Introduction to the Urinary System

**Figure 18-1**

- **Kidney**
  - Produces urine

- **Ureter**
  - Transports urine to the urinary bladder

- **Urinary bladder**
  - Temporarily stores urine prior to elimination

- **Urethra**
  - Conducts urine to exterior; in males, transports semen as well

Anterior view
18-1 The urinary system, consisting of the kidneys, ureters, urinary bladder, and urethra, has three primary functions.
Introduction to the Urinary System

• 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
Introduction to 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
Introduction to the Urinary System

• Four Homeostatic Functions of Urinary System
  1. Regulates blood volume and blood pressure:
     • By adjusting volume of water lost in urine
     • Releasing **erythropoietin** and **renin**
  2. Regulates plasma ion concentrations:
     • Sodium, potassium, and chloride ions (by controlling quantities lost in urine)
     • Calcium ion levels (through synthesis of calcitriol)
Introduction to the Urinary System

• Four Homeostatic Functions of Urinary System

3. Helps stabilize blood pH:
   • By controlling loss of hydrogen ions and bicarbonate ions in urine

4. Conserves valuable nutrients:
   • By preventing excretion while excreting organic waste products
18-2 The highly vascular kidneys contain functional units called nephrons, which perform filtration, reabsorption, and secretion.
The Kidneys

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

Figure 18-2a

Diaphragm
Left kidney
Renal artery and vein
Suprarenal gland
11th and 12th ribs
Right kidney
Lumbar (L1) vertebra
Ureter
Iliac crest
Inferior vena cava
Aorta
Urinary bladder
Urethra
The Kidneys

Figure 18-2b
The Kidneys

• Typical Adult Kidney
  – Is about 10 cm long, 5.5 cm wide, and 3 cm thick (4 in. × 2.2 in. × 1.2 in.)
  – Weighs about 150 g (5.25 oz)
The Kidneys

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

• Renal Cortex
  – Superficial portion of kidney in contact with renal capsule
  – Reddish brown and granular
The Kidneys

• Renal Pyramids
  – 6 to 18 distinct conical or triangular structures in renal medulla
    • Base abuts cortex
    • Tip (renal papilla) projects into renal sinus
• **Renal Columns**
  – Bands of cortical tissue separate adjacent renal pyramids
  – Extend into medulla
  – Have distinct granular texture
The Kidneys

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

• Major Calyx
  – Formed by four or five minor calyces
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
Figure 18-3a
The Kidneys

Figure 18-3b

- Renal cortex
- Renal medulla
- Renal pyramids
- Renal sinus
- Major calyx
- Minor calyx
- Renal pelvis
- Renal papilla
- Hilum
- Ureter
- Renal columns
- Fibrous capsule
The Kidneys

• Nephrons
  – Microscopic, tubular structures in cortex of each renal lobe
  – Where urine production begins
The Kidneys

Figure 18-3c

Renal corpuscle
Proximal convoluted tubule
Distal convoluted tubule
Collecting duct
Nephron loop
Blood Supply to Kidneys

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

Figure 18-4a

(a) Arteries and veins of kidney
Blood Supply to Kidneys

Figure 18-4b

Nephron

Cortex

Afferent arterioles

Medulla

(b) Circulation in cortex
Blood Supply to Kidneys

(c) Cortical nephron

(d) Juxtamedullary nephron

Figure 18-4 c,d
The Nephron

- Consists of renal tubule and renal corpuscle

- Renal tubule
  - Long tubular passageway
  - Begins at renal corpuscle

- Renal corpuscle
  - Spherical structure consisting of:
    - glomerular capsule (Bowman’s capsule)
    - cup-shaped chamber
    - capillary network (glomerulus)
The Nephron

• 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
• Three Functions of 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
The Nephron

• Segments of 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
The Nephron

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

• Each Nephron
  – Empties into the **collecting system**:
    • A series of tubes that carries tubular fluid away from nephron
The 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
Figure 18-5

**NEPHRON**

- **Proximal convoluted tubule**
  - Reabsorption of water, ions, and all organic nutrients

- **Distal convoluted tubule**
  - Secretion of ions, acids, drugs, toxins
  - Variable reabsorption of water and sodium ions (under hormonal control)

**COLLECTING SYSTEM**

- **Collecting duct**
  - Variable reabsorption of water and reabsorption or secretion of sodium, potassium, hydrogen, and bicarbonate ions

- **Papillary duct**
  - Delivery of urine to minor calyx

**KEY**

- **Water**
- **Solutes**
- **Filtrate**
- **Variable reabsorption or secretion**

**Nephron loop**

- Further reabsorption of water (descending limb) and both sodium and chloride ions (ascending limb)

