

CHAPTER 26

LECTURE OUTLINE

I. INTRODUCTION

- A. The urinary system consists of two kidneys, two ureters, one urinary bladder, and one urethra (Figure 26.1).
- B. Urine is excreted from each kidney through its ureter and is stored in the urinary bladder until it is expelled from the body through the urethra.
- C. The specialized branch of medicine that deals with structure, function, and diseases of the male and female urinary systems and the male reproductive system is known as nephrology. The branch of surgery related to male and female urinary systems and the male reproductive system is called urology.

II. OVERVIEW OF KIDNEY FUNCTIONS

- A. The major work of the urinary system is done by the kidneys.
- B. Kidneys contribute to homeostasis of body fluids by regulation of blood ionic composition, regulation of pH, regulation of blood volume, regulation of blood pressure, maintenance of blood osmolarity, producing hormones, regulating blood glucose level, and excreting wastes and foreign substances.

III. ANATOMY AND HISTOLOGY OF THE KIDNEYS

- A. The paired kidneys are retroperitoneal organs (Figure 26.2).
- B. External Anatomy of the Kidney
 - 1. Near the center of the concave medial border of the kidney is a vertical fissure called the hilus, through which the ureter leaves and blood vessels, lymphatic vessels, and nerves enter and exit (Figure 26.3).
 - 2. Three layers of tissue surround each kidney: the innermost renal capsule, the adipose capsule, and the outer renal fascia.
 - 3. Nephroptosis is an inferior displacement of the kidneys. It most often occurs in thin people. This condition is dangerous because the ureters may kink and block urine flow (Clinical Connection).
- C. Internal Anatomy of the Kidney
 - 1. Internally, the kidneys consist of cortex, medulla, pyramids, papillae, columns, calyces, and renal pelves (Figure 26.3).

2. The renal cortex and renal pyramids constitute the functional portion or parenchyma of the kidney.
3. The nephron is the functional unit of the kidney.

D. Blood and Nerve Supply of the Kidneys

1. Blood enters the kidney through the renal artery and exits via the renal vein. Figure 26.4 shows the branching pattern of renal blood vessels and the path of blood flow through the kidneys.
2. The nerve supply to the kidney is derived from the renal plexus (sympathetic division of ANS).

E. The Nephron

1. A nephron consists of a renal corpuscle where fluid is filtered, and a renal tubule into which the filtered fluid passes (Figure 26.5).
 - a. Nephrons perform three basic functions: glomerular filtration, tubular reabsorption, and tubular secretion.
2. A renal tubule consists of a proximal convoluted tubule (PCT), Nephron loop, and distal convoluted tubule (DCT). Distal convoluted tubules of several nephrons drain into to a single collecting duct and many collecting ducts drain into a small number of papillary ducts.
3. The Nephron loop consists of a descending limb, a thin ascending limb, and a thick ascending limb (Figure 26.5).
4. There are two types of nephrons that have differing structure and function.
 - a. A cortical nephron usually has its glomerulus in the outer portion of the cortex and a short Nephron loop that penetrates only into the outer region of the medulla (Figure 26.5a).
 - b. A juxtamedullary nephron usually has its glomerulus deep in the cortex close to the medulla; its long Nephron loop stretches through the medulla and almost reaches the renal papilla (Figure 26.5b).

F. Histology of the Nephron and Collecting Duct

1. Glomerular Capsule
 - a. The glomerular capsule consists of visceral and parietal layers (Figure 26.6).
 - b. The visceral layer consists of modified simple squamous epithelial cells called podocytes.
 - c. The parietal layer consists of simple squamous epithelium and forms the outer wall of the capsule.

