not reabsorbed and are lost in the urine. If the GFR is too low, nearly all the filtrate may be reabsorbed and certain waste products may not be adequately excreted.

GFR is directly related to the pressures that determine net filtration pressure; any change in net filtration pressure will affect GFR. Severe blood loss, for example, reduces mean arterial blood pressure and decreases the glomerular blood hydrostatic pressure. Filtration ceases if glomerular blood hydrostatic pressure drops to 45 mmHg because the opposing pressures add up to 45 mmHg.

Remarkably, when systemic blood pressure rises above normal, net filtration pressure and GFR increase very little. GFR is nearly constant when the mean arterial blood pressure is anywhere between 80 and 180 mmHg.

The mechanisms that regulate glomerular filtration rate operate in **two main ways:**

(1) by adjusting blood flow into and out of the glomerulus and

(2) by altering the glomerular capillary surface area available for filtration. GFR increases when blood flow into the glomerular capillaries increases.

Coordinated control of the diameter of both afferent and efferent arterioles regulates glomerular blood flow. Constriction of the afferent arteriole decreases blood flow into the glomerulus; dilation of the afferent arteriole increases it.

Three mechanisms control GFR: renal autoregulation, neural regulation, and hormonal regulation.

Renal Autoregulation of GFR

The kidneys themselves help maintain a constant renal blood flow and GFR despite normal, everyday changes in blood pressure, like those that occur during exercise. This capability is called **renal autoregulation** and consists of **two mechanisms the myogenic mechanism and tubuloglomerular feedback.**

The **myogenic mechanism** (myo- muscle; -genic producing) occurs when stretching triggers contraction of smooth muscle cells in the walls of afferent arterioles. As blood pressure rises, GFR also rises because renal blood flow increases.

However, the elevated blood pressure stretches the walls of the afferent arterioles. In response, smooth muscle fibers in the wall of the afferent arteriole contract, which narrows the arteriole's lumen. As a result, renal blood flow decreases, thus reducing GFR to its previous level. Conversely, when arterial blood pressure drops, the smooth muscle cells are stretched less and thus relax. The afferent arterioles dilate, renal blood flow increases, and GFR increases. The myogenic mechanism normalizes renal blood flow and GFR within seconds after a change in blood pressure.
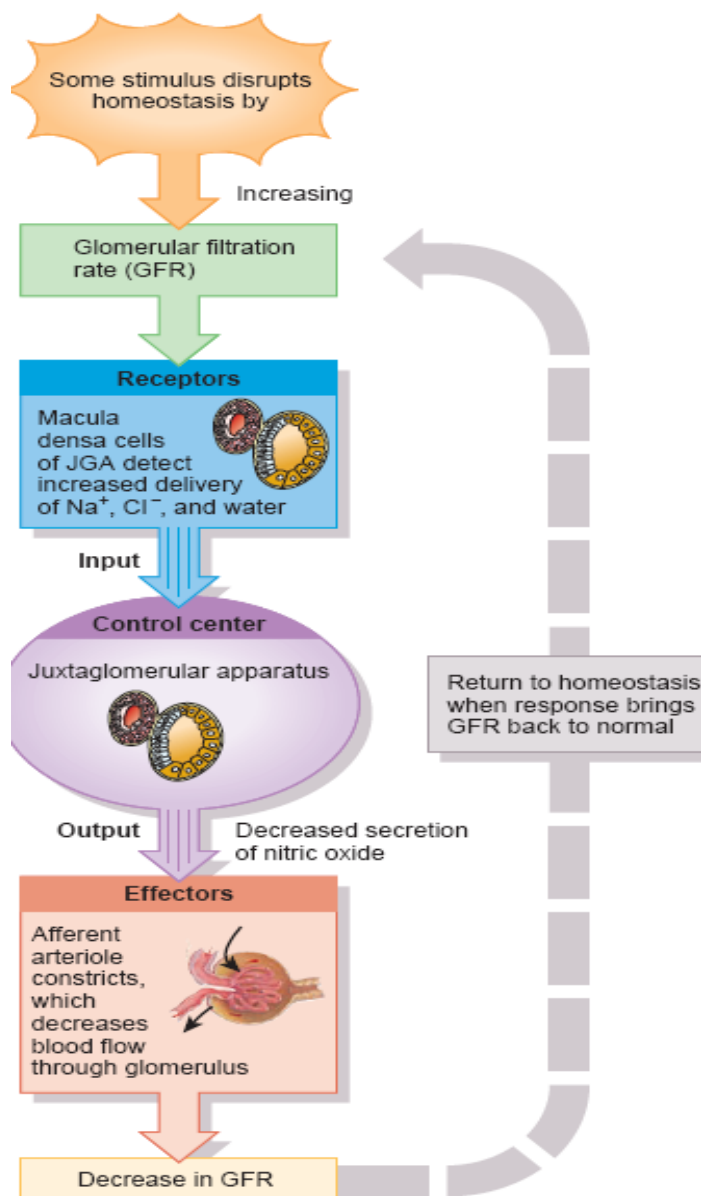
Figure: Tubuloglomerular feedback

