Chapter 26
The Urinary System

26-1 Urinary System Functions

• Three Functions of the Urinary System
  1. Excretion
     • Removal of organic wastes from body fluids
  2. Elimination
     • Discharge of waste products
  3. Homeostatic regulation
     • Of blood plasma volume and solute concentration

• Functions of the Urinary System
  • Kidneys — organs that produce urine
  • Urinary tract — organs that eliminate urine
    • Ureters (paired tubes)
    • Urinary bladder (muscular sac)
    • Urethra (exit tube)
  • Urination or micturition — process of eliminating urine
    • Contraction of muscular urinary bladder forces urine through urethra, and out of body

• Homeostatic Functions of the Urinary System
  • Regulates blood volume and blood pressure
    • By adjusting volume of water lost in urine
    • Releasing erythropoietin and renin
  • Regulates plasma ion concentrations
    • Sodium, potassium, and chloride ions (by controlling quantities lost in urine)

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• Calcium ion levels (through synthesis of calcitriol)

26-1 Urinary System Functions
• Homeostatic Functions of Urinary System
  • Helps stabilize blood pH
    • By controlling loss of hydrogen ions and bicarbonate ions in urine
  • Conserves valuable nutrients
    • By preventing excretion while excreting organic waste products
  • Assists liver
    • In detoxifying poisons

26-2 The Kidneys
• The Kidneys
  • Are located on either side of vertebral column
    • Left kidney lies superior to right kidney
    • Superior surface capped by adrenal gland
  • Position is maintained by:
    • Overlying peritoneum
    • Contact with adjacent visceral organs
    • Supporting connective tissues

26-2 The Kidneys
• Each Kidney Is Protected and Stabilized
  • By three concentric layers of connective tissue
  1. Fibrous capsule
    • A layer of collagen fibers
    • Covers outer surface of entire organ
  2. Perinephric fat capsule
    • A thick layer of adipose tissue
    • Surrounds renal capsule

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3. **Renal fascia**
   - A dense, fibrous outer layer
   - Anchors kidney to surrounding structures

### 26-2 The Kidneys

- **Typical Adult Kidney**
  - Is about 10 cm long, 50.5 cm wide, and 3 cm thick (4 in. × 2.2 in. × 1.2 in.)
  - Weighs about 150 g (5.25 oz)

- **Hilum**
  - Point of entry for *renal artery* and *renal nerves*
  - Point of exit for *renal vein* and ureter

### 26-2 The Kidneys

- **Sectional Anatomy of the Kidneys**
  - **Renal sinus**
    - Internal cavity within kidney
    - Lined by fibrous renal capsule
    - Bound to outer surfaces of structures in renal sinus
    - Stabilizes positions of ureter, renal blood vessels, and nerves

### 26-2 The Kidneys

- **Renal Cortex**
  - Superficial portion of kidney in contact with renal capsule
  - Reddish brown and granular

- **Renal Pyramids**
26-2 The Kidneys

• **Renal Columns**
  • Bands of cortical tissue separate adjacent renal pyramids
  • Extend into medulla
  • Have distinct granular texture

26-2 The Kidneys

• **Renal Lobe**
  • Consists of:
    • Renal pyramid
    • Overlying area of renal cortex
    • Adjacent tissues of renal columns
  • Produces urine

26-2 The Kidneys

• **Renal Papilla**
  • Ducts discharge urine into **minor calyx**, a cup-shaped drain

• **Major Calyx**
  • Formed by four or five minor calyces
26-2 The Kidneys

- **Renal Pelvis**
  - Large, funnel-shaped chamber
  - Consists of two or three major calyces
  - Fills most of renal sinus
  - Connected to ureter, which drains kidney

26-2 The Kidneys

- **Nephrons**
  - Microscopic, tubular structures in cortex of each renal lobe
  - Where urine production begins

26-2 The Kidneys

- **Blood Supply to the Kidneys**
  - Kidneys receive 20%–25% of total cardiac output
  - 1200 mL of blood flows through kidneys each minute
  - Kidney receives blood through renal artery

26-2 The Kidneys

- **Segmental Arteries**
  - Receive blood from **renal artery**
  - Divide into **interlobar arteries**
    - Which radiate outward through renal columns between renal pyramids
  - Supply blood to **arcuate arteries**
    - Which arch along boundary between cortex and medulla of kidney
26-2 The Kidneys

• **Afferent Arterioles**
  - Branch from each *cortical radiate artery* (also called *interlobular artery*)
  - Deliver blood to capillaries supplying individual nephrons

26-2 The Kidneys

• **Cortical Radiate Veins**
  - Also called *interlobular veins*
  - Deliver blood to *arcuate veins*
  - Empty into *interlobar veins*
    - Which drain directly into *renal vein*

26-2 The Kidneys

• **Renal Nerves**
  - Innervate kidneys and ureters
  - Enter each kidney at hilum
  - Follow tributaries of renal arteries to individual nephrons

26-2 The Kidneys

• **Sympathetic Innervation**
  - Adjusts rate of urine formation
    - By changing blood flow and blood pressure at nephron
  - Stimulates release of renin
    - Which restricts losses of water and salt in urine
    - By stimulating reabsorption at nephron
26-2 The Kidneys

• **The Nephron**
  • Consists of renal tubule and renal corpuscle
  • Renal tubule
    • Long tubular passageway
    • Begins at renal corpuscle

26-2 The Kidneys

• The Nephron
  • Renal corpuscle
    • Spherical structure consisting of:
      • *Glomerular capsule* (Bowman’s capsule)
      • Cup-shaped chamber
      • Capillary network (*glomerulus*)

26-2 The Kidneys

• **Glomerulus**
  • Consists of 50 intertwining capillaries
  • Blood delivered via afferent arteriole
  • Blood leaves in **efferent arteriole**
    • Flows into peritubular capillaries
    • Which drain into small venules
    • And return blood to venous system

