Note: Large images and tables on this page may necessitate printing in landscape mode.

The Urinary System: Introduction

The urinary system consists of the paired kidneys and ureters and the unpaired bladder and urethra. This system contributes to the maintenance of homeostasis by a complex process that involves **filtration, active absorption, passive absorption,** and **secretion.** The result is the production of urine, in which various metabolic waste products are eliminated. Urine produced in the kidneys passes through the ureters to the bladder, where it is temporarily stored and then released to the exterior through the urethra. The two kidneys produce about 125 mL of filtrate per minute; of this amount, 124 mL is absorbed in the organ, and only 1 mL is released into the ureters as urine. About 1500 mL of urine is formed every 24 h. The kidneys also regulate the fluid and electrolyte balance of the body and are the site of production of renin, a substance that participates in the regulation of blood pressure. Erythropoietin, a growth factor glycoprotein of 30 kDa that stimulates the production of erythrocytes, is also produced in the kidneys. Erythropoietin also hydroxylates vitamin D_3, a steroid prohormone, to its active form.
Kidneys

Each kidney has a concave medial border, the **hilum**â€”where nerves enter, blood and lymph vessels enter and exit, and the ureter exitsâ€”and a convex lateral surface (Figure 19â€“1). The **renal pelvis,** the expanded upper end of the ureter, is divided into two or three **major calyces.** Several small branches, the **minor calyces,** arise from each major calyx.

Figure 19â€“1.

Left: General organization of the kidney. **Right:** Parts of a juxtamedullary nephron and its collecting duct and tubule.

The kidney can be divided into an outer **cortex** and an inner **medulla** (Figures 19â€“1 and 19â€“2). In humans, the renal medulla consists of 10â€“18 conical or pyramidal

structures, the **medullary pyramids.** From the base of each medullary pyramid, parallel arrays of tubules, the **medullary rays,** penetrate the cortex (Figure 19â€“1).

Figure 19â€“2.

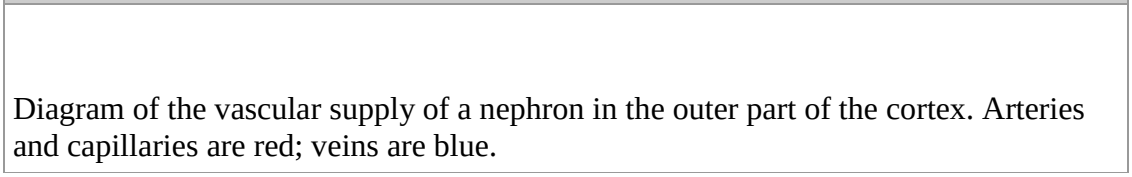


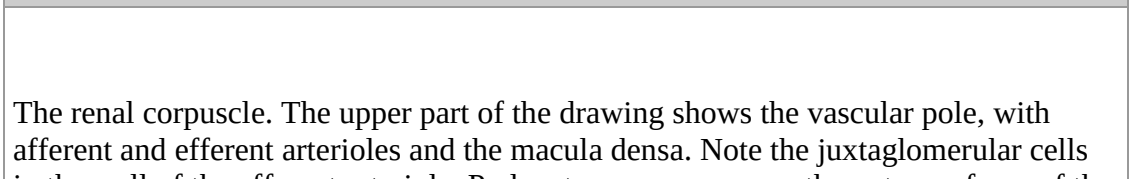
Diagram of the vascular supply of a nephron in the outer part of the cortex. Arteries and capillaries are red; veins are blue.

Each kidney is composed of 1â€“4 million **nephrons** (Gr. *nephros,* kidney). Each nephron consists of a dilated portion, the **renal corpuscle;** the **proximal convoluted tubule;** the **thin** and **thick limbs** of **Henle's loop;** the **distal convoluted tubule** (Figure 19â€“1); and the **collecting tubules** and **ducts.** Some investigators do not consider the collecting tubules and ducts to be part of the nephron. The nephron is the functional unit of the kidney.

Renal Corpuscles & Blood Filtration

Each renal corpuscle is about 200 m in diameter and consists of a tuft of capillaries, the **glomerulus,** surrounded by a double-walled epithelial capsule called **glomerular (Bowman's) capsule** (Figures 19â€“1, 19â€“2, and 19â€“3). The internal layer (the **visceral layer**) of the capsule envelops the capillaries of the glomerulus. The external layer forms the outer limit of the renal corpuscle and is called the **parietal layer** of Bowman's capsule (Figures 19â€“2, 19â€“3, and 19â€“4). Between the two layers of Bowman's capsule is the **urinary space,** which receives the fluid filtered through the capillary wall and the visceral layer. Each renal corpuscle has a **vascular pole,** where the **afferent arteriole** enters and the efferent arteriole leaves (Figure 19â€“3), and a **urinary pole,** where the proximal convoluted tubule begins (Figure 19â€“3). After entering the renal corpuscle, the afferent arteriole usually divides into two to five primary branches, each subdividing into capillaries and forming the renal glomerulus.