The second contributor to renal autoregulation, **tubuloglomerular feedback,** is so named because part of the renal tubules,the macula densa provides feedback to the glomerulus.

When GFR is above normal due to elevated systemic blood pressure, filtered fluid flows more rapidly along the renal tubules. As a result, the proximal convoluted tubule and loop of Henle have less time to reabsorb Na_, Cl_, and water. Macula densa cells are thought to detect the increased delivery of Na_, Cl_, and water and to inhibit release of nitric oxide (NO) from cells in the juxtaglomerular apparatus (JGA).

Because NO causes vasodilation, afferent arterioles constrict when the level of NO declines. As a result, less blood flows into the glomerular capillaries, and GFR decreases. When blood

pressure falls, causing GFR to be lower than normal, the opposite sequence of events occurs, although to a lesser degree.

Tubuloglomerular feedback operates more slowly than the myogenic mechanism.

Regulation of Glomerular Filteration Rate (GFR)

TYPE OF REGULATION	MAJOR STIMULUS	MECHANISM AND SITE OF ACTION	EFFECT ON GFR
Renal autoregulation			
Myogenic mechanism	Increased stretching of smooth muscle fibers in afferent arteriole walls due to increased blood pressure.	Stretched smooth muscle fibers contract, thereby narrowing the lumen of the afferent arterioles.	Decrease.
Tubuloglomerular feedback	Rapid delivery of Na^+ and Cl^- to the macula densa due to high systemic blood pressure.	Decreased release of nitric oxide (NO) by the juxtaglomerular apparatus causes constriction of afferent arterioles.	Decrease.
Neural regulation	Increase in level of activity of renal sympathetic nerves releases norepinephrine.	Constriction of afferent arterioles through activation of α_1 receptors and increased release of renin.	Decrease.
Hormone regulation			
Angiotensin II	Decreased blood volume or blood pressure stimulates production of angiotensin II.	Constriction of both afferent and efferent arterioles.	Decrease.
Atrial natriuretic peptide (ANP)	Stretching of the atria of the heart stimulates secretion of ANP.	Relaxation of mesangial cells in glomerulus increases capillary surface area available for filtration.	Increase.

Neural Regulation of GFR

Like most blood vessels of the body, those of the kidneys are supplied by sympathetic ANS fibers that release norepinephrine. Norepinephrine causes vasoconstriction through the activation of *alpha* receptors, which are particularly plentiful in the smooth muscle fibers of afferent arterioles.

At rest, sympathetic stimulation is moderately low, the afferent and efferent arterioles are dilated, and renal autoregulation of GFR prevails. With moderate sympathetic stimulation, both afferent and efferent arterioles constrict to the same degree. Blood flow into and out of the glomerulus is restricted to the same extent, which decreases GFR only slightly.

With **greater sympathetic stimulation**, however, as occurs during exercise or hemorrhage, vasoconstriction of the afferent arterioles predominates. As a result, blood flow into glomerular capillaries is greatly decreased, and GFR drops.

This lowering of renal blood flow has **two consequences**: (1) It reduces urine output, which helps conserve blood volume. (2) It permits greater blood flow to other body tissues.

Hormonal Regulation of GFR

Two hormones contribute to regulation of GFR. **Angiotensin II reduces GFR; atrial natriuretic peptide (ANP) increases GFR.**

Angiotensin II is a very potent vasoconstrictor that narrows both afferent and efferent arterioles and reduces renal blood flow, thereby decreasing GFR.