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26-2 The Kidneys

- **Filtration**
  - Occurs in renal corpuscle
  - Blood pressure
    - Forces water and dissolved solutes out of glomerular capillaries into *capsular space*
    - Produces protein-free solution (*filtrate*) similar to blood plasma

26-2 The Kidneys

- **Three Functions of the Renal Tubule**
  1. Reabsorb useful organic nutrients that enter filtrate
  2. Reabsorb more than 90% of water in filtrate
  3. Secrete waste products that failed to enter renal corpuscle through filtration at glomerulus

26-2 The Kidneys

- **Segments of the Renal Tubule**
  - Located in cortex
    - *Proximal convoluted tubule (PCT)*
    - *Distal convoluted tubule (DCT)*
  - Separated by *nephron loop (loop of Henle)*
    - U-shaped tube
    - Extends partially into medulla

26-2 The Kidneys

- **Organization of the Nephron**
  - Traveling along tubule, filtrate (*tubular fluid*) gradually changes
composition
• Changes vary with activities in each segment of nephron

26-2 The Kidneys
• Each Nephron
  • Empties into the **collecting system**
    • A series of tubes that carries tubular fluid away from nephron
  • **Collecting ducts**
    • Receive fluid from many nephrons
    • Each collecting duct:
      • Begins in cortex
      • Descends into medulla
      • Carries fluid to *papillary duct* that drains into a minor calyx

26-2 The Kidneys
• **Cortical Nephrons**
  • 85% of all nephrons
  • Located mostly within superficial cortex of kidney
  • Nephron loop (Loop of Henle) is relatively short
  • Efferent arteriole delivers blood to a network of *peritubular capillaries*
• **Juxtamedullary Nephrons**
  • 15% of nephrons
  • Nephron loops extend deep into medulla
  • Peritubular capillaries connect to *vasa recta*

26-2 The Kidneys
• The Renal Corpuscle
• Each renal corpuscle is 150–250 µm in diameter
  • **Glomerular capsule**
    • Is connected to initial segment of renal tubule
    • Forms outer wall of renal corpuscle
    • Encapsulates glomerular capillaries
  • **Glomerulus**
    • Knot of capillaries

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### 26-2 The Kidneys

#### The Glomerular Capsule

• Outer wall is lined by simple squamous **capsular epithelium**
  • Continuous with **visceral epithelium** that covers glomerular capillaries
    • Separated by **capsular space**

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#### The Visceral Epithelium

• Consists of large cells (**podocytes**)
  • With complex processes or “feet” (**pedicels**) that wrap around specialized dense layer of glomerular capillaries

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#### Filtration Slits

• Are narrow gaps between adjacent pedicels
• Materials passing out of blood at glomerulus
  • Must be small enough to pass between filtration slits

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#### The Glomerular Capillaries

• Are fenestrated capillaries
  • Endothelium contains large-diameter pores
• Blood Flow Control
  • Special supporting cells (mesangial cells)
    • Between adjacent capillaries
    • Control diameter and rate of capillary blood flow

26-2 The Kidneys
• The Filtration Membrane
  • Consists of:
    • Fenestrated endothelium
    • Dense layer
    • Filtration slits

26-2 The Kidneys
• Filtration
  • Blood pressure
    • Forces water and small solutes across membrane into capsular space
  • Larger solutes, such as plasma proteins, are excluded

26-2 The Kidneys
• Filtration at Renal Corpuscle
  • Is passive
  • Solutes enter capsular space
    • Metabolic wastes and excess ions
    • Glucose, free fatty acids, amino acids, and vitamins

• Reabsorption
  • Useful materials are recaptured before filtrate leaves kidneys
• Reabsorption occurs in proximal convoluted tubule

26-2 The Kidneys
• The **Proximal Convoluted Tubule (PCT)**
  • Is the first segment of renal tubule
  • Entrance to PCT lies opposite point of connection of afferent and efferent arterioles with glomerulus
• Epithelial Lining of PCT
  • Is simple cuboidal
  • Has microvilli on apical surfaces
  • Functions in *reabsorption*
  • Secretes substances into lumen

26-2 The Kidneys
• Tubular Cells
  • Absorb organic nutrients, ions, water, and plasma proteins from tubular fluid
  • Release them into *peritubular fluid* (interstitial fluid around renal tubule)

26-2 The Kidneys
• The **Nephron Loop** (*Loop of Henle*)
  • Renal tubule turns toward renal medulla
  • **Descending limb**
    • Fluid flows toward renal pelvis
  • **Ascending limb**
    • Fluid flows toward renal cortex
  • Each limb contains:
26-2 The Kidneys

- The Thick Descending Limb
  - Has functions similar to PCT
    - Pumps sodium and chloride ions out of tubular fluid

- Ascending Limbs
  - Of juxtamedullary nephrons in medulla
    - Create high solute concentrations in peritubular fluid

26-2 The Kidneys

- The Thin Segments
  - Are freely permeable to water
    - Not to solutes
  - Water movement helps concentrate tubular fluid

- The Thick Ascending Limb
  - Ends at a sharp angle near the renal corpuscle
    - Where DCT begins

26-2 The Kidneys

- The Distal Convoluted Tubule (DCT)
  - The third segment of the renal tubule
  - Initial portion passes between afferent and efferent arterioles
  - Has a smaller diameter than PCT
• Epithelial cells lack microvilli

26-2 The Kidneys

• Three Processes at the DCT
  1. Active secretion of ions, acids, drugs, and toxins
  2. Selective reabsorption of sodium and calcium ions from tubular fluid
  3. Selective reabsorption of water
     • Concentrates tubular fluid

26-2 The Kidneys

• The Juxtaglomerular Complex (JGC)
  • An endocrine structure that secretes:
    • Hormone erythropoietin
    • Enzyme renin
  • Formed by:
    • Macula densa
    • Juxtaglomerular cells