Figure 19â€“3.



The renal corpuscle. The upper part of the drawing shows the vascular pole, with afferent and efferent arterioles and the macula densa. Note the juxtaglomerular cells in the wall of the afferent arteriole. Podocyte processes cover the outer surfaces of the glomerular capillaries; the part of the podocyte containing the nucleus protrudes into the urinary space. Note the flattened cells of the parietal layer of Bowman's capsule. The lower part of the drawing shows the urinary pole and the proximal convoluted tubule.

Figure 19â€“4.

Electron micrograph of a rat kidney showing part of a renal corpuscle, including the parietal layer of Bowman's capsule, the urinary space, glomerular capillaries containing erythrocytes, the visceral layer of Bowman's capsule, the peritubular capillary, and the proximal tubule. x2850. (Courtesy of SL Wissig.)

The parietal layer of Bowman's capsule consists of a simple squamous epithelium supported by a basal lamina and a thin layer of reticular fibers. At the urinary pole, the epithelium changes to the simple cuboidal, or low columnar, epithelium characteristic of the proximal tubule (Figure 19â€“3).

During embryonic development, the epithelium of the parietal layer remains relatively unchanged, whereas the internal, or visceral, layer is greatly modified. The cells of this internal layer, the **podocytes** (Figures 19â€“3, 19â€“5, 19â€“6, and 19â€“7), have a cell body from which arise several **primary processes.** Each primary process gives rise to numerous **secondary processes,** called **pedicels** (Figures 19â€“5, 19â€“6, and 19â€“7), that embrace the capillaries of the glomerulus. At a periodic distance of 25 nm, the secondary processes are in direct contact with the basal lamina. However, the cell bodies of podocytes and their primary processes do not touch the basement membrane (Figures 19â€“5 and 19â€“7).

Figure 19â€“5.

Schematic representation of a glomerular capillary with the visceral layer of Bowman's capsule (formed of podocytes). In this capillary, endothelial cells are fenestrated, but the basal lamina on which they rest is continuous. At left is a podocyte shown in partial section. As viewed from the outside, the part of the podocyte that contains the nucleus protrudes into the urinary space. Each podocyte has many primary processes, from which arise an even greater number of secondary processes that are in contact with the basal lamina. (Modified and redrawn from Gordon. Reproduced, with permission, from Ham AW: *Histology,* 6th ed. Lippincott, 1969.)

Figure 19â€“6.

Scanning electron micrograph showing Bowman's visceral epithelial cells, or podocytes (P), surrounding capillaries of the renal glomerulus. Two orders of branching of the podocyte processes are apparent: the primary processes (1) and the secondary processes, or pedicels (2). The small spaces between adjacent processes constitute the filtration slits (arrows). x10,700.

Figure 19â€“7.

Electron micrograph showing the cell bodies of two podocytes and the alternation of secondary processes from two different cells (arrows). The urinary space and the glomerular capillary are indicated. x9000. (Courtesy of SL Wissig.)

The secondary processes of podocytes interdigitate, defining elongated spaces about 25 nm wideâ€”the **filtration slits.** Spanning adjacent processes (and thus bridging the filtration slits) is a diaphragm about 6 nm thick. Podocytes have bundles of actin filaments in their cytoplasm that give them a contractile capacity (Figures 19â€“7 and 19â€“8).

Figure 19â€“8.

Electron micrograph of the filtration barrier in a renal corpuscle. Note the endothelium (E) with open fenestrae (arrowhead), the fused basal laminae (basement membrane) of epithelial and endothelial cells (BL), and the processes of podocytes (P). The basement membrane consists of a central lamina densa bounded on both sides by a light-staining lamina rara. Arrows indicate the thin diaphragms crossing the filtration slits. x45,750. (Courtesy of SL Wissig.)

Between the fenestrated endothelial cells of the glomerular capillaries and the

podocytes that cover their external surfaces is a thick (0.1- m) basement membrane (Figures 19â€“8 and 19â€“9). This membrane is believed to be the filtration barrier that separates the urinary space and the blood in the capillaries. The basement membrane is derived from the fusion of capillary- and podocyte-produced basal laminae. With the aid of the electron microscope, a central electron-dense layer (**lamina densa**) and, on each side, a more electron-lucent layer (**lamina rara;** Figure 19â€“8) can be distinguished. The two electron-lucent laminae rarae contain

fibronectin, which may serve to bind them to the cells. The lamina densa is a meshwork of type IV collagen and laminin in a matrix containing the negatively charged proteoglycan heparan sulfate that restricts the passage of cationic molecules. Thus, the glomerular basement membrane is a selective macromolecular filter in which the lamina densa acts as a physical filter, whereas the anionic sites in the laminae rarae act as a charge barrier. Particles greater than 10 nm in diameter do not readily cross the basal lamina, and negatively charged proteins with a molecular mass greater than that of albumin (69 kDa) pass across only sparingly.