Cells in the atria of the heart secrete **atrial natriuretic peptide (ANP).** Stretching of the atria, as occurs when blood volume increases, stimulates secretion of ANP. By causing relaxation of the glomerular mesangial cells, ANP increases the capillary surface area available for filtration. Glomerular filtration rate rises as the surface area increases.

TUBULAR REABSORPTION AND TUBULAR SECRETION

The volume of fluid entering the proximal convoluted tubules in just half an hour is greater than the total blood plasma volume because the normal rate of glomerular filtration is so high. Clearly some of this fluid must be returned somehow to the bloodstream. Reabsorption is the return of most of the filtered water and many of the filtered solutes to the bloodstream, is the second basic function of the nephron and collecting duct. Normally, about 99% of the filtered water is reabsorbed.

Epithelial cells all along the renal tubule and duct carry out reabsorption, but **proximal convoluted tubule cells make the largest contribution**. Solutes that are reabsorbed by both active and passive processes include glucose, amino acids, urea, and ions such as Na_ (sodium), K_ (potassium), Ca2_ (calcium), Cl_ (chloride), HCO3 _ (bicarbonate), and HPO4 2_ (phosphate).

Once fluid passes through the proximal convoluted tubule, cells located more distally fine-tune the reabsorption processes tomaintain homeostatic balances of water and selected ions. Most small proteins and peptides that pass through the filter also are reabsorbed, usually via pinocytosis.

The third function of nephrons and collecting ducts is tubular secretion, the transfer of materials from the blood and tubule cells into tubular fluid. Secreted substances include hydrogen ions (H_), K_, ammonium ions (NH4_), creatinine, and certain drugs such as penicillin. Tubular secretion has two important outcomes:

(1) The secretion of H_ helps control blood pH.

(2) The secretion of other substances helps eliminate them from the body.

As a result of tubular secretion, certain substances pass from blood into urine and may be detected by a urinalysis. It is especially important to test athletes for the presence of performance-enhancing drugs such as anabolic steroids, plasma expanders, erythropoietin, hCG, hGH, and amphetamines. Urine tests can also be used to detect the presence of alcohol or illegal drugs such as marijuana, cocaine, and heroin.

TUBULAR REABSORPTION

Tubular reabsorption takes place from the renal tubules into the peritubular capillaries. In a 24-hour period, the kidneys form 150 to 180 liters of filtrate, and normal urinary output in that time is 1 to 2 liters. Therefore, it becomes apparent that most of the renal filtrate does not become urine. Approximately 99% of the filtrate is reabsorbed back into the blood in the peritubular capillaries. Only about 1% of the filtrate will enter the renal pelvis as urine. Most reabsorption and secretion (about 65%) take place in the proximal convoluted tubules, whose cells have **microvilli** that greatly increase their surface area. The distal convoluted tubules and collecting tubules are also important sites for the reabsorption of water.

Substances Filtered, Reabsorbed, and Excreted in Urine

SUBSTANCE	FILTERED* (ENTERS GLOMERULAR CAPSULE PER DAY)	REABSORBED (RETURNED TO BLOOD PER DAY)	URINE (EXCRETED PER DAY)
Water	180 liters	178–179 liters	1–2 liters
Proteins	2.0 g	1.9 g	0.1 g
Sodium ions (Na^+)	579 g	575 g	4 g
Chloride ions (Cl^-)	640 g	633.7 g	6.3 g
Bicarbonate ions (HCO_3^-)	275 g	274.97 g	0.03 g
Glucose	162 g	162 g	0 g
Urea	54 g	24 g	30 g[†]
Potassium ions (K^+)	29.6 g	29.6 g	2.0 g[‡]
Uric acid	8.5 g	7.7 g	0.8 g
Creatinine	1.6 g	0 g	1.6 g

Mechanisms of Reabsorption

1. Active transport: the cells of the renal tubule use **ATP** to transport most of the useful materials from the filtrate to the blood. These useful materials include **glucose, amino acids, vitamins, and positive ions.** For many of these substances, the renal tubules have a **threshold level** of reabsorption. This means that there is a limit to how much the tubule can remove from the filtrate.