26-2 The Kidneys

• Macula Densa
  • Epithelial cells of DCT, near renal corpuscle
  • Tall cells with densely clustered nuclei

• Juxtaglomerular Cells
  • Smooth muscle fibers in wall of afferent arteriole
    • Associated with cells of macula densa
    • Together with macula densa forms juxtaglomerular complex (JGC)
26-2 The Kidneys

• The Collecting System
  • The distal convoluted tubule opens into the collecting system
  • Individual nephrons drain into a nearby **collecting duct**
  • Several collecting ducts:
    • Converge into a larger **papillary duct**
    • Which empties into a minor calyx
  • Transports tubular fluid from nephron to renal pelvis
  • Adjusts fluid composition
  • Determines final osmotic concentration and volume of urine

26-3 Renal Physiology

• The Goal of Urine Production
  • Is to maintain homeostasis
    • By regulating volume and composition of blood
    • Including excretion of metabolic waste products

26-3 Renal Physiology

• Three Organic Waste Products
  1. **Urea**
  2. **Creatinine**
  3. **Uric acid**

• Organic Waste Products
  • Are dissolved in bloodstream
  • Are eliminated only while dissolved in urine
Removal is accompanied by water loss

26-3 Renal Physiology
• The Kidneys
  • Usually produce concentrated urine
    • 1200–1400 mOsm/L (four times plasma concentration)
• Kidney Functions
  • To concentrate filtrate by glomerular filtration
    • Failure leads to fatal dehydration
  • Absorbs and retains valuable materials for use by other tissues
    • Sugars and amino acids

26-3 Renal Physiology
• Basic Processes of Urine Formation
  1. Filtration
  2. Reabsorption
  3. Secretion

26-3 Renal Physiology
• An Overview of Renal Function
  • Water and solute reabsorption
    • Primarily along proximal convoluted tubules
  • Active secretion
    • Primarily at proximal and distal convoluted tubules
  • Long loops of juxtamedullary nephrons and collecting system
    • Regulate final volume and solute concentration of urine

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26-3 Renal Physiology

• **Filtration**
  - Hydrostatic pressure forces water through membrane pores
    - Small solute molecules pass through pores
    - Larger solutes and suspended materials are retained
  - Occurs across capillary walls
    - As water and dissolved materials are pushed into interstitial fluids

26-3 Renal Physiology

• **Filtration**
  - In some sites, such as the liver, pores are large
    - Plasma proteins can enter interstitial fluids
  - At the renal corpuscle
    - Specialized membrane restricts all circulating proteins

26-3 Renal Physiology

• **Reabsorption and Secretion**
  - At the kidneys, it involves:
    - Diffusion
    - Osmosis
    - Channel-mediated diffusion
    - Carrier-mediated transport

26-3 Renal Physiology

• **Types of Carrier-Mediated Transport**
  - *Facilitated diffusion*
• Active transport
• Cotransport
• Countertransport

26-3 Renal Physiology

• Characteristics of Carrier-Mediated Transport
  1. A specific substrate binds to carrier protein that facilitates movement across membrane
  2. A given carrier protein usually works in one direction only
  3. Distribution of carrier proteins varies among portions of cell surface
  4. The membrane of a single tubular cell contains many types of carrier proteins
  5. Carrier proteins, like enzymes, can be saturated

• Transport maximum ($T_m$) and the Renal Threshold
  • If nutrient concentrations rise in tubular fluid:
    • Reabsorption rates increase until carrier proteins are saturated
  • Concentration higher than transport maximum:
    • Exceeds reabsorptive abilities of nephron
    • Some material will remain in the tubular fluid and appear in the urine
      • Determines the renal threshold

• Renal Threshold
  • Is the plasma concentration at which:
    • A specific compound or ion begins to appear in urine
• Varies with the substance involved

26-3 Renal Physiology
• Renal Threshold for Glucose
  • Is approximately 180 mg/dL
  • If plasma glucose is greater than 180 mg/dL:
    • $T_m$ of tubular cells is exceeded
    • Glucose appears in urine
      • Glycosuria

26-3 Renal Physiology
• Renal Threshold for Amino Acids
  • Is lower than glucose (65 mg/dL)
  • Amino acids commonly appear in urine
    • After a protein-rich meal
    • Aminoaciduria

26-3 Renal Physiology
• Ways of Expressing Osmotic Concentration
  • Osmolarity
    • Total number of solute particles per liter
    • Expressed in osmoles per liter (Osm/L) or milliosmoles per liter (mOsm/L)
    • Body fluids have osmotic concentration of about 300 mOsm/L

26-3 Renal Physiology
• Other Measurements
  • Ion concentrations
    • In milliequivalents per liter (mEq/L)
  • Concentrations of large organic molecules
    • Grams or milligrams per unit volume of solution (mg/dL or g/dL)

26-3 Renal Physiology
• Cortical and Juxtamedullary Nephrons
  • Nephron loop in cortical nephron
    • Is short
    • Does not extend far into medulla
  • Nephron loop in juxtamedullary nephron
    • Is long
    • Extends deep into renal pyramids
    • Functions in water conservation and forms concentrated urine

26-4 Glomerular Filtration
• The Process of Glomerular Filtration
  • Involves passage across a filtration membrane
    • Three components of membrane
      1. Capillary endothelium
      2. Dense layer
      3. Filtration slits

26-4 Glomerular Filtration
• Glomerular Capillaries
  • Are fenestrated capillaries
  • Have pores 60–100 nm diameter
- Prevent passage of blood cells
- Allow diffusion of solutes, including plasma proteins

26-4 Glomerular Filtration
- The Dense Layer
  - Is more selective
  - Allows diffusion of only:
    - Small plasma proteins
    - Nutrients
    - Ions

26-4 Glomerular Filtration
- The Filtration Slits
  - Are the finest filters
  - Have gaps only 6–9 nm wide
  - Prevent passage of most small plasma proteins