- d. Fluid filtered from the glomerular capillaries enters the capsular space, the space between the two layers of the glomerular capsule.
2. Renal Tubule and Collecting Duct
 - a. Table 26.1 illustrates the histology of the cells that form the renal tubule and collecting duct.
 - b. The juxtaglomerular apparatus (JGA) consists of the juxtaglomerular cells of an afferent arteriole and the macula densa. The JGA helps regulate blood pressure and the rate of blood filtration by the kidneys (Figure 26.6).
 - c. Most of the cells of the distal convoluted tubule are principal cells that have receptors for ADH and aldosterone. A smaller number are intercalated cells which play a role in the homeostasis of blood pH.
 - d. The number of nephrons is constant from birth. They may increase in size, but not in number

IV. HOMEOSTASIS OF BLOOD VOLUME AND COMPOSITION

- A. Nephrons and collecting ducts perform three basic processes while producing urine: glomerular filtration, tubular secretion, and tubular reabsorption (Figure 26.7).
- B. By filtering, reabsorbing, and secreting, nephrons maintain homeostasis of blood.

V. GLOMERULAR FILTRATION

- A. Introduction
 1. The fluid that enters the capsular space is termed glomerular filtrate.
 2. The fraction of plasma in the afferent arterioles of the kidneys that becomes filtrate is termed the filtration fraction.
- B. The Filtration Membrane
 1. The filtering unit of a nephron is the endothelial-capsular membrane. It consists of the glomerular endothelium, glomerular basement membrane, and slit membranes between pedicels of podocytes.
 2. Filtered substances move from the blood stream through three barriers: a glomerular endothelial cell, the basal lamina, and a filtration slit formed by a podocyte (Figure 26.8).
 3. The principle of filtration - to force fluids and solutes through a membrane by pressure - is the same in glomerular capillaries as in capillaries elsewhere in the body.

4. The three features of the renal corpuscle that enhance its filtering capacity include the large surface area across which filtration can occur, the thin and porous nature of the filtration membrane, and the high level of glomerular capillary blood pressure.

C. Net Filtration Pressure

1. Glomerular filtration depends on three main pressures, one that promotes and two that oppose filtration (Figure 26.9).
2. Filtration of blood is promoted by glomerular blood hydrostatic pressure (GBHP) and opposed by capsular hydrostatic pressure (CHP) and blood colloid osmotic pressure (BCOP). The net filtration pressure (NFP) is about 10 mm Hg.
3. In some kidney diseases, damaged glomerular capillaries become so permeable that plasma proteins enter the filtrate, causing an increase in NFP and GFR and a decrease in BCOP. (Clinical Connection)

D. Homeostasis of GFR

1. Glomerular filtration rate (GFR) is the amount of filtrate formed by both kidneys per minute; in a normal adult, it is about 125 ml/minute. This amounts to 180 liters per day.
 - a. GFR is directly related to the pressures that determine net filtration pressure.
 - b. Surprisingly, when system blood pressure rises above the normal resting level, net filtration pressure and GFR increase very little.
 - c. The mechanisms that regulate GFR adjust blood flow into and out of the glomerulus and alter the glomerular capillary surface area available for filtration.
 - d. The three principal mechanisms that control GFR are renal autoregulation, neural regulation, and hormonal regulation.
2. Renal Autoregulation of GFR
 - a. This is an intrinsic mechanism with the kidneys consisting of the myogenic mechanism and tubuloglomerular feedback.
 - b. The myogenic mechanism occurs because stretching causes contraction of smooth muscle cells in the wall of the afferent arteriole.
 - c. Tubuloglomerular feedback occurs as the macula densa provides feedback to the glomerulus (Figure 26.10).
3. Neural regulation of GFR is through the ANS.
 - a. ANS fibers release norepinephrine on alpha 1 receptors causing vasoconstriction.

4. Hormonal regulation of GFR
 - a. Hormonal regulation of GFR is through the action of angiotensin II and atrial natriuretic peptide.
5. Table 26.2 summarizes the way in which GFR is regulated.

VI. TUBULAR REABSORPTION AND TUBULAR SECRETION

A. Principles of Tubular reabsorption and tubular secretion

1. The normal rate of glomerular filtration is so high that the volume of fluid entering the proximal convoluted tubule in half an hour is greater than the total plasma volume.
2. Reabsorption returns most of the filtered water and many of the filtered solutes to the bloodstream using both active and passive transport processes.
3. Table 26.3 compares the amounts of substances that are filtered, reabsorbed, and excreted in urine with the amounts present in blood plasma.
4. Tubular secretion, the transfer of materials from the blood and tubule cells into tubular fluid, helps control blood pH and helps eliminate other substances from the body.