For example, if the filtrate level of **glucose** is normal, the tubules will reabsorb all of the glucose, and none will be found in the urine. If, the blood glucose level is above normal, the amount of glucose in the filtrate will also be above normal and will exceed the threshold level of reabsorption. In this situation, some glucose will remain in the filtrate and be present in urine. The reabsorption **of Ca_2** ions is increased by parathyroid hormone (PTH). The parathyroid glands secrete PTH when the blood calcium level decreases. The reabsorption of Ca_2 ions by the kidneys is one of the mechanisms by which the blood calcium level is raised back to normal. The hormone aldosterone, secreted by the adrenal cortex, increases the reabsorption **of Na_** ions and the excretion **of K_ ions**. Besides regulating the blood levels of sodium and potassium, aldosterone also affects the volume of blood.

2. Passive transport: many of the negative ions that are returned to the blood are reabsorbed following the reabsorption of positive ions, because unlike charges attract.

3. Osmosis: the reabsorption of water follows the reabsorption of minerals, especially sodium ions.

4. Pinocytosis: small proteins are too large to be reabsorbed by active transport. They become adsorbed to the membranes of the cells of the proximal convoluted tubules. Normally all proteins in the filtrate are reabsorbed; none is found in urine.

TUBULAR SECRETION

This mechanism also changes the composition of urine. In **tubular secretion**, substances are actively **secreted from the blood** in the peritubular capillaries **into the filtrate** in the renal tubules. **Waste products, such as ammonia** and some **creatinine**, and **the metabolic products** of medications may be secreted into the filtrate to be eliminated in urine.

Hydrogen ions (H−) may be secreted by the tubule cells to help maintain the normal pH of blood.

HORMONES THAT INFLUENCE REABSORPTION OF WATER

Aldosterone is secreted by the adrenal cortex in response to a **high blood potassium level, to a low blood sodium level, or to a decrease in blood pressure.** When aldosterone stimulates the reabsorption of Na− ions, water follows from the filtrate back to the blood. This helps maintain normal blood volume and blood pressure. The antagonist to aldosterone is **atrial natriuretic peptide** (ANP), which is secreted by the atria of the heart when the atrial walls are stretched by high blood pressure or greater blood volume. ANP decreases the reabsorption of Na− ions by the kidneys; these remain in the filtrate, as does water, and are excreted. By increasing the elimination of sodium and water, ANP lowers blood volume and blood pressure.

Antidiuretic hormone (ADH) is released by the posterior pituitary gland when **the amount of water in the body decreases**. Under the influence of ADH, the distal convoluted tubules and collecting tubules are able to reabsorb more water from the renal filtrate. This helps maintain normal blood volume and blood pressure, and also permits the kidneys to produce urine that is more concentrated than body fluids. Producing concentrated urine is essential to prevent excessive water loss while still excreting all the substances that must be eliminated. If the amount of water in the body increases, however, the secretion of ADH diminishes, and the kidneys will reabsorb less water. Urine then becomes dilute, and water is eliminated until its concentration in the body returns to normal. This may occur following ingestion of excessive quantities of fluids.

SUMMARY OF URINE FORMATION

1. The kidneys form urine from blood plasma. Blood flow through the kidneys is a major factor in determining urinary output.

2. Glomerular filtration is the first step in urine formation. Filtration is not selective in terms of usefulness of materials; it is selective only in terms of size. High blood pressure in the glomeruli forces plasma, dissolved materials, and small proteins into Bowman's capsules; the fluid is now called renal filtrate.

3. Tubular reabsorption is selective in terms of usefulness. Nutrients such as glucose, amino acids, and vitamins are reabsorbed by active transport and may have renal threshold levels. Positive ions are reabsorbed by active transport and negative ions are reabsorbed most often by passive transport. Water is reabsorbed by osmosis, and small proteins are reabsorbed by pinocytosis. Reabsorption takes place from the filtrate in the renal tubules to the blood in the peritubular capillaries.

4. Tubular secretion takes place from the blood in the peritubular capillaries to the filtrate in the renal tubules and can ensure that wastes such as creatinine or excess H⁻ ions are actively put into the filtrate to be excreted.