26-4 Glomerular Filtration
- Filtration Pressures
  - Glomerular filtration is governed by the balance between:
    - Hydrostatic pressure (fluid pressure)
    - Colloid osmotic pressure (of materials in solution) on either side of capillary walls

26-4 Glomerular Filtration
- Hydrostatic Pressure
• Glomerular hydrostatic pressure is blood pressure in glomerular capillaries
• Tends to push water and solute molecules
  • Out of plasma
  • Into the filtrate
• Is significantly higher than capillary pressures in systemic circuit
  • Due to arrangement of vessels at glomerulus

26-4 Glomerular Filtration
• Glomerular Blood Vessels
  • Blood leaving glomerular capillaries
    • Flows into an efferent arteriole with a diameter smaller than afferent arteriole
  • Efferent arteriole produces resistance
    • Requires relatively high pressures to force blood into it

26-4 Glomerular Filtration
• Capsular Hydrostatic Pressure (CsHP)
  • Opposes glomerular hydrostatic pressure
  • Pushes water and solutes
    • Out of filtrate
    • Into plasma
  • Results from resistance to flow along nephron and conducting system
  • Averages about 15 mm Hg

26-4 Glomerular Filtration
• Net Hydrostatic Pressure (NHP)
• Is the difference between:
  • Glomerular hydrostatic pressure and capsular hydrostatic pressure

• **Colloid Osmotic Pressure**
  • Is the osmotic pressure resulting from the presence of suspended proteins
  • Blood colloid osmotic pressure (BCOP)
    • Tends to draw water out of filtrate and into plasma
    • Opposes filtration
    • Averages 25 mm Hg

26-4 Glomerular Filtration
• **Net Filtration Pressure (NFP)**
  • Is the average pressure forcing water and dissolved materials:
    • Out of glomerular capillaries
    • Into capsular spaces
  • At the glomerulus is the difference between:
    • Hydrostatic pressure and blood colloid osmotic pressure across glomerular capillaries

26-4 Glomerular Filtration
• The **Glomerular Filtration Rate (GFR)**
  • Is the amount of filtrate kidneys produce each minute
  • Averages 125 mL/min
  • About 10% of fluid delivered to kidneys
    • Leaves bloodstream
    • Enters capsular spaces

26-4 Glomerular Filtration
• **Creatinine Clearance Test**
  • Is used to estimate GFR
  • A more accurate GFR test uses *inulin*
    • Which is not metabolized

• **Filtrate**
  • Glomeruli generate about 180 liters of filtrate per day
    • 99% is reabsorbed in renal tubules

### 26-4 Glomerular Filtration

• **Filtration Pressure**
  • Glomerular filtration rate depends on filtration pressure
  • Any factor that alters filtration pressure alters GFR

### 26-4 Glomerular Filtration

• **Control of the GFR**
  • Three interacting levels of control
    1. **Autoregulation** (local level)
    2. **Hormonal regulation** (initiated by kidneys)
    3. **Autonomic regulation** (by sympathetic division of ANS)

### 26-4 Glomerular Filtration

• **Autoregulation of the GFR**
  • Maintains GFR despite changes in local blood pressure and blood flow
    • By changing diameters of afferent arterioles, efferent arterioles, and glomerular capillaries
  • Reduced blood flow or glomerular blood pressure triggers:
    • Dilation of afferent arteriole
• Dilation of glomerular capillaries
• Constriction of efferent arterioles

26-4 Glomerular Filtration
• Autoregulation of the GFR
  • Rise in renal blood pressure
    • Stretches walls of afferent arterioles
    • Causes smooth muscle cells to contract
    • Constricts afferent arterioles
    • Decreases glomerular blood flow

26-4 Glomerular Filtration
• Hormonal Regulation of the GFR
  • By hormones of the:
    • Renin–angiotensin system
    • Natriuretic peptides (ANP and BNP)

26-4 Glomerular Filtration
• The Renin–Angiotensin System
  • Three stimuli cause the juxtaglomerular complex (JGC) to release renin
    1. Decline in blood pressure at glomerulus due to decrease in blood volume, fall in systemic pressures, or blockage in renal artery or tributaries
    2. Stimulation of juxtaglomerular cells by sympathetic innervation
    3. Decline in osmotic concentration of tubular fluid at macula densa
26-4 Glomerular Filtration

- The Renin–Angiotensin System: Angiotensin II Activation
  - Constricts efferent arterioles of nephron
    - Elevating glomerular pressures and filtration rates
  - Stimulates reabsorption of sodium ions and water at PCT
  - Stimulates secretion of aldosterone by adrenal cortex
  - Stimulates thirst
  - Triggers release of antidiuretic hormone (ADH)
    - Stimulates reabsorption of water in distal portion of DCT and collecting system

26-4 Glomerular Filtration

- The Renin–Angiotensin System: Angiotensin II
  - Increases sympathetic motor tone
    - Mobilizing the venous reserve
    - Increasing cardiac output
    - Stimulating peripheral vasoconstriction
  - Causes brief, powerful vasoconstriction
    - Of arterioles and precapillary sphincters
  - Elevating arterial pressures throughout body

26-4 Glomerular Filtration

- The Renin–Angiotensin System
  - Aldosterone
    - Accelerates sodium reabsorption in DCT and cortical portion of collecting system

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• Hormonal Regulation of the GFR
  • Increased Blood Volume
    • Automatically increases GFR
      • To promote fluid loss
    • Hormonal factors further increase GFR
      • Accelerating fluid loss in urine

26-4 Glomerular Filtration
• Hormonal Regulation of the GFR
  • Natriuretic Peptides
    • Are released by the heart in response to stretching walls due to increased blood volume or pressure
    • Atrial natriuretic peptide (ANP) is released by atria
    • Brain natriuretic peptide (BNP) is released by ventricles
    • Trigger dilation of afferent arterioles and constriction of efferent arterioles
    • Elevate glomerular pressures and increase GFR