B. Reabsorption Routes

1. A substance being reabsorbed can move between adjacent tubule cells or through an individual tubule cell before entering a peritubular capillary (Figure 26.11).
2. Fluid leakage between cells is known as paracellular reabsorption.
3. In transcellular reabsorption, a substance passes from the fluid in the tubule lumen through the apical membrane of a tubule cell, across the cytosol, and out into interstitial fluid through the basolateral membrane.

C. Transport Mechanisms

1. Solute reabsorption drives water reabsorption. The mechanisms that accomplish Na^+ reabsorption in each portion of the renal tubule and collecting duct recover not only filtered Na^+ but also other electrolytes, nutrients, and water.
2. Transport across membranes can be either active or passive (See Chapter 3).
 - a. In primary active transport the energy derived from ATP is used to “pump” a substance across a membrane.
 - b. In secondary active transport the energy stored in an ion’s electrochemical gradient drives another substance across the membrane.
3. Transport Maximum (T_m)

- a. Each type of symporter has an upper limit on how fast it can work, called the transport maximum (T_m).
4. The mechanism for water reabsorption by the renal tubule and collecting duct is osmosis.
 - a. About 90% of the filtered water reabsorbed by the kidneys occurs together with the reabsorption of solutes such as Na^+ , Cl^- , and glucose.
 - b. Water reabsorption together with solutes in tubular fluid is called obligatory water reabsorption.
 - c. Reabsorption of the final water, facultative reabsorption, is based on need and occurs in the collecting ducts and is regulated by ADH.
 - d. When the blood concentration of glucose is above 200 mg/mL, the renal symporters cannot work fast enough to reabsorb all the glucose that enters the glomerular filtrate. As a result, some glucose remains in the urine, a condition called glucosuria. (Clinical Connection)

D. Reabsorption and Secretion in the Proximal Convoluted Tubule

1. Reabsorption in the Proximal Convoluted Tubule

- a. The majority of solute and water reabsorption from filtered fluid occurs in the proximal convoluted tubules and most absorptive processes involve Na^+ .
 - b. Proximal convoluted tubule Na^+ transporters promote reabsorption of 100% of most organic solutes, such as glucose and amino acids; 80-90% of bicarbonate ions; 65% of water, Na^+ , and K^+ ; 50% of Cl^- ; and a variable amount of Ca^{+2} , Mg^{+2} , and HPO_4^{-2} .
 - c. Normally, 100% of filtered glucose, amino acids, lactic acid, water-soluble vitamins, and other nutrients are reabsorbed in the first half of the PCT by Na^+ symporters. Figure 26.12 shows the operation of the main Na^+ -glucose symporters in PCT cells.
 - d. Diffusion of Cl^- into interstitial fluid via the paracellular route leaves tubular fluid more positive than interstitial fluid. This electrical potential difference promotes passive paracellular reabsorption of Na^+ , K^+ , Ca^{+2} , and Mg^{+2} (Figure 26.14).
 - e. Reabsorption of Na^+ and other solutes creates an osmotic gradient that promotes reabsorption of water by osmosis.
- ##### 2. Secretion of NH_3 and NH_4^+ in the Proximal Convoluted Tubule

- a. Na^+/H^+ antiporters achieve Na^+ and HCO_3^- reabsorption to the peritubular capillaries while, at the same time, secreting H^+ into the tubule (Figure 26.13).
- b. urea and ammonia in the blood are both filtered at the glomerulus and secreted by the proximal convoluted tubule cells into the tubules.
- c. At the pH inside tubule cells, most NH_3 quickly binds to H^+ and becomes NH_4^+ . NH_4^+ can substitute for H^+ aboard Na^+/H^+ antiporters and be secreted into tubular fluid.

E. Reabsorption in the nephron loop

1. The Nephron loop sets the stage for independent regulation of both the volume and osmolarity of body fluids.
2. $\text{Na}^+/\text{K}^+/\text{Cl}^-$ symporters reclaim Na^+ , Cl^- , and K^+ ions from the tubular lumen fluid (Figure 26.15).
3. Because K^+ leakage channels return much of the K^+ back into tubular fluid, the main effect of the $\text{Na}^+/\text{K}^+/\text{Cl}^-$ symporters is reabsorption of Na^+ and Cl^- .
4. Although about 15% of the filtered water is reabsorbed in the descending limb, little or no water is reabsorbed in the ascending limb.