Figure 19â€“9.

Photomicrograph of a renal cortex showing parts of two renal corpuscles, macula densa, and distal and proximal convoluted tubules. The collagen type IV of the basement membrane of the glomerular capillaries is clearly visible (arrows). The collagen of the parietal layer of Bowman's capsule and the basal membrane of a distal tubule are shown by the arrowhead. Picrosirius stain. Medium magnification.

The blood flow in the two kidneys of an adult amounts to 1.2â€“1.3 L of blood per minute. This means that all the circulating blood in the body passes through the kidneys every 4â€“5 min. The glomeruli are composed of arterial capillaries in which the hydrostatic pressureâ€”about 45 mm Hgâ€”is higher than that found in other capillaries.

The glomerular filtrate is formed in response to the hydrostatic pressure of blood, which is opposed by the osmotic (oncotic) pressure of plasma colloids (20 mm Hg), and the hydrostatic pressure of the fluids in Bowman's capsule (10 mm Hg). The net filtration pressure at the afferent end of glomerular capillaries is 15 mm Hg.

The glomerular filtrate has a chemical composition similar to that of blood plasma but contains almost no protein, because macromolecules do not readily cross the glomerular filter. The largest protein molecules that succeed in crossing the glomerular filter have a molecular mass of about 70 kDa, and small amounts of plasma albumin appear in the filtrate.

MEDICAL APPLICATION

In diseases such as diabetes mellitus and glomerulonephritis, the glomerular filter is altered and becomes much more permeable to proteins, with the subsequent release of protein into the urine (**proteinuria**).

The endothelial cells of glomerular capillaries are of the fenestrated variety, but they lack the thin diaphragm that spans the openings of other fenestrated capillaries (Figure 19â€“7).

In addition to endothelial cells and podocytes, the glomerular capillaries have **mesangial** (Gr. *mesos,* middle, + *angeion,* vessel) cells adhering to their walls (Figures 19â€“10 and 19â€“11). Mesangial cells are contractile and have receptors for angiotensin II. When these receptors are activated, the glomerular flow is reduced. Mesangial cells also have receptors for the natriuretic factor produced by cardiac atria cells. This factor is a vasodilator and relaxes the mesangial cells, probably increasing the blood flow and the effective surface area available for filtration. Mesangial cells also have several other functions: they give structural support to the glomerulus, synthesize extracellular matrix, endocytose and dispose of normal and pathological (immune complex) molecules trapped by the glomerular basement membrane, and probably produce chemical mediators such as cytokines and prostaglandins. In the vascular pole but outside the glomerulus, there are the so-called **extraglomerular mesangial cells** that form part of the juxtaglomerular apparatus (described below).

Figure 19â€“10.

Mesangial cell located between capillaries enveloped by the basement membrane.

Figure 19â€“11.

Electron micrograph showing a mesangial cell (MC) and the amorphous mesangial matrix surrounding it. The matrix helps to support the capillary loops where a basement membrane is lacking. Some of the mesangial cell's processes (arrows) reach the capillary lumen, passing between endothelial cells (asterisks). The capillary at left contains an erythrocyte (RBC) and a leukocyte (L). BM, basement membrane; EC, endothelial cell; Pd, pedicels; PN, podocyte nucleus; U, urinary space.

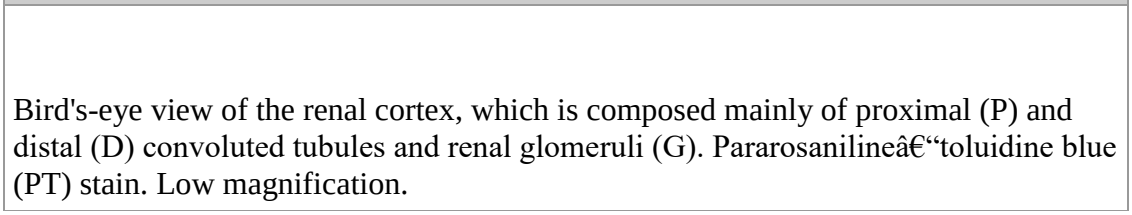
Proximal Convoluted Tubule

At the urinary pole of the renal corpuscle, the squamous epithelium of the parietal layer of Bowman's capsule is continuous with the cuboidal, or low columnar, epithelium of the proximal convoluted tubule (Figures 19â€“1, 19â€“3, and 19â€“9). This tubule is longer than the distal convoluted tubule and is therefore more frequently seen near renal corpuscles in the renal cortex.

