# The Urinary System Outline

25.1 The kidneys have three distinct regions and a rich blood supply (pp. 963–965; Figs. 25.1–25.5)

A. Location and External Anatomy (p. 963; Figs. 25.1–25.3)
   1. The kidneys are bean-shaped organs that lie retroperitoneal in the superior lumbar region.
   2. The medial surface is concave and has a vertical cleft, the renal hilum, which leads into a renal sinus, where the blood vessels, nerves, and lymphatics lie.
   3. The kidneys are surrounded by an outer renal fascia that anchors the kidney and adrenal gland to surrounding structures, a perirenal fat capsule that surrounds and cushions the kidney, and a fibrous capsule that prevents surrounding infections from reaching the kidney.

B. Internal Gross Anatomy (p. 964; Fig. 25.4)
   1. There are three distinct regions of the kidney: the cortex, the medulla, and the renal pelvis.
   2. Major and minor calyces collect urine and empty it into the renal pelvis.

C. Blood and Nerve Supply (p. 965; Fig. 25.5)
   1. Blood supply into the kidneys progresses to the cortex through renal arteries to segmental, lobar, interlobar, arcuate, and cortical radiate (interlobular) arteries.
   2. Afferent arterioles branching away from the cortical radiate arteries give rise to the microscopic vasculature that is the key element of kidney function.
   3. Veins trace the arterial circulation in reverse: Blood draining from the renal cortex progresses through the cortical radiate, arcuate, and interlobar veins and back to renal veins.
   4. The renal plexus regulates renal blood flow by adjusting the diameter of renal arterioles and influencing the urine-forming role of the nephrons.

25.2 Nephrons are the functional units of the kidney (pp. 966–970; Figs. 25.6–25.10)

A. Each renal corpuscle is composed of a tuft of capillaries (the glomerulus) and surrounded by a glomerular capsule (Bowman's capsule). (p. 967; Figs. 25.6–25.7)
   1. The glomerular capillaries are fenestrated to increase permeability, allowing the formation of solute-rich, but protein-free, filtrate.
   2. The glomerular capsule has a parietal layer that contributes to capsular structure and a visceral layer associated with the glomerular capillaries, consisting of podocytes that allow filtrate to pass into the space within the glomerular capsule.

B. The Renal Tubule and Collecting Duct (pp. 967–969; Figs. 25.8–25.9)
   1. The renal tubule begins at the glomerular capsule as the proximal convoluted tubule, continues through a hairpin loop, and the nephron loop, and turns into a distal convoluted tubule before emptying into a collecting duct.

a. The wall of the proximal convoluted tubule has dense microvilli to increase surface area for absorption from, and secretion to, the urine.
b. The nephron loop has a descending limb and an ascending limb that has both thick and thin segments.
c. The distal convoluted tubule is similar to the proximal convoluted tubule, except the cells almost entirely lack microvilli.

2. The collecting duct contains principal cells that help maintain the body's water and sodium balance and intercalated cells that play a role in acid-base balance.
a. The collecting ducts collect filtrate from many nephrons and extend through the renal pyramid to the renal papilla, where they empty into a minor calyx.

C. There are two classes of nephrons: 85% are cortical nephrons, which are located almost entirely within the cortex; 15% are juxtamedullary nephrons located near the cortex-medulla junction. (p. 969; Fig. 25.8)

D. Nephron Capillary Beds (p. 969; Figs. 25.8–25.9)
1. The renal tubule of each nephron is closely associated with two capillary beds: the glomerulus; and the peritubular capillaries and vasa recta.
a. The glomerulus is specialized for filtration and is fed and drained by an afferent and efferent arteriole, which serves to maintain the high pressure in the glomerulus needed to favor filtration.
b. Peritubular capillaries are low-pressure, porous capillaries that closely surround adjacent renal tubules to absorb solutes and water from the tubule cells.
c. The vasa recta arise from the efferent arterioles near juxtamedullary nephrons and run parallel to the longest nephron loops.