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The Nephron

• **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*
The Nephron

• 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
• The Glomerular Capsule
  – Outer wall is lined by simple squamous capsular epithelium:
    • Continuous with visceral epithelium that covers glomerular capillaries:
      – separated by capsular space
• The Visceral Epithelium
  – Consists of large cells (podocytes):
    • With complex processes or “feet” (pedicels) that wrap around specialized lamina densa of glomerular capillaries
• **Filtration Slits**
  – Are narrow gaps between adjacent pedicels
  – Materials passing out of blood at glomerulus:
    • Must be small enough to pass between filtration slits
Figure 18-6a
The Renal Corpuscle

Figure 18-6c

Glomerular capillary
Podocyte
Podocyte processes (pedicels)

(SEM × 27,248)

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The Nephron

• 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
The Nephron

• Tubular Cells
  – Absorb organic nutrients, ions, water, and plasma proteins from tubular fluid
  – Release them into peritubular fluid (interstitial fluid around renal tubule)
The Nephron

- Nephron loop (also called loop of Henle)
  - Renal tubule turns toward renal medulla:
    - Leads to nephron loop
  - Descending limb:
    - Fluid flows toward renal pelvis
  - Ascending limb:
    - Fluid flows toward renal cortex
- Each limb contains:
  - Thick segment
  - Thin segment
• 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
The Nephron

• 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
The Nephron

• Juxtaglomerular Complex
  – An endocrine structure that secretes:
    • Hormone erythropoietin
    • Enzyme renin
  – Formed by:
    • Macula densa
    • Juxtaglomerular cells
The Nephron

• 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)**
The Nephron

• 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
<table>
<thead>
<tr>
<th>REGION</th>
<th>PRIMARY FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renal corpuscle</td>
<td>Filtration of plasma to initiate urine formation</td>
</tr>
<tr>
<td>Proximal convoluted tubule (PCT)</td>
<td>Reabsorption of ions, organic molecules, vitamins, water</td>
</tr>
<tr>
<td>Nephron loop</td>
<td>Descending limb: reabsorption of water from tubular fluid</td>
</tr>
<tr>
<td></td>
<td>Ascending limb: reabsorption of ions; creates the concentration gradient in the medulla, enabling the kidney to produce concentrated urine</td>
</tr>
<tr>
<td>Distal convoluted tubule (DCT)</td>
<td>Reabsorption of sodium ions; secretion of acids, ammonia, and drugs</td>
</tr>
<tr>
<td>Collecting duct</td>
<td>Reabsorption of water and of sodium and bicarbonate ions</td>
</tr>
<tr>
<td>Papillary duct</td>
<td>Conduction of urine to minor calyx</td>
</tr>
</tbody>
</table>
18-3 Different portions of the nephron form urine by filtration, reabsorption, and secretion
The goal of urine production

- Is to maintain homeostasis
- By regulating volume and composition of blood
- Including excretion of metabolic waste products
Renal Physiology

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

• Organic Waste Products
  – Are dissolved in the bloodstream
  – Are eliminated only while dissolved in urine
  – Removal is accompanied by water loss
Basic Processes of Urine Formation

1. Filtration
2. Reabsorption
3. Secretion
### Significant Differences in Solute Concentrations Between Urine and Plasma

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>URINE</th>
<th>PLASMA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IONS (meq/L)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium ($\text{Na}^+$)</td>
<td>90</td>
<td>140</td>
</tr>
<tr>
<td>Potassium ($\text{K}^+$)</td>
<td>47.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Chloride ($\text{Cl}^-$)</td>
<td>153.3</td>
<td>99</td>
</tr>
<tr>
<td>Bicarbonate ($\text{HCO}_3^-$)</td>
<td>1.9</td>
<td>24.8</td>
</tr>
<tr>
<td><strong>METABOLITES AND NUTRIENTS (mg/dL)</strong></td>
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</tr>
<tr>
<td>Glucose</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Lipids</td>
<td>0.002</td>
<td>600</td>
</tr>
<tr>
<td>Amino acids</td>
<td>100</td>
<td>4.2</td>
</tr>
<tr>
<td>Proteins</td>
<td>62</td>
<td>7.5 g/dL</td>
</tr>
<tr>
<td><strong>NITROGENOUS WASTES (mg/dL)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urea</td>
<td>900</td>
<td>10–20</td>
</tr>
<tr>
<td>Creatinine</td>
<td>150</td>
<td>1–1.5</td>
</tr>
<tr>
<td>Ammonia</td>
<td>60</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Uric acid</td>
<td>40</td>
<td>3</td>
</tr>
</tbody>
</table>
Filtration at the Glomerulus