26-4 Glomerular Filtration
• Autonomic Regulation of the GFR
  • Mostly consists of sympathetic postganglionic fibers
  • Sympathetic activation
    • Constricts afferent arterioles
    • Decreases GFR
    • Slows filtrate production
  • Changes in blood flow to kidneys due to sympathetic stimulation
    • May be opposed by autoregulation at local level

26-5 Reabsorption and Secretion
• Reabsorption
  • Recovers useful materials from filtrate
• Secretion
• Ejects waste products, toxins, and other undesirable solutes

• Reabsorption and Secretion
  • Occur in every segment of nephron
    • Except renal corpuscle
    • Relative importance changes from segment to segment

26-5 Reabsorption and Secretion
• Reabsorption and Secretion at the PCT
  • PCT cells normally reabsorb 60%–70% of filtrate produced in renal corpuscle
  • Reabsorbed materials enter peritubular fluid
    • And diffuse into peritubular capillaries

26-5 Reabsorption and Secretion
• Five Functions of the PCT
  1. Reabsorption of organic nutrients
  2. Active reabsorption of ions
  3. Reabsorption of water
  4. Passive reabsorption of ions
  5. Secretion

26-5 Reabsorption and Secretion
• Sodium Ion Reabsorption
  • Is important in every PCT process
  • Ions enter tubular cells by:
    • Diffusion through leak channels
    • Sodium-linked cotransport of organic solutes
    • Countertransport for hydrogen ions
26-5 Reabsorption and Secretion

- The Nephron Loop and Countercurrent Multiplication
  - Nephron loop reabsorbs about 1/2 of water and 2/3 of sodium and chloride ions remaining in tubular fluid
    - By the process of countercurrent exchange

- Countercurrent Multiplication
  - Is exchange that occurs between two parallel segments of loop of Henle
    - The thin, descending limb
    - The thick, ascending limb

- Countercurrent
  - Refers to exchange between tubular fluids moving in opposite directions
    - Fluid in descending limb flows toward renal pelvis
    - Fluid in ascending limb flows toward cortex

- Multiplication
  - Refers to effect of exchange
    - Increases as movement of fluid continues

- Parallel Segments of Nephron Loop
• Are very close together, separated only by peritubular fluid
• Have very different permeability characteristics

26-5 Reabsorption and Secretion
• The Thin Descending Limb
  • Is permeable to water
  • Is relatively impermeable to solutes
• The Thick Ascending Limb
  • Is relatively impermeable to water and solutes
  • Contains active transport mechanisms
    • Pump Na\(^+\) and Cl\(^-\) from tubular fluid into peritubular fluid of medulla

26-5 Reabsorption and Secretion
• Sodium and Chloride Pumps
  • Elevate osmotic concentration in peritubular fluid
    • Around thin descending limb
  • Cause osmotic flow of water
    • Out of thin descending limb into peritubular fluid
    • Increasing solute concentration in thin descending limb

26-5 Reabsorption and Secretion
• Concentrated Solution
  • Arrives in thick ascending limb
  • Accelerates Na\(^+\) and Cl\(^-\) transport into peritubular fluid of medulla

• Solute Pumping
• At ascending limb:
  • Increases solute concentration in descending limb
  • Which accelerates solute pumping in ascending limb

26-5 Reabsorption and Secretion
• Countercurrent Multiplication
  • Active transport at apical surface
    • Moves Na\(^+\), K\(^+\) and Cl\(^-\) out of tubular fluid
  • Uses carrier protein

\[ \text{Na}^+\text{-K}^+\text{/2 Cl}^- \text{ transporter} \]

26-5 Reabsorption and Secretion
• Na\(^+\)-K\(^+\)/2 Cl\(^-\) Transporter
  • Each cycle of pump carries ions into tubular cell
    • 1 sodium ion
    • 1 potassium ion
    • 2 chloride ions

26-5 Reabsorption and Secretion
• Potassium Ions
  • Are pumped into peritubular fluid by cotransport carriers
  • Are removed from peritubular fluid by sodium–potassium exchange pump
  • Diffuse back into lumen of tubule through potassium leak channels

• Sodium and Chloride Ions
  • Removed from tubular fluid in ascending limb
  • Elevate osmotic concentration of peritubular fluid around thin
26-5 Reabsorption and Secretion

• The Thin Descending Limb
  • Is permeable to water, impermeable to solutes
  • As tubular fluid flows along thin descending limb:
    • Osmosis moves water into peritubular fluid, leaving solutes behind
    • Osmotic concentration of tubular fluid increases

26-5 Reabsorption and Secretion

• The Thick Ascending Limb
  • Has highly effective pumping mechanism
    • 2/3 of Na\(^+\) and Cl\(^-\) are pumped out of tubular fluid before it reaching DCT
    • Solute concentration in tubular fluid declines

26-5 Reabsorption and Secretion

• Tubular Fluid at DCT
  • Arrives with osmotic concentration of 100 mOsm/L
    • 1/3 concentration of peritubular fluid of renal cortex
  • Rate of ion transport across thick ascending limb:
    • Is proportional to ion’s concentration in tubular fluid

26-5 Reabsorption and Secretion

• Regional Differences
  • More Na\(^+\) and Cl\(^-\) are pumped into medulla:
    • At start of thick ascending limb than near cortex
• Regional difference in ion transport rate:
  • Causes concentration gradient within medulla

26-5 Reabsorption and Secretion
• The Concentration Gradient of the Medulla
  • Maximum solute concentration of peritubular fluid near turn of nephron loop
    • 1200 mOsm/L
      • 2/3 (750 mOsm/L) from Na\(^+\) and Cl\(^-\)
        • Pumped out of ascending limb
      • Remainder from urea

26-5 Reabsorption and Secretion
• Urea and the Concentration Gradient
  • Thick ascending limb of nephron loop, DCT, and collecting ducts are impermeable to urea
  • As water is reabsorbed, concentration of urea rises
  • Tubular fluid reaching papillary duct contains 450 mOsm/L urea
  • Papillary ducts are permeable to urea
    • Concentration in medulla averages 450 mOsm/L