5. Hormones such as aldosterone, ANP, and ADH influence the reabsorption of water and help maintain normal blood volume and blood pressure. The secretion of ADH determines whether a concentrated or dilute urine will be formed.

6. Waste products remain in the renal filtrate and are excreted in urine.

THE KIDNEYS AND ACID–BASE BALANCE

The kidneys are the organs most responsible for maintaining the pH of blood and tissue fluid within normal ranges. If body fluids are becoming **too acidic**, the kidneys will secrete **more H⁻ ions into the renal filtrate** and will **return more HCO3⁻ ions to the blood**. This will help raise the pH of the blood back to normal. If body fluids that are becoming **too alkaline**, the kidneys will **return H⁻ ions to the blood** and **excrete HCO3 ⁻ ions in urine**. This will help lower the pH of the blood back to normal. The cells of the renal tubules can secrete H⁻ ions or ammonia in exchange for Na⁻ ions and, by doing so, influence the reabsorption of other ions. Hydrogen ions are obtained from the reaction of CO_2 and water. An amine group from an amino acid is combined with an H⁻ ion to form ammonia. The tubule cell secretes the H⁻ ion and the ammonia into the renal filtrate, and two Na⁻ ions are reabsorbed in exchange. In the filtrate, the H⁻ ion and ammonia form NH4 ⁻ (an ammonium radical), which reacts with a chloride ion (Cl⁻) to form NH4Cl (ammonium chloride) that is excreted in urine. As the Na⁻ ions are returned to the blood in the peritubular capillaries, HCO3 ⁻ ions follow. Two H⁻ ions have been excreted in urine, and two Na_ ions and two HCO3 ⁻ ions have been returned to the blood. As reactions like these take place, the body fluids are prevented from becoming too acidic.

ELIMINATION OF URINE

The ureters, urinary bladder, and urethra do not change the composition or amount of urine, but are responsible for the periodic elimination of urine.

URETERS

Each **ureter** extends from the hilus of a kidney to the lower, posterior side of the urinary bladder. Like the kidneys, the ureters are retroperitoneal, that is, behind the peritoneum of the dorsal abdominal cavity. The smooth muscle in the wall of the ureter contracts in peristaltic waves to propel urine toward the urinary bladder. As the bladder fills, it expands and compresses the lower ends of the ureters to prevent backflow of urine.

URINARY BLADDER

Urinary Bladder
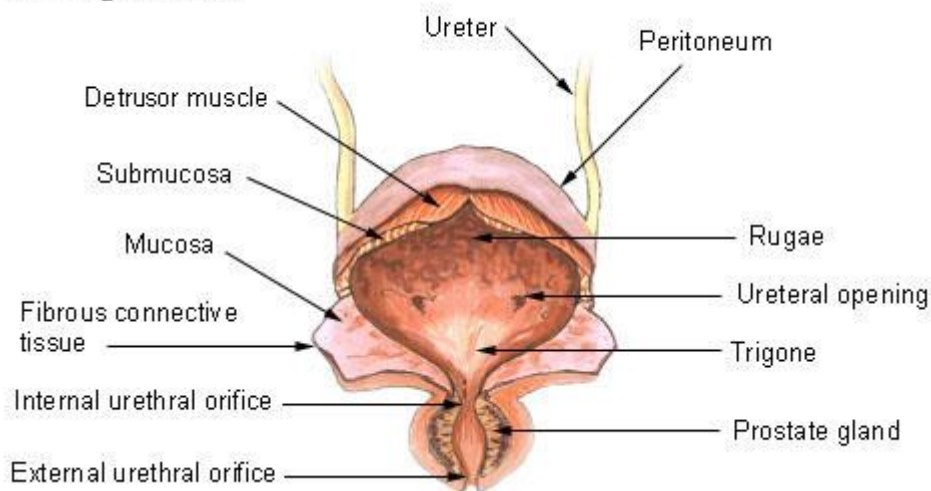
The **urinary bladder** is a muscular sac below the peritoneum and behind the pubic bones. In women, the bladder is inferior to the uterus; in men, the bladder is superior to the prostate gland. The bladder **is a reservoir for accumulating urine, and it contracts to eliminate urine**. The mucosa of the bladder is **transitional epithelium**, which permits expansion without tearing the lining. When the bladder is empty, the mucosa appears wrinkled; these folds are **rugae**, which also permit expansion. On the floor of the bladder is a triangular area called the **trigone**, which has no rugae and does not expand. The points of the triangle are the openings of the two ureters and that of the urethra. The smooth muscle layer in the wall of the