E. The juxtaglomerular complex is a structural arrangement between the afferent arteriole and the distal convoluted tubule that forms granular cells and macula densa cells. (p. 970; Fig. 25.10)
1. The macula densa are cells in the ascending limb that act as chemoreceptors that monitor NaCl content of filtrate entering the distal convoluted tubule.
2. Granular cells, derived from the wall of the arterioles, act as mechanoreceptors that monitor blood pressure and house secretory vesicles that contain the enzyme renin.

## 25.3 Overview: Filtration, absorption, and secretion are the key processes of urine formation (p. 971; Fig. 25.11)

A. Of the approximately 1200 ml of blood that passes through the glomeruli each minute, roughly 650 ml is blood plasma, and one-fifth of this is filtered across the glomerulus. (p. 971)

B. Filtrate contains everything found in blood plasma except proteins, while urine contains unneeded substances, such as excess salts and metabolic wastes. (p. 971)

C. Roughly 180 L of filtrate is formed per day, although less than 1% of this amount leaves the body as urine. (p. 971)

## 25.4 Urine formation, step 1: The glomeruli make filtrate (pp. 971–976; Figs. 25.12–25.14)

A. Glomerular filtration is a passive, nonselective process in which hydrostatic pressure forces fluids through the glomerular membrane. (p. 971)

B. The filtration membrane is a porous membrane that allows free passage of water and solutes smaller than plasma proteins. (pp. 973–974; Fig. 25.12)
   1. The filtration membrane consists of three layers: the fenestrated endothelium of the glomerular capillaries, a basement membrane consisting of negatively charged glycoproteins that inhibit the filtration of negatively charged molecules, and the podocytes of the visceral layer of the glomerular capsule.

C. Pressures That Affect Filtration (p. 973; Fig. 25.13)
   1. The net filtration pressure responsible for filtrate formation is given by the balance of hydrostatic pressure in the glomerulus against the combined forces of capsular hydrostatic pressure, and colloid osmotic pressure of glomerular blood.
      a. The hydrostatic pressure in glomerular capillaries $(HP_{gc})$, essentially glomerular blood pressure, is the chief force pushing water and solutes out of the blood across the filtration membrane and measures around 55 mm Hg.
      b. The hydrostatic pressure in the capsular space $(HP_{cs})$ represents the pressure exerted by the filtrate within the capsule and is higher than the pressure surrounding most capillaries due to the confinement of the filtrate.
      c. The colloid osmotic pressure in glomerular capillaries $(OP_{gc})$ is the pressure exerted by the proteins in the blood.

D. The glomerular filtration rate is the volume of filtrate formed each minute by all the glomeruli of the kidneys combined and is directly proportional to three factors: the net filtration pressure, total surface area available for filtration, and filtration membrane permeability. (pp. 973–974)

E. Regulation of glomerular filtration allows the body to both maintain filtration and maintain blood pressure. (pp. 974–976; Figs. 25.14–25.15)
   1. Renal autoregulation uses a myogenic mechanism related to the degree of stretch of the afferent arteriole, and a tubuloglomerular feedback mechanism that responds to the rate of filtrate flow in the tubules.
   2. Extrinsic neural mechanisms include stress-induced sympathetic responses that inhibit filtrate formation by constricting the afferent arterioles.
   3. The renin-angiotensin-aldosterone mechanism causes an increase in systemic blood pressure: Renin secretion may be promoted by sympathetic stimulation, signals from macula densa cells, or reduced stretch of granular cells.

## 25.5 Urine formation, step 2: Most of the filtrate is reabsorbed into the blood (pp. 976–981; Figs. 25.15–25.17; Table 25.1)

A. Tubular reabsorption is a selective transepithelial process that begins as soon as the filtrate enters the proximal convoluted tubule. (p. 976; Fig. 25.15; Table 25.1)
   1. In healthy kidneys, nearly all organic nutrients such as glucose and amino acids are reabsorbed, while the absorption of water and ions is continually regulated and adjusted.

2. Active tubular reabsorption requires direct or indirect use of ATP, while passive tubular reabsorption involves movement of molecules down their electrochemical gradients by diffusion, facilitated diffusion, or osmosis.

B. Tubular Reabsorption of Sodium (pp. 978–979; Fig. 25.16)

1. The most abundant cation of the filtrate is $Na^+$: Basolateral primary active transport of $Na^+$ creates gradients that drive apical secondary active transport of $Na^+$.