26-5 Reabsorption and Secretion
• Benefits of Countercurrent Multiplication
  1. Efficiently reabsorbs solutes and water
    • Before tubular fluid reaches DCT and collecting system
  2. Establishes concentration gradient
    • That permits passive reabsorption of water from tubular fluid in collecting system
      • Regulated by circulating levels of antidiuretic hormone (ADH)
26-5 Reabsorption and Secretion

- Reabsorption and Secretion at the DCT
  - Composition and volume of tubular fluid

  - Changes from capsular space to distal convoluted tubule
    - Only 15%–20% of initial filtrate volume reaches DCT
    - Concentrations of electrolytes and organic wastes in arriving tubular fluid no longer resemble blood plasma

26-5 Reabsorption and Secretion

- Reabsorption at the DCT
  - Selective reabsorption or secretion, primarily along DCT, makes final adjustments in solute composition and volume of tubular fluid

  - Tubular Cells at the DCT
    - Actively transport Na\(^+\) and Cl\(^-\) out of tubular fluid
    - Along distal portions
      - Contain ion pumps
      - Reabsorb tubular Na\(^+\) in exchange for K\(^+\)

26-5 Reabsorption and Secretion

- *Aldosterone*
  - Is a hormone produced by the adrenal cortex
  - Controls ion pump and channels
  - Stimulates synthesis and incorporation of Na\(^+\) pumps and channels
    - In plasma membranes along DCT and collecting duct
  - Reduces Na\(^+\) lost in urine
26-5 Reabsorption and Secretion

- **Hypokalemia**
  - Produced by prolonged aldosterone stimulation
  - Dangerously reduces plasma concentration

- **Natriuretic Peptides (ANP and BNP)**
  - Oppose secretion of aldosterone
    - And its actions on DCT and collecting system

- **Parathyroid Hormone and Calcitriol**
  - Circulating levels regulate calcium ion reabsorption at the DCT

26-5 Reabsorption and Secretion

- **Secretion at the DCT**
  - Blood entering peritubular capillaries
    - Contains undesirable substances that did not cross filtration membrane at glomerulus
  - Rate of $K^+$ and $H^+$ secretion rises or falls
    - According to concentrations in peritubular fluid
    - Higher concentration and higher rate of secretion

26-5 Reabsorption and Secretion

- **Potassium Ion Secretion**
  - Ions diffuse into lumen through potassium leak channels
    - At apical surfaces of tubular cells
  - Tubular cells exchange $Na^+$ in tubular fluid
    - For excess $K^+$ in body fluids
26-5 Reabsorption and Secretion

- **Hydrogen Ion Secretion**
  - Is generated by dissociation of carbonic acid by enzyme *carbonic anhydrase*
  - Secretion is associated with reabsorption of sodium
    - Secreted by sodium-linked countertransport
    - In exchange for Na\(^+\) in tubular fluid
  - Bicarbonate ions diffuse into bloodstream
    - Buffer changes in plasma pH

- **Acidosis**
  - Lactic acidosis
    - Develops after exhaustive muscle activity
  - Ketoacidosis
    - Develops in starvation or diabetes mellitus

- **Control of Blood pH**
  - By H\(^+\) removal and bicarbonate production at kidneys
• Is important to homeostasis

• Alkalosis
  • Abnormally high blood pH
  • Can be caused by prolonged aldosterone stimulation
    • Which stimulates secretion

26-5 Reabsorption and Secretion
• Response to Acidosis
  • PCT and DCT deaminate amino acids
    • Ties up H⁺
    • Yields ammonium ions (NH₄⁺) and bicarbonate ions (HCO₃⁻)
  • Ammonium ions are pumped into tubular fluid
    • Bicarbonate ions enter bloodstream through peritubular fluid

26-5 Reabsorption and Secretion
• Benefits of Tubular Deamination
  • Provides carbon chains for catabolism
  • Generates bicarbonate ions to buffer plasma

26-5 Reabsorption and Secretion
• Reabsorption and Secretion along the Collecting System
  • Collecting ducts
    • Receive tubular fluid from nephrons
    • Carry it toward renal sinus
26-5 Reabsorption and Secretion

• Regulating Water and Solute Loss in the Collecting System
  • By aldosterone
    • Controls sodium ion pumps
    • Actions are opposed by natriuretic peptides
  • By ADH
    • Controls permeability to water
    • Is suppressed by natriuretic peptides

26-5 Reabsorption and Secretion

• Reabsorption in the Collecting System
  • Sodium ion reabsorption
  • Bicarbonate reabsorption
  • Urea reabsorption

• Secretion in the Collecting System
  • Of hydrogen or bicarbonate ions
  • Controls body fluid pH

26-5 Reabsorption and Secretion

• Low pH in Peritubular Fluid
  • Carrier proteins
    • Pump $H^+$ into tubular fluid
    • Reabsorb bicarbonate ions

• High pH in Peritubular Fluid
  • Collecting system
    • Secretes bicarbonate ions
    • Pumps $H^+$ into peritubular fluid
26-5 Reabsorption and Secretion
• The Control of Urine Volume and Osmotic Concentration
  • Through control of water reabsorption
  • Water is reabsorbed by osmosis in:
    • Proximal convoluted tubule
    • Descending limb of nephron loop

26-5 Reabsorption and Secretion
• Water Reabsorption
  • Occurs when osmotic concentration of peritubular fluid exceeds that of tubular fluid
  • 1%–2% of water in original filtrate is recovered
    • During sodium ion reabsorption
    • In distal convoluted tubule and collecting system

26-5 Reabsorption and Secretion
• **Obligatory Water Reabsorption**
  • Is water movement that cannot be prevented
  • Usually recovers 85% of filtrate produced