bladder is called the **detrusor muscle**. It is a muscle in the form of a sphere; when it contracts it becomes a smaller sphere, and its volume diminishes. Around the opening of the urethra the muscle fibers of the detrusor form the **internal urethral sphincter** (or sphincter of the bladder), which is involuntary.

URETHRA

The **urethra** carries urine from the bladder to the exterior. The **external urethral sphincter** is made of the surrounding skeletal muscle of the pelvic floor, and is under voluntary control.

In women, the urethra is 1 to 1.5 inches (2.5 to 4 cm) long and is anterior to the vagina. In **men, the urethra is 7 to 8 inches (17 to 20 cm) long**. The first part just outside the bladder is called **the prostatic urethra** because it is surrounded by the prostate gland. The next inch is the **membranous urethra,** around which is the external urethral sphincter. The longest portion is **the cavernous urethra** (or spongy or penile urethra), which passes through the cavernous (or erectile) tissue of the penis. The **male urethra carries semen as well as urine.**

THE URINATION REFLEX

Urination may also be called **micturition** or **voiding**. This reflex is a spinal cord reflex over which voluntary control may be exerted. The stimulus for the reflex is stretching of the detrusor muscle of the bladder. **The bladder can hold as much as 800 mL of urine**, or even more, but the reflex is activated long before the maximum is reached. When urine volume reaches **200 to 400 mL, t**he stretching is sufficient to generate sensory impulses that travel to the sacral spinal cord. Motor impulses return along parasympathetic nerves to the detrusor muscle, causing contraction. At the same time, the internal urethral sphincter relaxes. If the external urethral sphincter is voluntarily relaxed, urine flows into the urethra, and the bladder is emptied. Urination can be prevented by voluntary contraction of the external urethral sphincter. However, if the bladder continues to fill and be stretched, voluntary control is eventually no longer possible.

CHARACTERISTICS OF URINE

The characteristics of urine include the **physical and chemical aspects** that are often evaluated as part of a urinalysis.

Amount: normal urinary **output per 24 hours is 1 to 2 liters.** Many factors can significantly change output. Excessive sweating or loss of fluid through diarrhea will decrease urinary output (**oliguria**) to conserve body water. Excessive fluid intake will increase urinary output (**polyuria**). Consumption of alcohol will also increase output because alcohol inhibits the secretion of ADH, and the kidneys will reabsorb less water.

Color: the typical yellow color of urine (from urochrome, a breakdown product of bile) is often referred to as "straw" or "amber." Concentrated urine is a deeper yellow (amber) than is dilute urine. Freshly voided urine is also clear rather than cloudy.

Specific gravity: the normal range **is 1.010 to 1.025**; this is a measure of the dissolved materials in urine. The specific gravity of distilled water is 1.000, meaning that there are no solutes present. Therefore, the higher the specific gravity number, the more dissolved material is present. Someone who has been exercising strenuously and has lost body water in sweat will usually produce less urine, which will be more concentrated and have a higher specific gravity. The specific gravity of the urine is an indicator of the concentrating ability of the kidneys: The kidneys must excrete the waste products that are constantly formed in as little water as possible.

Ph: the pH range of urine is between **4.6 and 8.0,** with an average value **of 6.0.** Diet has the greatest influence on urine pH. A vegetarian diet will result in a more alkaline urine, whereas a high-protein diet will result in a more acidic urine.

Constituents: urine is approximately 95% water, which is the solvent for waste products and salts. Salts are not considered true waste products because they may well be utilized by the body when needed, but excess amounts will be excreted in urine.