C. Tubular Reabsorption of Nutrients, Water, and Ions (p. 979; Fig. 25.16)

1. Secondary active transport, driven by primary absorption of $Na^+$, is used to absorb glucose, amino acids, some ions, and vitamins (cotransported with $Na^+$).
2. Passive tubular reabsorption of water occurs down osmotic gradients created by the absorption of $Na^+$ and other solutes.
   a. Absorption of water in the collecting duct requires antidiuretic hormone (ADH).
3. Passive reabsorption of solutes such as lipid-soluble solutes, some ions, and urea occurs down concentration gradients created by the absorption of water from the filtrate.

D. Transport maximums exist for most substances that are reabsorbed via transport protein; when the concentration of a solute in the urine exceeds the saturation point of the transporters, excess is lost in the urine. (p. 979)

E. Reabsorptive capabilities in the tubules and collecting duct differ from one area to another. (p. 979–980; Fig. 25.17; Table 25.1)

1. The proximal convoluted tubule is most active in reabsorption; nearly all glucose, amino acids, and vitamins are absorbed there, 65% of water and $Na^+$.
2. Absorption of water and ions in the nephron loop is not coupled: the descending limb of the nephron loop is permeable to water, while the ascending limb is impermeable to water but passively and actively transports ions.
3. The distal convoluted tubule and collecting duct have $Na^+$ and water permeability regulated by the hormones aldosterone, antidiuretic hormone, and atrial natriuretic peptide, which allows fine-tuning of final urine concentration.

25.6 Urine formation, step 3: Certain substances are secreted into the filtrate (p. 981; Fig. 25.17)

A. Tubular secretion is most active in the proximal convoluted tubule, but also occurs in the collecting ducts and distal convoluted tubules. (p. 981; Fig. 25.17)

B. Tubular secretion disposes of unwanted solutes, eliminates unwanted, reabsorbed solutes, rids the body of excess $K^+$, and controls blood pH. (p. 981; Fig. 25.17)

25.7 The kidneys create and use an osmotic gradient to regulate urine concentration and volume (pp. 981–986; Figs. 25.18–25.19; Focus Figure 25.1)

A. The countercurrent multiplier utilizes gradients created by absorption of ions from the ascending limb and water from the descending limb to drive absorption from the urine. (p 984; Fig. 25.18; Focus Figure 25.1)
   1. Absorption of much of the $Na^+$ and $Cl^-$ in the thick ascending limb uses active transport, but uses passive transport in the thin segment of the ascending limb.

B. The countercurrent exchanger serves to preserve the medullary concentration gradient by preventing rapid removal of salts from the interstitial space and removing reabsorbed water. (p. 984; Fig. 25.18)

C. Formation of concentrated urine occurs in response to the release of ADH, which makes the collecting ducts permeable to water and increases water uptake from the urine. (pp. 984–985; Fig. 25.19)

D. Urea Recycling and the Medullary Osmotic Gradient (p. 986)
   1. Urea enters the filtrate from the medullary interstitial fluid in the thin ascending limb; absorption of water in the cortical collecting duct concentrates urea in the urine, which then moves back into the medullary interstitial fluid in the deepest part of the collecting duct.

E. Diuretics act to increase urine output by either acting as an osmotic diuretic or by inhibiting $Na^+$ and resulting obligatory water reabsorption. (p. 986)

25.8 Renal function is evaluated by analyzing blood and urine (pp. 986–988; Table 25.2)

A. Renal clearance refers to the volume of plasma that is cleared of a specific substance in a given time. (pp. 986–987; Table 25.2)
   1. Inulin is used as a clearance standard to determine glomerular filtration rate because it is not reabsorbed, stored, or secreted.
   2. If the clearance value for a substance is less than that for inulin, then some of the substance is being reabsorbed; if the clearance value is greater than the inulin clearance rate, then some of the substance is being secreted. A clearance value of zero indicates the substance is completely reabsorbed.