The cells of this cuboidal epithelium have an acidophilic cytoplasm (Figures 19â€“12, 19â€“13, and 19â€“14) because of the presence of numerous elongated mitochondria.

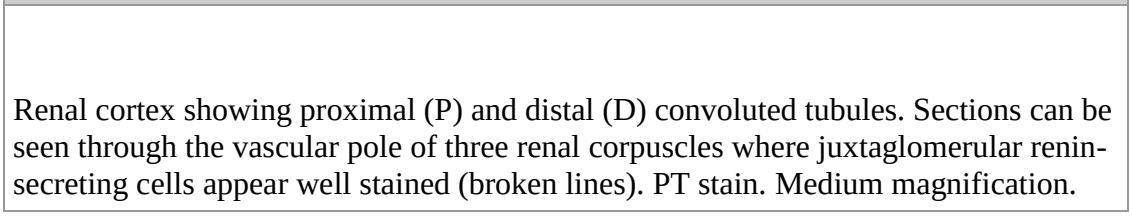
The cell apex has abundant microvilli about 1 m in length, which form a **brush border** (Figures 19â€“14, 19â€“15, and 19â€“16). Because the cells are large, each transverse section of a proximal tubule contains only three to five spherical nuclei.

Figure 19â€“12.



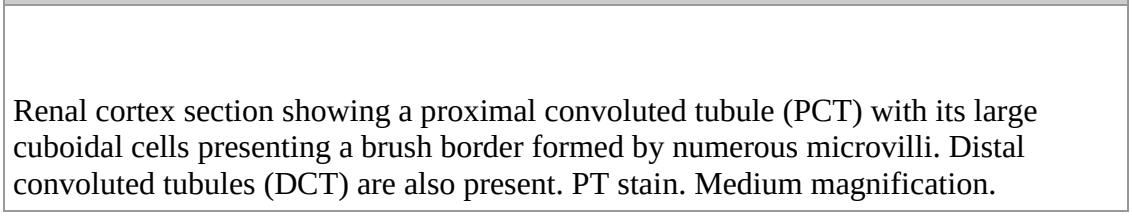
Bird's-eye view of the renal cortex, which is composed mainly of proximal (P) and distal (D) convoluted tubules and renal glomeruli (G). Pararosanilineâ€“toluidine blue (PT) stain. Low magnification.

Figure 19â€“13.



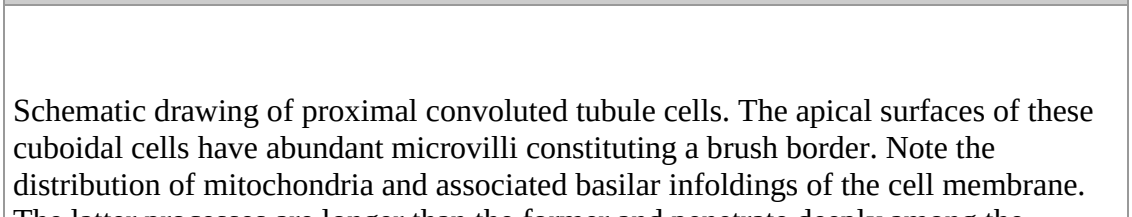
Renal cortex showing proximal (P) and distal (D) convoluted tubules. Sections can be seen through the vascular pole of three renal corpuscles where juxtaglomerular renin-secreting cells appear well stained (broken lines). PT stain. Medium magnification.

Figure 19â€“14.



Renal cortex section showing a proximal convoluted tubule (PCT) with its large cuboidal cells presenting a brush border formed by numerous microvilli. Distal convoluted tubules (DCT) are also present. PT stain. Medium magnification.

Figure 19â€“15.



Schematic drawing of proximal convoluted tubule cells. The apical surfaces of these cuboidal cells have abundant microvilli constituting a brush border. Note the distribution of mitochondria and associated basilar infoldings of the cell membrane. The latter processes are longer than the former and penetrate deeply among the neighboring cells. Artificial spaces between the cells are shown to make the drawing easier to understand. (Modified from Bulger R: Am J Anat 1965;116:237.)

Figure 19â€“16.

Cellular ultrastructure of the nephron, represented schematically. Cells of the thick ascending limb of Henle's loop and the distal tubule are different in their ultrastructures and functions.

In the living animal, proximal convoluted tubules have a wide lumen and are surrounded by peritubular capillaries. In routine histological preparations, the brush border is usually disorganized and the peritubular capillary lumens are greatly reduced in size or collapsed.