F. Reabsorption in the the Early DCT

1. As fluid flows along the DCT, reabsorption of Na^+ and Cl^- continues due to Na^+/Cl^- symporters.
2. The DCT serves as the major site where parathyroid hormone stimulates reabsorption of Ca^{2+} .
3. The solutes are reabsorbed with little accompanying water.

G. Reabsorption and Secretion in the Late DCT and Collecting Duct

1. Na^+ passes through the apical membrane of principal cells via Na^+ leakage channels. Sodium pumps actively transport Na^+ across the basolateral membrane (Figure 26.16).
2. The secretion of K^+ through K^+ leakage channels in the principal cells is the main source of K^+ that is excreted in urine.
3. Principal cells secrete a variable amount of K^+ (Figure 26.16). Because of basolateral Na^+/K^+ pumps continually bringing K^+ into the principal cells, K^+ remains high. K^+ leakage channels are also present. They permit K^+ to diffuse down the concentration gradient into the tubular fluid.

H. Homeostatic Regulation of Tubular Reabsorption and Secretion

1. Four hormones affect the extent of Na⁺, Cl⁻, and H₂O reabsorption and K⁺ secretion by the renal tubules.
2. In the renin-angiotensin-aldosterone system, angiotensin II increases blood volume and blood pressure and is a major regulator of electrolyte reabsorption and secretion along with aldosterone which also increases reabsorption of water in the collecting duct.
3. Antidiuretic hormone (ADH)
 - a. regulates facultative water reabsorption by increasing the water permeability of principal cells (Figure 26.17).
4. Atrial natriuretic peptide (ANP)
 - a. can inhibit both water and electrolyte reabsorption.
5. Parathyroid hormone
 - a. promotes Calcium reabsorption
6. Table 26.4 summarizes the hormonal regulation of tubular reabsorption and tubular secretion.

VII. HOMEOSTATIC PRODUCTION OF DILUTE AND CONCENTRATED URINE

- A. The rate at which water is lost from the body depends mainly on ADH, which controls water permeability of principal cells in the collecting duct (and in the last portion of the distal convoluted tubule).
- B. Formation of Dilute Urine
 1. When ADH level is very low, the kidneys produce dilute urine and excrete excess water; in other words, renal tubules absorb more solutes than water (Figure 26.18).
 2. Although solutes are being reabsorbed in the thick ascending limb, the water permeability of this portion of the nephron is always quite low, so water cannot follow by osmosis.
 3. The fluid entering the distal convoluted tubule is thus more dilute than plasma.
 4. The early distal convoluted tubule cells are not very permeable to water and are not regulated by ADH.
 5. Finally, the principal cells of the late distal convoluted tubules and collecting ducts are impermeable to water when the ADH level is very low.
 6. Thus, tubular fluid becomes progressively more dilute as it flows onward. By the time the tubular fluid drains into the renal pelvis, its concentration can be as low as 65–70 mOsm/liter.

C. Formation of Concentrated Urine

1. When ADH level is high, the kidneys secrete concentrated urine and conserve water; a large volume of water is reabsorbed from the tubular fluid into interstitial fluid, and the solute concentration of urine is high.
2. Production of concentrated urine involves ascending limb cells of the Nephron loop establishing the osmotic gradient in the renal medulla, collecting ducts reabsorbing more water and urea, and urea recycling causing a build up of urea in the renal medulla (Figure 26.19).

D. Counter current Multiplication

1. The countercurrent mechanism also contributes to the excretion of concentrated urine.
2. Countercurrent multiplication involves the long loops of Henle of juxtamedullary nephrons (figure 26.19a)
 - a. Symporters in thick ascending limb cells of the Nephron loop cause a buildup of Na and Cl in the renal medulla
 - b. Countercurrent flow through the descending and ascending limbs of the Nephron loop establishes an osmotic gradient in the renal medulla
 - c. Cells in the collecting ducts reabsorb more water and urea
 - d. Urea recycling causes a buildup of urea in the renal medulla

E. Counter Current Exchange

1. solutes and water are passively exchanged between the blood of the vasa recta and interstitial fluid of the renal medulla as a result of countercurrent flow (figure 26.19b)

F. Figure 26.20 summarizes the processes of filtration, reabsorption, and secretion in each segment of the nephron and collecting ducts. Hormonal effects are also noted.