• 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
• 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
Reabsorption and Secretion at the Renal Tubule

- Reabsorption and Secretion
  - At the kidneys, they involve:
    - Diffusion
    - Osmosis
    - Channel-mediated diffusion
    - Carrier-mediated transport
Reabsorption and Secretion at the Renal Tubule

- 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
Reabsorption and Secretion at the PCT

- PCT cells normally reabsorb 60% to 70% of filtrate produced in renal corpuscle
- Reabsorbed materials enter peritubular fluid:
  - And diffuse into peritubular capillaries
Reabsorption and Secretion at the Renal Tubule

- 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
Reabsorption and Secretion at the Renal Tubule

• The Nephron Loop
  – Nephron loop reabsorbs about 1/2 of water and 2/3 of sodium and chloride ions remaining in tubular fluid
  – Concentrates the medulla
Reabsorption and Secretion at the Renal Tubule

• 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
Reabsorption and Secretion at the DCT

- Composition and volume of tubular fluid:
  - Changes from capsular space to distal convoluted tubule:
    - only 15% to 20% of initial filtrate volume reaches DCT
    - concentrations of electrolytes and organic wastes in arriving tubular fluid no longer resemble blood plasma
Reabsorption and Secretion at the Renal Tubule

• 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\(^+\)
Reabsorption and Secretion at the Renal Tubule

• Aldosterone
  – Is a hormone produced by suprarenal cortex
  – Controls ion pump and channels
  – Stimulates synthesis and incorporation of $\text{Na}^+$ pumps and channels
    • In plasma membranes along DCT and collecting duct
  – Reduces $\text{Na}^+$ lost in urine
Reabsorption and Secretion at the Renal Tubule

• 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
Reabsorption and Secretion at the Renal Tubule

- **Potassium Ion Secretion**
  - Ions diffuse into lumen through potassium channels:
    - At apical surfaces of tubular cells
  - Tubular cells exchange Na\(^+\) in tubular fluid:
    - For excess K\(^+\) in body fluids
Hydrogen Ion Secretion

- Hydrogen ions are 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
Reabsorption and Secretion at the Renal Tubule

• Reabsorption and Secretion along the Collecting System
  – Collecting ducts:
    • Receive tubular fluid from nephrons
    • Carry it toward renal sinus
Reabsorption and Secretion at the Renal Tubule

• 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
Reabsorption and Secretion at the Renal Tubule

- ADH
  - Hormone that causes special water channels 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
Reabsorption and Secretion at the Renal Tubule

• Without ADH
  – Water is not reabsorbed
  – All fluid reaching DCT is lost in urine:
    • Producing large amounts of dilute urine
Figure 18-7

The Effects of ADH on the DCT and Collecting Duct

(a) Absence of ADH

- Large volume of dilute urine

(b) Presence of ADH

- Small volume of concentrated urine

**KEY**

- Water-permeable
- Solute-permeable
- Water-impermeable
- Solute-impermeable

- Osmotic water flow
- Cotransport carrier

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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
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
# Table 18-3 General Characteristics of Normal Urine

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Normal Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>4.5–8 (average: 6.0)</td>
</tr>
<tr>
<td>Specific gravity (density of urine/density of pure water)</td>
<td>1.003–1.030</td>
</tr>
<tr>
<td>Osmotic concentration (Osmolarity) (number of solute particles per liter; for comparison, fresh water (\approx) 5 mOsm/L, body fluids (\approx) 300 mOsm/L and sea water (\approx) 1000 mOsm/L)</td>
<td>855–1335 mOsm/L</td>
</tr>
<tr>
<td>Water content</td>
<td>93–97%</td>
</tr>
<tr>
<td>Volume</td>
<td>700–2000 mL/day</td>
</tr>
<tr>
<td>Color</td>
<td>Clear yellow</td>
</tr>
<tr>
<td>Odor</td>
<td>Varies with composition</td>
</tr>
<tr>
<td>Bacterial content</td>
<td>None (sterile)</td>
</tr>
</tbody>
</table>

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Summary: 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
Summary: Renal Function

• 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
Summary: 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
Summary: Renal Function

• 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
Figure 18-8
18-4 Normal kidney function depends on a stable GFR
Control of the GFR

- Autoregulation (local level)
- Autonomic regulation (by sympathetic division of ANS)
- Hormonal regulation (initiated by kidneys)
Local Regulation of Kidney Function

• 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
Local Regulation of Kidney Function

• Autoregulation of the GFR
  – Reduced blood flow or glomerular blood pressure triggers:
    • Dilation of afferent arteriole
    • Dilation of glomerular capillaries
    • Constriction of efferent arterioles
  – Rise in renal blood pressure:
    • Stretches walls of afferent arterioles
    • Causes smooth muscle cells to contract
    • Constricts afferent arterioles
    • Decreases glomerular blood flow
Sympathetic Activation and Kidney Function