The apical cytoplasm of these cells has numerous canaliculi between the bases of the microvilli; these canaliculi increase the capacity of the proximal tubule cells to absorb macromolecules. Pinocytotic vesicles are formed by evaginations of the apical membranes and contain macromolecules (mainly proteins with a molecular mass less than 70 kDa) that have passed across the glomerular filter. The pinocytotic vesicles fuse with lysosomes, where macromolecules are degraded, and monomers are returned to the circulation. The basal portions of these cells have abundant membrane invaginations and lateral interdigitations with neighboring cells. The Na^+/K^+-ATPase (sodium pump) responsible for actively transporting sodium ions out of the cells is localized in these basolateral membranes. Mitochondria are concentrated at the base of the cell (Figure 19â€“4) and arranged parallel to the long axis of the cell. This mitochondrial location and the increase in the area of the cell membrane at the base of the cell are characteristic of cells engaged in active ion transport (see Chapter 4: Epithelial Tissue). Because of the extensive interdigitations of the lateral membranes, no discrete limits can be observed (in the light microscope) between cells of the proximal tubule. The glomerular filtrate formed in the renal corpuscle passes into the proximal convoluted tubule, where the processes of absorption and excretion begin. The proximal convoluted tubule absorbs all the glucose and amino acids and about 85% of the sodium chloride and water contained in the filtrate, in addition to phosphate and calcium. Glucose, amino acids, and sodium are absorbed by these tubular cells through an active process involving Na^+/K^+-ATPase (sodium pump) located in the basolateral cell membranes. Water diffuses passively, following the osmotic gradient. When the amount of glucose in the filtrate exceeds the absorbing capacity of the proximal tubule, urine becomes more abundant and contains glucose.

In addition to these activities, the proximal convoluted tubule secretes creatinine and substances foreign to the organism, such as para-aminohippuric acid and penicillin, from the interstitial plasma into the filtrate. This is an active process referred to as tubular secretion.

Henle's Loop

Henle's loop is a **U**-shaped structure consisting of a **thick descending limb,** a **thin descending limb,** a **thin ascending limb,** and a **thick ascending limb.** The thick limbs

are very similar in structure to the distal convoluted tubule (Figure 19â€“16). In the outer medulla, the thick descending limb, with an outer diameter of about 60 m, suddenly narrows to about 12 m and continues as the thin descending limb. The lumen of this segment of the nephron is wide because the wall consists of squamous epithelial cells whose nuclei protrude only slightly into the lumen (Figures 19â€“16, 19â€“17, and 19â€“18).

Figure 19â€“17.

Distal convoluted tubules (DCT) characterized by the absence of brush border. Note also a thin portion of Henle's loop (THL) and a blood capillary (arrowhead). PT stain. Medium magnification.

Figure 19â€“18.

Electron micrograph of the thin limb of Henle's loop (H) composed entirely of squamous cells. Note the fenestrated capillaries with erythrocytes (C) and the interstitium (I) with bundles of collagen fibrils. x3300. (Courtesy of J Rhodin.)

Approximately one-seventh of all nephrons are located near the corticomedullary junction and are therefore called **juxtamedullary nephrons.** The other nephrons are called **cortical nephrons.** All nephrons participate in the processes of filtration, absorption, and secretion. Juxtamedullary nephrons, however, are of prime importance in establishing the gradient of hypertonicity in the medullary interstitiumâ€”the basis of the kidneys' ability to produce hypertonic urine. Juxtamedullary nephrons have very long Henle's loops, extending deep into the medulla. These loops consist of a short thick descending limb, long thin descending and ascending limbs, and a thick ascending limb. Cortical nephrons, on the other hand, have very short thin descending limbs and no thin ascending limbs (Figure 19â€“2).

Henle's loop is involved in water retention; only animals with such loops in their kidneys are capable of producing hypertonic urine and thus maintaining body water. Henle's loop creates a gradient of hypertonicity in the medullary interstitium that influences the concentration of the urine as it flows through the collecting ducts.

Although the thin descending limb of the loop is freely permeable to water, the entire ascending limb is impermeable to water. In the thick ascending limb, sodium chloride is actively transported out of the tubule to establish the gradient of hypertonicity in the

medullary interstitium that is necessary for urine concentration. The osmolarity of the interstitium at the tips of the medullary pyramids is about four times that of blood.

Distal Convoluted Tubule

The thick ascending limb of Henle's loop penetrates the cortex; after describing a certain trajectory, it becomes tortuous and is called the distal convoluted tubule. This tubule, like the ascending limb, is lined with simple cuboidal epithelium (Figures 19â€“16, 19â€“17, and 19â€“19).

Figure 19â€“19.

Region of the kidney consisting mainly of distal convoluted tubules (DCT) and thin segments of Henle's loop (asterisks). Capillaries filled with blood appear in red. PT stain. Medium magnification.