Nitrogenous wastes: as their name indicates, all of these wastes contain nitrogen. Urea is formed by liver cells when excess amino acids are deaminated to be used for energy production. Creatinine comes from the metabolism of creatine phosphate, an energy source in

muscles. Uric acid comes from the metabolism of nucleic acids, that is, the breakdown of DNA and RNA. Although these are waste products, there is always a certain amount of each in the blood.   Blood Tests and Kidney Function describes the relationship between blood levels of these waste products and kidney function. Other non-nitrogenous waste products include small amounts of urobilin from the hemoglobin of old RBCs and may include the metabolic products of medications.When a substance not normally found in urine does appear there, there is a reason for it. The reason may be quite specific or more general.

ABNORMAL CONSTITUENTS IN URINE

Characteristic	Reason(s)
Glycosuria (presence of glucose)	As long as blood glucose levels are within normal limits, filtrate levels will also be normal and will not exceed the threshold level for reabsorption. In an untreated diabetic, for example, blood glucose is too high; therefore the filtrate glucose level is too high. The kidneys reabsorb glucose up to their threshold level, but the excess remains in the filtrate and is excreted in urine.
Proteinuria (presence of protein)	Most plasma proteins are too large to be forced out of the glomeruli, and the small proteins that enter the filtrate are reabsorbed by pinocytosis. The presence of protein in the urine indicates that the glomeruli have become too permeable, as occurs in some types of kidney disease.
Hematuria (presence of blood—RBCs)	The presence of RBCs in urine may also indicate that the glomeruli have become too permeable. Another possible cause might be bleeding somewhere in the urinary tract. Pinpointing the site of bleeding would require specific diagnostic tests.
Bacteriuria (presence of bacteria)	Bacteria give urine a cloudy rather than clear appearance; WBCs may be present also. The presence of bacteria means that there is an infection somewhere in the urinary tract. Further diagnostic tests would be needed to determine the

	precise location.
Ketonuria (presence of ketones)	Ketones are formed from fats and proteins that are used for energy production. A trace of ketones in urine is normal. Higher levels of ketones indicate an increased use of fats and proteins for energy. This may be the result of malfunctioning carbohydrate metabolism (as in diabetes mellitus) or simply the result of a high-protein diet.

AGING AND THE URINARY SYSTEM

With age, the number of nephrons in the kidneys decreases, often to half the original number by the age of 70 to 80, and the kidneys lose some of their concentrating ability. The glomerular filtration rate also decreases, partly as a consequence of arteriosclerosis and diminished renal blood flow. Despite these changes, excretion of nitrogenous wastes usually remains adequate.The urinary bladder decreases in size, and the tone of the detrusor muscle decreases. These changes may lead to a need to urinate more frequently. Urinary incontinence (the inability to control voiding) is *not* an inevitable consequence of aging, and can be prevented or minimized. Elderly people are, however, more at risk for infections of the urinary tract, especially if voiding leaves residual urine in the bladder.

o **Applications to the nursing care**

1) *FLOATING KIDNEY*

A floating kidney is one that has moved out of its normal position. This may happen in very thin people whose renal cushion of adipose tissue is thin, or it may be the result of a sharp blow to the back that dislodges a kidney. A kidney can function in any position; the problem with a floating kidney is that the ureter may become twisted or kinked. If urine cannot flow through the ureter, the urine backs up and collects in the renal pelvis. Incoming urine from the renal tubules then backs up as well. If the renal filtrate cannot flow out of Bowman's capsules, the pressure within Bowman's capsules increases, opposing the blood pressure in

the glomeruli. Glomerular filtration then cannot take place efficiently. If uncorrected, this may lead to permanent kidney damage.

2) *RENAL FAILURE AND HEMODIALYSIS*

Renal failure, the inability of the kidneys to function properly, may be the result of three general causes, which may be called prerenal, intrinsic renal, and postrenal.

"*Prerenal*" means that the problem is "before" the kidneys, that is, in the blood flow to the kidneys. Any condition that decreases blood flow to the kidneys may result in renal damage and failure. Examples are severe hemorrhage or very low blood pressure following a heart attack (MI).

"*Intrinsic renal*" means that the problem is in the kidneys themselves. Diabetes and hypertension damage the blood vessels of the kidneys, and are the causes of 70% of all cases of end-stage renal failure. Bacterial infections of the kidneys or exposure to chemicals (certain antibiotics) may cause damage to the nephrons. Polycystic kidney disease is a genetic disorder in which the kidney tubules dilate and become nonfunctional. Severe damage may not be apparent until age 40 to 60 years but may then progress to renal failure.