G. Diuretics are drugs that increase urine flow rate. They work by a variety of mechanisms. The most potent ones are the loop diuretics, such as furosemide, which inhibits the symporters in the thick ascending limb of the Nephron loop. (Clinical Connection)

VIII. EVALUATION OF KIDNEY FUNCTION

A. An analysis of the volume and physical, chemical, and microscopic properties of urine, called urinalysis, reveals much about the state of the body.

1. Table 26.5 summarizes the principal physical characteristics of urine.
2. Table 26.6 lists several abnormal constituents of urine that may be detected as part of a urinalysis.

- B. Two blood screening tests can provide information about kidney function.
 - 1. One screening test is the blood urea nitrogen (BUN), which measures the level of nitrogen in blood that is part of urea.
 - 2. Another test is measurement of plasma creatinine.
- C. Renal plasma clearance expresses how effectively the kidneys remove (clear) a substance from blood plasma.
 - 1. The clearance of inulin gives the glomerular filtration rate.
 - 2. The clearance of para-aminohippuric acid gives the rate of renal plasma flow.
- D. Dialysis is the separation of large solutes from smaller ones through use of a selectively permeable membrane. (Clinical Connection)
 - 1. Filtering blood through an artificial kidney machine is called hemodialysis. This procedure filters the blood of wastes and adds nutrients.
 - 2. A portable method of dialysis is called continuous ambulatory peritoneal dialysis.

IX. URINE STORAGE, TRANSPORTATION, AND ELIMINATION

- A. Urine drains through papillary ducts into minor calyces, which joint to become major calyces that unite to form the renal pelvis (Figure 26.3). From the renal pelvis, urine drains into the ureters and then into the urinary bladder, and finally, out of the body by way of the urethra (Figure 26.1).
- B. Ureters
 - 1. Each of the two ureters connects the renal pelvis of one kidney to the urinary bladder (Figure 26.21).
 - 2. The ureters transport urine from the renal pelvis to the urinary bladder, primarily by peristalsis, but hydrostatic pressure and gravity also contribute.
 - 3. The ureters are retroperitoneal and consist of a mucosa, muscularis, and fibrous coat.
- C. Urinary Bladder
 - 1. The urinary bladder is a hollow muscular organ situated in the pelvic cavity posterior to the pubic symphysis.
 - 2. Anatomy and Histology of the Urinary Bladder
 - a. In the floor of the urinary bladder is a small, smooth triangular area, the trigone. The ureters enter the urinary bladder near two posterior points in the triangle; the urethra drains the urinary bladder from the anterior point of the triangle (Figure 26.21).

- b. Histologically, the urinary bladder consists of a mucosa (with rugae), a lamina propria, a muscularis (detrusor muscle), and a serous coat.
 - 1. In the area around the opening to the urethra, the circular fibers of the muscularis form the internal urethral sphincter.
 - 2. Below the internal sphincter is the external urethral sphincter, which is composed of skeletal (voluntary) muscle.
- 3. Micturition Reflex
 - a. Urine is expelled from the urinary bladder by an act called micturition, commonly known as urination or voiding.
 - b. When the volume of urine in the bladder reaches a certain amount (usually 200-400 ml), stretch receptors in the urinary bladder wall transmit impulses that initiate a spinal micturition reflex. Older children and adults may also initiate or inhibit micturition voluntarily.
 - c. Cystoscopy allows direct examination of the interior of the urinary bladder and is used for detecting bladder cancer and infections (Clinical Connection)

D. Urethra

- 1. the urethra is a tube leading from the floor of the urinary bladder to the exterior (Figure 26.22).
- 2. Histologically, the wall of the urethra consists of either three coats in females or two coats in males.
- 3. The function of the urethra is to discharge urine from the body. The male urethra also serves as the duct for ejaculation of semen (reproductive fluid).
- 4. figure 26.22 depicts differences in the urethra between males and females.
- 5. A lack of voluntary control over micturition is referred to as incontinence; failure to void urine completely or normally is termed retention (Clinical Connection).