• **Facultative Water Reabsorption**
  • Controls volume of water reabsorbed along DCT and collecting system
    • 15% of filtrate volume (27 liters/day)
    • Segments are relatively impermeable to water
    • Except in presence of ADH
26-5 Reabsorption and Secretion

- **ADH**
  - Hormone that causes special *water channels* (*aquaporins*) to appear in apical cell membranes
  - Increases rate of osmotic water movement
  - Higher levels of ADH increase:
    - Number of water channels
    - Water permeability of DCT and collecting system

- **Osmotic Concentration**
  - Of tubular fluid arriving at DCT
    - 100 mOsm/L
  - In the presence of ADH (in cortex)
    - 300 mOsm/L
  - In minor calyx
    - 1200 mOsm/L

- **Without ADH**
  - Water is not reabsorbed
  - All fluid reaching DCT is lost in urine
    - Producing large amounts of dilute urine

- **The Hypothalamus**
• Continuously secretes low levels of ADH
  • DCT and collecting system are always permeable to water
• At normal ADH levels
  • Collecting system reabsorbs 16.8 liters/day (9.3% of filtrate)

26-5 Reabsorption and Secretion

• Urine Production
  • A healthy adult produces:
    • 1200 mL per day (0.6% of filtrate)
    • With osmotic concentration of 800–1000 mOsm/L

26-5 Reabsorption and Secretion

• Diuresis
  • Is the elimination of urine
  • Typically indicates production of large volumes of urine
• Diuretics
  • Are drugs that promote water loss in urine
  • Diuretic therapy reduces:
    • Blood volume
    • Blood pressure
    • Extracellular fluid volume

26-5 Reabsorption and Secretion

• The Function of the Vasa Recta
  • To return solutes and water reabsorbed in medulla to general circulation without disrupting the concentration gradient
  • Some solutes absorbed in descending portion do not diffuse out in ascending portion

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• More water moves into ascending portion than is moved out of descending portion

26-5 Reabsorption and Secretion
• Osmotic Concentration
  • Blood entering the vasa recta:
    • Has osmotic concentration of 300 mOsm/L
  • Increases as blood descends into medulla
    • Involves solute absorption and water loss
  • Blood flowing toward cortex:
    • Gradually decreases with solute concentration of peritubular fluid
    • Involves solute diffusion and osmosis

26-5 Reabsorption and Secretion
• The Vasa Recta
  • Carries water and solutes out of medulla
  • Balances solute reabsorption and osmosis in medulla

26-5 Reabsorption and Secretion
• The Composition of Normal Urine
  • Results from filtration, absorption, and secretion activities of nephrons
  • Some compounds (such as urea) are neither excreted nor reabsorbed
  • Organic nutrients are completely reabsorbed
    • Other compounds missed by filtration process (e.g., creatinine) are actively secreted into tubular fluid
26-5 Reabsorption and Secretion

- **The Composition of Normal Urine**
  - A urine sample depends on osmotic movement of water across walls of tubules and collecting ducts
  - Is a clear, sterile solution
  - Yellow color (pigment urobilin)
    - Generated in kidneys from urobilinogens
  - **Urinalysis**, the analysis of a urine sample, is an important diagnostic tool

26-5 Summary of Renal Function

- **Seven Steps of Renal Function**
  - **Step 1 Glomerulus**
    - Filtrate produced at renal corpuscle has the same composition as blood plasma (minus plasma proteins)
  - **Step 2 Proximal Convoluted Tubule (PCT)**
    - Active removal of ions and organic substrates
      - Produces osmotic water flow out of tubular fluid
      - Reduces volume of filtrate
      - Keeps solutions inside and outside tubule isotonic
  - **Step 3 PCT and Descending Limb**
    - Water moves into peritubular fluids, leaving highly concentrated tubular fluid
    - Reduction in volume occurs by obligatory water reabsorption
  - **Step 4 Thick Ascending Limb**
    - Tubular cells actively transport Na\(^+\) and Cl\(^-\) out of tubule
    - Urea accounts for higher proportion of total osmotic concentration

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26-5 Summary of Renal Function

• Seven Steps of Renal Function
  • Step 5 DCT and Collecting Ducts
    • Final adjustments in composition of tubular fluid
    • Osmotic concentration is adjusted through active transport (reabsorption or secretion)
  • Step 6 DCT and Collecting Ducts
    • Final adjustments in volume and osmotic concentration of tubular fluid
    • Exposure to ADH determines final urine concentration

• Step 7 Vasa Recta
  • Absorbs solutes and water reabsorbed by nephron loop and the ducts
  • Maintains concentration gradient of medulla

• Urine Production
  • Ends when fluid enters the renal pelvis

26-6 Urine Transport, Storage, and Elimination

• Urine Transport, Storage, and Elimination
  • Take place in the urinary tract
    • Ureters
    • Urinary bladder
    • Urethra

• Structures
  • Minor and major calyces, renal pelvis, ureters, urinary bladder,
and proximal portion of urethra
• Are lined by *transitional epithelium*
• That undergoes cycles of distention and contraction

26-6 Urine Transport, Storage, and Elimination
• The Ureters
  • Are a pair of muscular tubes
  • Extend from kidneys to urinary bladder
  • Begin at renal pelvis
  • Pass over *psoas major muscles*
  • Are retroperitoneal, attached to posterior abdominal wall
  • Penetrate posterior wall of the urinary bladder
  • Pass through bladder wall at oblique angle
  • *Ureteral openings* are slit-like rather than rounded
  • Shape helps prevent backflow of urine when urinary bladder contracts

26-6 Urine Transport, Storage, and Elimination
• Histology of the Ureters
  • The wall of each ureter has three layers
    1. Inner mucosa
       • *Transitional epithelium and lamina propria*
    2. Middle muscular layer
       • Longitudinal and circular bands of smooth muscle
    3. Outer connective tissue layer
       • Continuous with fibrous renal capsule and peritoneum