"*Postrenal*" means that the problem is "after" the kidneys, somewhere in the rest of the urinary tract. Obstruction of urine flow may be caused by kidney stones, a twisted ureter, or prostatic hypertrophy. Treatment of renal failure involves correcting the specific cause, if possible. If not possible, and kidney damage is permanent, the person is said to have chronic renal failure.

Hemodialysis is the use of an artificial kidney machine to do what the patient's nephrons can no longer do. The patient's blood is passed through minute tubes surrounded by fluid (dialysate) with the same chemical composition as plasma. Waste products and excess minerals diffuse out of the patient's blood into the fluid of the machine. Although hemodialysis does prolong life for those with chronic renal failure, it does not fully take the place of functioning kidneys. The increasing success rate of kidney transplants, however, does indeed provide the possibility of a normal life for people with chronic renal failure.

3) ERYTHROPOIETIN

Anemia is one of the most debilitating consequences of renal failure, one that hemodialysis cannot reverse. Diseased kidneys stop producing erythropoietin, a natural stimulus for RBC production. Erythropoietin can be produced by genetic engineering and is available for hemodialysis patients.

In the past, their anemia could only be treated with transfusions, which exposed these patients to possible immunologic complications of repeated exposure to donated blood or to viral diseases. The synthetic erythropoietin eliminates such risks. Others who benefit from this medication are cancer patients and AIDS patients with severe anemia.

4) KIDNEY STONES

Kidney stones, or **renal calculi**, are crystals of the salts that are normally present in urine. A very high concentration of salts in urine may trigger precipitation of the salt and formation of crystals, which can range in size from microscopic to 10 to 20 mm in diameter. The most common type of kidney stone is made of calcium salts; a less common type is made of uric acid. Kidney stones are most likely to form in the renal pelvis. Predisposing factors include decreased fluid intake or overingestion of minerals (as in mineral supplements), both of which lead to the formation of a very concentrated urine. The entry of a kidney stone into a ureter may cause intense pain (renal colic) and bleeding. Obstruction of a ureter by a stone may cause backup of urine and possible kidney damage.Treatments include surgery to remove the stone, or lithotripsy, the use of shock waves to crush the stone into pieces small enough to be eliminated without damage to the urinary tract. A recent study links lithotripsy with an increased risk of diabetes or hypertension later in life, though the mechanisms that would bring about these conditions have not yet been discovered.

5) BLOOD TESTS AND KIDNEY FUNCTION

Waste products are normally present in the blood, and the concentration of each varies within a normal range. As part of the standard lab work called blood chemistry, the levels of the three nitrogenous waste products are determined (urea, creatinine, and uric acid). If blood levels of these three substances are within normal ranges, it may be concluded that the kidneys are excreting these wastes at normal rates.

If, however, these blood levels are elevated, one possible cause is that kidney function has been impaired. Of the three, the creatinine level is probably the most reliable indicator of kidney functioning. Blood urea nitrogen (BUN) may vary considerably in certain situations not directly related to the kidneys. For example, BUN may be elevated as a consequence of a high-protein diet or of starvation when body protein is being broken down at a faster rate than normal.

Uric acid levels may also vary according to diet. However, elevated blood levels of all three nitrogenous wastes usually indicate impaired glomerular filtration.

6) *URINARY TRACT INFECTIONS*

Infections may occur anywhere in the urinary tract and are most often caused by the microbial agents of sexually transmitted infections diseases or by the bacteria that are part of the normal flora of the colon. In women especially, the urinary and anal openings are in close proximity, and colon bacteria on the skin of the perineum may invade the urinary tract. The use of urinary catheters in hospitalized or bedridden patients may also be a factor if sterile technique is not carefully followed.

Cystitis is inflammation of the urinary bladder. Symptoms include frequency of urination, painful voiding, and low back pain.

Nephritis (or pyelonephritis) is inflammation of the kidneys. Although this may be the result of a systemic bacterial infection, nephritis is a common complication of untreated lower urinary tract infections such as cystitis. Possible symptoms are fever and flank pain (in the area of the kidneys). Untreated nephritis may result in severe damage to nephrons and progress to renal failure.