The distal convoluted tubules differ from the proximal convoluted tubules (both found in the cortex) because they have no brush border, no apical canaliculi, and smaller cells. Because distal tubule cells are flatter and smaller than those of the proximal tubule, more nuclei are seen in the distal tubule than in the proximal tubule. Cells of the distal convoluted tubule have elaborate basal membrane invaginations and associated mitochondria indicative of their ion-transporting function (Figure 19â€“16).

The distal convoluted tubule establishes contact with the vascular pole of the renal corpuscle of its parent nephron. At this point of close contact, the distal tubule is modified, as is the afferent arteriole. In this juxtaglomerular region, cells of the distal convoluted tubule usually become columnar, and their nuclei are closely packed together. Most of the cells have a Golgi complex in the basal region. This modified segment of the wall of the distal tubule, which appears darker in microscopic preparations because of the close proximity of its nuclei, is called the **macula densa** (Figures 19â€“3, 19â€“20, and 19â€“21). The cells of the macula densa are sensitive to the ionic content and water volume of the tubular fluid, producing molecular signals that promote the liberation of the enzyme renin in the circulation.

Figure 19â€“20.

Renal cortex showing a distal convoluted tubule with a macula densa formed by closely packed epithelial cells (broken line). This structure is sensitive to the ionic concentration of the filtrate in the distal tubule and is believed to influence glomerular filtration. PT stain. Medium magnification.

Figure 19â€“21.

Photomicrograph of renal cortex. A macula densa is clearly seen (arrow) at the vascular pole of a renal corpuscle. Picrosiriusâ€“hematoxylin (PSH) stain. Medium magnification.

In the distal convoluted tubule, there is ion exchange if aldosterone is present in high enough concentration: Sodium is absorbed, and potassium ions are secreted. This mechanism influences the total salt and water content of the body. The distal tubule also secretes hydrogen and ammonium ions into tubular urine. This activity is essential for maintenance of the acidâ€“base balance in the blood.

Collecting Tubules & Ducts

Urine passes from the distal convoluted tubules to collecting tubules that join each other to form larger, straight collecting ducts, which widen gradually as they approach the tips of the medullary pyramids (Figure 19â€“1).

The smaller collecting tubules are lined with cuboidal epithelium and have a diameter

of approximately 40 m. As they penetrate deeper into the medulla, their cells increase in height until they become columnar. The diameter of the collecting duct

reaches 200 m near the tips of the medullary pyramids.

Along their entire extent, collecting tubules and ducts are composed of cells that stain weakly (Figure 19â€“22) with the usual stains. They have an electron-lucent cytoplasm with few organelles (Figure 19â€“23). In collecting tubules and cortical collecting ducts, a dark-staining intercalated cell is also seen; its significance is not understood. The intercellular limits of the collecting tubule and duct cells are clearly visible in the light microscope (Figure 19â€“22). Cortical collecting ducts are joined at right angles by several generations of smaller collecting tubules that drain each medullary ray. In the medulla, collecting ducts are a major component of the urine-concentrating mechanism.

Figure 19â€“22.

Photomicrograph of renal medulla with two collecting ducts consisting of cuboidal cells resting on a basement membrane. In this hypertonic region of the kidney,

because of the action of the hypophyseal antidiuretic hormone, water is reabsorbed, controlling the water balance of the body. PT stain. Medium magnification.

Figure 19â€“23.

Electron micrograph of a collecting tubule wall. M, mitochondria; NU, nucleolus. x15,000.

The epithelium of collecting ducts is responsive to argininevasopressin, or antidiuretic hormone, secreted by the posterior pituitary. If water intake is limited, antidiuretic hormone is secreted and the epithelium of the collecting ducts becomes permeable to water, which is absorbed from the glomerular filtrate, transferred to blood capillaries, and thus retained in the body. In the presence of antidiuretic hormone, intramembrane particles in the luminal membrane aggregate to form what may be channels for water absorption.

Juxtaglomerular Apparatus

Adjacent to the renal corpuscle, the tunica media of the afferent arteriole has modified smooth muscle cells. These cells are called **juxtaglomerular (JG) cells** (Figures 19â€“3, 19â€“13, 19â€“24, and 19â€“25) and have a cytoplasm full of secretory granules. Secretions of JG cells play a role in the maintenance of blood pressure. The macula densa of the distal convoluted tubule is usually located near the region of the afferent arteriole that contains the JG cells; together, this portion of the arteriole and the macula densa form the JG apparatus (Figures 19â€“3 and 19â€“24). Also a part of the JG apparatus are some light-staining cells whose functions are not well understood. They are called **extraglomerular mesangial cells** or **lacis cells.** The internal elastic membrane of the afferent arteriole disappears in the area of the JG cells.

Figure 19â€“24.

Photomicrograph of an afferent arteriole entering a renal corpuscle. The wall of this arteriole shows the renin-producing juxtaglomerular (JG) cells (broken line). At the upper right is a distal convoluted tubule (DCT) with many elongated mitochondria. PT stain. High magnification.