26-6 Urine Transport, Storage, and Elimination
Peristaltic Contractions
- Begin at renal pelvis
- Sweep along ureter
- Force urine toward urinary bladder
- Every 30 seconds

26-6 Urine Transport, Storage, and Elimination
- The Urinary Bladder
  - Is a hollow, muscular organ
  - Functions as temporary reservoir for urine storage
  - Full bladder can contain 1 liter of urine

26-6 Urine Transport, Storage, and Elimination
- Bladder Position
  - Is stabilized by several peritoneal folds
  - Posterior, inferior, and anterior surfaces
    - Lie outside peritoneal cavity
  - Ligamentous bands
    - Anchor urinary bladder to pelvic and pubic bones

26-6 Urine Transport, Storage, and Elimination
- Umbilical Ligaments of Bladder
  - Median umbilical ligament extends:
    - From anterior, superior border
    - Toward umbilicus
  - Lateral umbilical ligaments
    - Pass along sides of bladder to umbilicus
    - Are vestiges of two umbilical arteries
26-6 Urine Transport, Storage, and Elimination

• The Mucosa
  • Lining the urinary bladder, has folds (rugae) that disappear as bladder fills

• The Trigone of the Urinary Bladder
  • Is a triangular area bounded by:
    • Openings of ureters
    • Entrance to urethra
  • Acts as a funnel
    • Channels urine from bladder into urethra

26-6 Urine Transport, Storage, and Elimination

• The Urethral Entrance
  • Lies at apex of trigone
    • At most inferior point in urinary bladder

• The Neck of the Urinary Bladder
  • Is the region surrounding urethral opening
  • Contains a muscular internal urethral sphincter
    • Smooth muscle fibers of sphincter
    • Provides involuntary control of urine discharge

26-6 Urine Transport, Storage, and Elimination

• Urinary Bladder Innervation
  • Postganglionic fibers
    • From ganglia in hypogastric plexus
  • Parasympathetic fibers
    • From intramural ganglia controlled by pelvic nerves
26-6 Urine Transport, Storage, and Elimination

• Histology of the Urinary Bladder
  • The wall of the urinary bladder contains mucosa, submucosa, and muscularis layers
    • The Muscularis Layer
      • Consists of the detrusor muscle
      • Inner and outer layers of longitudinal smooth muscle with a circular layer in between

26-6 Urine Transport, Storage, and Elimination

• The Urethra
  • Extends from neck of urinary bladder
  • To the exterior of the body

26-6 Urine Transport, Storage, and Elimination

• The Male Urethra
  • Extends from neck of urinary bladder to tip of penis (18–20 cm; 7–8 in.)
  • Prostatic urethra passes through center of prostate gland
  • Membranous urethra includes short segment that penetrates the urogenital diaphragm
  • Spongy urethra (penile urethra) extends from urogenital diaphragm to external urethral orifice

26-6 Urine Transport, Storage, and Elimination

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• The Female Urethra
  • Is very short (3–5 cm; 1–2 in.)
  • Extends from bladder to vestibule
  • External urethral orifice is near anterior wall of vagina

26-6 Urine Transport, Storage, and Elimination
• The External Urethral Sphincter
  • In both sexes
    • Is a circular band of skeletal muscle
    • Where urethra passes through urogenital diaphragm
  • Acts as a valve
  • Is under voluntary control
    • Via perineal branch of pudendal nerve
  • Has resting muscle tone
  • Voluntary relaxation permits micturition

26-6 Urine Transport, Storage, and Elimination
• Histology of the Urethra
  • Lamina propria is thick and elastic
  • Mucous membrane has longitudinal folds
  • Mucin-secreting cells lie in epithelial pockets

26-6 Urine Transport, Storage, and Elimination
• Male Structures of the Urethra
  • Epithelial mucous glands
    • Form tubules that extend into lamina propria
  • Connective tissues of lamina propria
• Anchor urethra to surrounding structures

• Female Structures of the Urethra
  • Lamina propria contains extensive network of veins
  • Complex is surrounded by concentric layers of smooth muscle

26-6 Urine Transport, Storage, and Elimination
• The Micturition Reflex and Urination
  • As the bladder fills with urine:
    • Stretch receptors in urinary bladder stimulate sensory fibers in pelvic nerve
    • Stimulus travels from afferent fibers in pelvic nerves to sacral spinal cord
  • Efferent fibers in pelvic nerves:
    • Stimulate ganglionic neurons in wall of bladder

26-6 Urine Transport, Storage, and Elimination
• The Micturition Reflex and Urination
  • Postganglionic neuron in intramural ganglion stimulates detrusor muscle contraction
  • Interneuron relays sensation to thalamus
  • Projection fibers from thalamus deliver sensation to cerebral cortex
  • Voluntary relaxation of external urethral sphincter causes relaxation of internal urethral sphincter

26-6 Urine Transport, Storage, and Elimination
• The Micturition Reflex and Urination
  • Begins when stretch receptors stimulate parasympathetic
preganglionic motor neurons
• Volume >500 mL triggers micturition reflex

26-6 Urine Transport, Storage, and Elimination
• Infants
  • Lack voluntary control over urination
  • Corticospinal connections are not established

• Incontinence
  • Is the inability to control urination voluntarily
  • May be caused by trauma to internal or external urethral sphincter

26-7 Effects of Aging on the Urinary System
• Age-related Changes
  • Decline in number of functional nephrons
  • Reduction in GFR
  • Reduced sensitivity to ADH
  • Problems with micturition reflex
    • Sphincter muscles lose tone leading to incontinence
    • Control of micturition can be lost due to a stroke, Alzheimer’s disease, and other CNS problems
    • In males, urinary retention may develop if enlarged prostate gland compresses the urethra and restricts urine flow

26-8 The Excretory System
• The Excretory System
  • Includes all systems with excretory functions that affect body
fluid composition

- Urinary system
- Integumentary system
- Respiratory system
- Digestive system