B. Urine (pp. 987–988; Table 25.2)
   1. Freshly voided urine is clear and pale to deep yellow due to urochrome, a pigment resulting from the destruction of hemoglobin, and is slightly aromatic but develops an ammonia odor if allowed to stand due to bacterial metabolism of urea.
   2. Urine is usually slightly acidic (around pH 6) but can vary from about 4.5–8.0 in response to changes in metabolism or diet, and has a higher specific gravity than water, due to the presence of solutes.
   3. Urine volume is about 95% water and 5% solutes, the largest solute fraction devoted to the nitrogenous wastes urea, creatinine, and uric acid.

25.9 The ureters, bladder, and urethra transport, store, and eliminate urine (pp. 988–992; Figs. 25.20–25.23)

A. Ureters are tubes that actively convey urine from the kidneys to the bladder. (pp. 988–989; Figs. 25.20, 25.22)
   1. The walls of the ureters consist of an inner mucosa continuous with the kidney pelvis and the bladder, a double-layered muscularis, and a connective tissue adventitia covering the external surface.

B. The urinary bladder is a muscular sac that expands as urine is produced by the kidneys to allow storage of urine until voiding is convenient. (pp. 989–990; Figs. 25.21–25.22)
   1. The bladder is a retroperitoneal organ on the pelvic floor, just posterior to the pubic symphysis, and has openings in the interior for the ureters and urethra, which form a triangular region called the trigone.
   2. The wall of the bladder has three layers: an outer adventitia, a middle layer of detrusor muscle, and an inner mucosa that is highly folded to allow distention of the bladder without a large increase in internal pressure.
   3. The bladder, when full, has a capacity of around 500 ml of urine; as it fills, the bladder expands, the wall stretches and thins, and the folds, rugae, disappear.

C. The urethra is a muscular tube that drains urine from the body; it is 3–4 cm long in females, but closer to 20 cm in males. (p. 990; Fig. 25.21)
   1. There are two sphincter muscles associated with the urethra: the internal urethral sphincter, which is involuntary and formed from detrusor smooth muscle; and the external urethral sphincter, which is voluntary and formed by the skeletal muscle at the urogenital diaphragm.
   2. The external urethral orifice lies between the clitoris and vaginal opening in females, and it is located at the tip of the penis in males.

D. Micturition, or urination, is the act of emptying the bladder. (pp. 990–991; Fig. 25.23)
   1. Three things must happen simultaneously in order for micturition to occur: The detrusor must contract, the internal urethral sphincter must open, and the external urethral sphincter must open.
   2. As urine accumulates, distention of the bladder activates stretch receptors, which trigger spinal reflexes, resulting in storage of urine.
      a. Visceral afferent impulses excite parasympathetic neurons, and inhibit sympathetic neurons, resulting in contraction of the detrusor, and the internal sphincter opens.
      b. Visceral afferent impulses also decrease the rate of firing of somatic efferents that maintain contraction of the external sphincter, allowing it to open.
   3. There are two centers in the pons that participate in control of micturition: The pontine storage center inhibits micturition, while the pontine micturition center promotes the reflex.

Developmental Aspects of the Urinary System (pp. 992–993; Fig. 25.24)

A. In the developing fetus, the mesoderm-derived urogenital ridges give rise to three sets of kidneys: the pronephros, mesonephros, and metanephros. (pp. 992–993; Fig. 25.24)
   1. The pronephros forms and degenerates during the fourth through sixth weeks, but the pronephric duct persists, and connects later-developing kidneys to the cloaca.
   2. The mesonephros develops from the pronephric duct, which then is named the mesonephric duct, and persists until development of the metanephros.
   3. The metanephros develops at about five weeks, and forms ureteric buds that give rise to the ureters, renal pelvis, calyces, and collecting ducts.

4. The *cloaca* subdivides to form the future rectum, anal canal, and the urogenital sinus, which gives rise to the bladder and urethra.

B. Newborns void most frequently because the bladder is small and the kidneys cannot concentrate urine until two months of age. (p. 993)

C. From two months of age until adolescence, urine output increases until the adult output volume is achieved. (p. 993)

D. Voluntary control of the urinary sphincters depends on nervous system development, and complete control of the bladder even during the night does not usually occur before 4 years of age. (p. 985)

E. In old age, kidney function declines due to shrinking of the kidney as nephrons decrease in size and number; the bladder also shrinks and loses tone, resulting in frequent urination. (p. 985)