Figure 19â€“25.

Photomicrographs of two renal corpuscles. **Left:** A macula densa with the characteristic close proximity of its nuclei. In this location, cells of the distal tubules are smaller. **Right:** A portion of a juxtaglomerular apparatus showing the wall of the afferent arteriole with cells that have secretory granules (arrowheads) containing renin.

When examined with the electron microscope, JG cells show characteristics of protein-secreting cells, including an abundant rough endoplasmic reticulum, a highly developed Golgi complex, and secretory granules measuring approximately 10â€“40 nm in diameter. JG cells produce the enzyme **renin,** which acts on a plasma proteinâ€”**angiotensinogen**â€”to produce an inactive decapeptide, **angiotensin I.** As a result of the action of a converting enzyme present in high concentration in lung endothelial cells, this substance loses two amino acids and becomes an active vasopressive octapeptide, **angiotensin II.**

MEDICAL APPLICATION

After a significant hemorrhage (decreased blood volume promotes a decreased blood pressure), there is an increase in renin secretion. Angiotensin II is produced, enhancing blood pressure by both constricting arterioles and stimulating the secretion of the adrenocortical hormone **aldosterone.** Aldosterone acts on cells of the renal tubules (mostly the distal tubules) to increase the absorption of sodium and chloride ions from the glomerular filtrate. This increase in sodium and chloride ions, in turn, expands the fluid volume (particularly blood plasma volume), leading to an increase in blood pressure due to increased blood volume.

Decreased blood pressure caused by other factors (eg, sodium depletion, dehydration) that decrease blood volume also activates the reninâ€“angiotensin IIâ€“aldosterone mechanism that contributes to the maintenance of blood pressure.

Blood Circulation

Each kidney receives blood from its **renal artery,** which usually divides into two branches before entering the organ. One branch goes to the anterior part of the kidney and the other to the posterior part. While still in the hilum, these branches give rise to arteries that branch again to form the **interlobar arteries** located between the renal pyramids (Figure 19â€“26). At the level of the corticomedullary junction, the interlobar arteries form the **arcuate arteries. Interlobular arteries** branch off at right angles from the arcuate arteries and follow a course in the cortex perpendicular to the renal capsule. Interlobular arteries form the boundaries of the renal lobules, which consist of a medullary ray and the adjacent cortical labyrinth (Figure 19â€“26). From the interlobular arteries arise the **afferent arterioles,** which supply blood to the capillaries of the glomeruli. Blood passes from these capillaries into the **efferent arterioles,** which at once branch again to form a **peritubular capillary network** that will nourish the proximal and distal tubules and carry away absorbed ions and low-molecular-weight

materials. The efferent arterioles that are associated with juxtamedullary nephrons form long, thin capillary vessels. These vessels, which follow a straight path into the medulla and then loop back toward the corticomedullary boundary, are called **vasa recta** (straight vessels). The descending vessel is a continuous-type capillary, whereas the ascending vessel has a fenestrated endothelium. These vessels, containing blood that has been filtered through the glomeruli, provide nourishment and oxygen to the medulla. Because of their looped structure, they do not carry away the high osmotic gradient set up in the interstitium by Henle's loop.

Figure 19â€“26.

Circulation of blood in the kidney. Arcuate arteries are seen in the border between the cortex and the medulla.

The capillaries of the outer cortex and the capsule of the kidney converge to form the **stellate veins** (so called because of their configuration when seen from the surface of the kidney), which empty into the interlobular veins.

Veins follow the same course as arteries (Figure 19â€“26). Blood from interlobular veins flows into arcuate veins and from there to the interlobar veins. Interlobar veins converge to form the renal vein through which blood leaves the kidney.

Renal Interstitium

The space between uriniferous tubules and blood and lymph vessels is called the **renal interstitium.** It occupies a very small volume in the cortex but increases in the medulla. The renal interstitium contains a small amount of connective tissue with fibroblasts, some collagen fibers, and, mainly in the medulla, a highly hydrated ground substance rich in proteoglycan. In the medulla the secreting cells called **interstitial cells** are found. They contain cytoplasmic lipid droplets and are implicated in the synthesis of prostaglandins and prostacyclin.

Effects of Adrenal Steroids

Steroid hormones of the adrenal cortex, mainly **aldosterone,** increase distal tubular absorption of sodium from the filtrate and thus decrease sodium loss in the urine. Aldosterone also facilitates the elimination of potassium and hydrogen ions. This hormone is crucial in maintaining electrolyte balance in the body.

MEDICAL APPLICATION

Aldosterone deficiency in adrenalectomized animals and in humans with **Addison disease** results in an excessive loss of sodium in the urine.