X. WASTE MANAGEMENT IN OTHER BODY SYSTEMS

- A. One of the many functions of the urinary system is to rid the body of waste materials.
- B. Other organs, tissues and processes contribute to waste management.
 - 1. Buffers prevent an increase in the acidity of body fluids.
 - 2. The blood transports wastes.
 - 3. The liver is the primary site for metabolic recycling.
 - 4. The lungs excrete CO₂, H₂O, and heat.

5. Sweat glands eliminate excess heat, water, and CO₂, plus small quantities of salts and urea.
6. The GI tract eliminates solid, undigested foods, waste, some CO₂, H₂O, salts and heat.

XI. DEVELOPMENT OF THE URINARY TRACT

- A. The kidneys develop from intermediate mesoderm.
- B. They develop in the following sequence: pronephros, mesonephros, and metanephros (Figure 26.23).

XII. AGING AND THE URINARY SYSTEM

- A. After age 40, the effectiveness of kidney function begins to decrease.
- B. Common problems related to aging include incontinence and urinary tract infections (UTIs). Other pathologies include polyuria, nocturia, increased frequency of urination, dysuria, retention, hematuria, acute and chronic kidney inflammations and renal calculi, and prostate disorders or cancer in males.

XIII. DISORDERS: HOMEOSTATIC IMBALANCES

- A. Renal Calculi
 1. Crystals of salts present in urine can precipitate and solidify into renal calculi or kidney stones. They may block the ureter and can sometimes be removed by shock wave lithotripsy.
- B. Urinary Tract Infections
 1. The term urinary tract infection (UTI) is used to describe either an infection of a part of the urinary system or the presence of large numbers of microbes in urine. UTIs include urethritis (inflammation of the urethra), cystitis (inflammation of the urinary bladder), pyelonephritis (inflammation of the kidneys), and pyelitis (inflammation of the renal pelvis and its calyces).
- C. Glomerular Diseases
 1. Glomerulonephritis (Bright's disease) is an inflammation of the glomeruli of the kidney. One of the most common causes is an allergic reaction to the toxins given off by streptococcal bacteria that have recently infected another part of the body, especially the throat. The glomeruli may be permanently damaged, leading to acute or chronic renal failure.

2. Chronic renal failure refers to a progressive and generally irreversible decline in glomerular filtration rate that may result from chronic glomerulonephritis, pyelonephritis, polycystic disease, or traumatic loss of kidney tissue.

D. Renal Failure

1. By definition, renal failure is a decrease or cessation of glomerular filtration
2. There are two types; Acute renal failure and chronic renal failure
 - a. Acute renal failure: suppression of urine flow caused by low blood volume, decreased cardiac output, damage to renal tubules or kidney stones
 - b. Chronic renal failure: progressive and usually irreversible decline in GFR
 1. Chronic renal failure develops in three stages: stage one represents a 75% loss of functional neurons. Stage two is characterized by diminished GFR and stage three by 90% loss of functional neurons

E. Polycystic kidney disease

1. one of the most common inherited disorders. In infants it results in death at birth or shortly thereafter. In adults, it accounts for 6-12% of kidney transplantations. In this disorder, the kidney tubules become riddled with hundreds or thousands of cysts, and inappropriate apoptosis of cells in noncystic tubules leads to progressive impairment of renal function and eventually to renal failure.

F. Urinary bladder cancer

1. is more common in males than females. If detected early, prognosis is generally good.

G. Kidney transplant

1. During the transplant the renal artery and vein of the transplanted kidney are attached to a nearby artery or vein in the pelvis and the ureter is attached to the urinary bladder.

H. Cystoscopy

1. A procedure that allows for the direct examination of the mucosa of the urethra, the urinary bladder and in males the prostate.

XIV. MEDICAL TERMINOLOGY - Alert students to the medical terms associated with the urinary system.