Bladder & Urinary Passages

The bladder and the urinary passages store the urine formed in the kidneys and conduct it to the exterior. The calyces, renal pelvis, ureter, and bladder have the same basic histological structure, with the walls of the ureters becoming gradually thicker as proximity to the bladder increases.

The mucosa of these organs consists of **transitional epithelium** (Figure 19â€“27) and a lamina propria of loose-to-dense connective tissue. Surrounding the lamina propria of these organs is a dense woven sheath of smooth muscle.

Figure 19â€“27.

Compare the structure of the transitional epithelium when the urinary bladder is empty (**A**) or full (**B**). When the bladder is full, the capacity of epithelial cells to slide upon one another reduces the thickness of the epithelium. As a result, the interior surface of the bladder increases. In **B,** note the thin strands of collagen fibers separating bundles of smooth muscle cells. PSH stain. Medium magnification.

The transitional epithelium of the bladder in the undistended state is five or six cells in thickness; the superficial cells are rounded and bulge into the lumen. These cells are frequently polyploid or binucleate. When the epithelium is stretched, as when the bladder is full of urine, the epithelium is only three or four cells in thickness, and the superficial cells become squamous.

The superficial cells of the transitional epithelium have a special membrane of thick plates separated by narrow bands of thinner membrane that are responsible for the osmotic barrier between urine and tissue fluids. When the bladder contracts, the membrane folds along the thinner regions, and the thicker plates invaginate to form fusiform cytoplasmic vesicles. These vesicles represent a reservoir of these thick plates that can be stored in the cytoplasm of the cells of the empty bladder and used to cover the increased cell surface in the full bladder. This luminal membrane is assembled in the Golgi complex and has an unusual chemical composition; cerebroside is the major component of the polar lipid fraction.

The muscular layers in the calyces, renal pelvis, and ureters have a helical arrangement. As the ureteral muscle cells reach the bladder, they become longitudinal. The muscle fibers of the bladder run in every direction (without distinct layers) until they approach the bladder neck, where three distinct layers can be identified: The internal longitudinal layer, distal to the bladder neck, becomes circular around the prostatic urethra and the prostatic parenchyma in men. It extends to the external meatus in women. Its fibers form the true involuntary urethral sphincter. The middle layer ends at the bladder neck,

and the outer longitudinal layer continues to the end of the prostate in men and to the external urethral meatus in women.

The ureters (Figure 19â€“28) pass through the wall of the bladder obliquely, forming a valve that prevents the backflow of urine. The intravesical ureter has only longitudinal muscle fibers.

Figure 19â€“28.

Photomicrograph showing the main components of the ureter, which consists of an inner layer of transitional epithelium, a highly vascularized connective tissue, a smooth muscle layer, and an outer layer of connective tissue. PT stain. Low magnification.

The urinary passages are covered externally by an adventitial membrane, except for the upper part of the bladder, which is covered by serous peritoneum.

Urethra

The urethra is a tube that carries the urine from the bladder to the exterior. In men, sperm also pass through it during ejaculation. In women, the urethra is exclusively a urinary organ.

Male Urethra

The male urethra consists of four parts: **prostatic, membranous, bulbous,** and **pendulous.** The initial part of the urethra passes through the prostate (see Chapter 21: The Male Reproductive System), which is situated very close to the bladder, and the ducts that transport the secretions of the prostate open into the prostatic urethra.

In the dorsal and distal part of the **prostatic urethra,** there is an elevation, the **verumontanum** (from Latin, meaning mountain ridge), that protrudes into its interior. A closed tube called the prostatic utricle opens into the tip of the verumontanum; this tube has no known function. The ejaculatory ducts open on the sides of the verumontanum. The seminal fluid enters the proximal urethra through these ducts to be stored just before ejaculation. The prostatic urethra is lined with transitional epithelium.

The **membranous urethra** extends for only 1 cm and is lined with stratified or pseudostratified columnar epithelium. Surrounding this part of the urethra is a sphincter of striated muscle, the **external sphincter** of the urethra. The voluntary external striated sphincter adds further closing pressure to that exerted by the involuntary urethral sphincter. The latter is formed by the continuation of the internal longitudinal muscle of the bladder.

The **bulbous** and **pendulous** parts of the urethra are located in the **corpus spongiosum** of the penis. The urethral lumen dilates distally, forming the **fossa navicularis.** The epithelium of this portion of the urethra is mostly pseudostratified and columnar, with stratified and squamous areas.

Littre's glands are mucous glands found along the entire length of the urethra but mostly in the pendulous part. The secretory portions of some of these glands are directly linked to the epithelial lining of the urethra; others have excretory ducts.

Female Urethra

The female urethra is a tube 4â€“5 cm long, lined with stratified squamous epithelium and areas of pseudostratified columnar epithelium. The mid part of the female urethra is surrounded by an external striated voluntary sphincter.
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