• 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
Hormonal Regulation of the GFR

• By hormones of the
  – Renin–angiotensin system
  – Natriuretic peptides (ANP and BNP)
Hormonal Regulation of the GFR

• The Renin–Angiotensin System
  – Three stimuli cause the juxtaglomerular complex (JGA) to release **renin**:
    • Decline in blood pressure at glomerulus due to decrease in blood volume
    • Fall in systemic pressures due to blockage in renal artery or tributaries
    • Stimulation of juxtaglomerular cells by sympathetic innervation due to decline in osmotic concentration of tubular fluid at macula densa
Hormonal Regulation of the GFR

• 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 suprarenal (adrenal) cortex
  – Stimulates thirst
  – Triggers release of antidiuretic hormone (ADH):
    • Stimulates reabsorption of water in distal portion of DCT and collecting system
Hormonal Regulation of the GFR

• 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 the body
Hormonal Regulation of the GFR

• The Renin–Angiotensin System
  – Aldosterone:
    • Accelerates sodium reabsorption:
      – in DCT and cortical portion of collecting system
Hormonal Regulation of the GFR

Figure 18-9
Hormonal Regulation of the GFR

• Atrial Natriuretic Peptides
  – Are released by the heart in response to stretching walls due to increased blood volume or pressure
  – Trigger dilation of afferent arterioles and constriction of efferent arterioles
  – Elevates glomerular pressures and increases GFR
18-5 Urine is transported by the ureters, stored in the bladder, and eliminated through the urethra, aided by the micturition reflex.
Urine Transport, Storage, and Elimination

• Takes place in the urinary tract
  – Ureters
  – Urinary bladder
  – Urethra
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 slitlike rather than rounded
- Shape helps prevent backflow of urine when urinary bladder contracts
The Urinary Bladder

- Is a hollow, muscular organ
  - Functions as a temporary reservoir for urine storage
  - Full bladder can contain 1 liter of urine
The Urinary Bladder

• 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
Organs for the Conduction and Storage of Urine

Figure 18-10a
Organs for the Conduction and Storage of Urine

Figure 18-10b
Organs for the Conduction and Storage of Urine

(c) Urinary bladder in male

Figure 18-10c
The Urethra

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

• 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**
The Urethra

• 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
The Urethra

- 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
  - Voluntarily relaxation permits **micturition**
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
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**
The Micturition Reflex and Urination

- Begins when stretch receptors stimulate parasympathetic preganglionic motor neurons
- Volume >500 mL triggers micturition reflex
The Micturition Reflex

Figure 18-11

1. Sensory fiber in pelvic nerve
2a. Parasympathetic preganglionic motor fiber in pelvic nerve
2b. Interneuron relays sensation to thalamus.
3a. Postganglionic neuron in intramural ganglion stimulates detrusor muscle contraction.
3b. Projection fibers from thalamus deliver sensation to cerebral cortex.
4. Voluntary relaxation of external urethral sphincter causes relaxation of internal urethral sphincter.

Following Step 4, urination occurs.
18-6 Fluid balance, electrolyte balance, and acid–base balance are interrelated and essential to homeostasis.
Introduction

• Water
  – Is 99% of fluid outside cells (extracellular fluid)
  – Is an essential ingredient of cytosol (intracellular fluid)
  – All cellular operations rely on water:
    • As a diffusion medium for gases, nutrients, and waste products
• Fluid Balance
  – Is a daily balance between:
    • Amount of water gained
    • Amount of water lost to environment
  – Involves regulating content and distribution of body water in ECF and ICF
• The Digestive System
  – Is the primary source of water gains:
    • Plus a small amount from metabolic activity

• The Urinary System
  – Is the primary route of water loss
Electrolytes

- Are ions released through dissociation of inorganic compounds
- Can conduct electrical current in solution

**Electrolyte balance:**

- When the gains and losses of all electrolytes are equal
- Primarily involves balancing rates of absorption across digestive tract with rates of loss at kidneys and sweat glands
• Acid–Base Balance
  – Precisely balances production and loss of hydrogen ions (pH)
  – The body generates acids during normal metabolism:
    • Tends to reduce pH
Fluid, Electrolyte, and Acid–Base Balance

• The Kidneys
  – Secrete hydrogen ions into urine
  – Generate buffers that enter bloodstream:
    • In distal segments of distal convoluted tubule (DCT) and collecting system

• The Lungs
  – Affect pH balance through elimination of carbon dioxide
Fluid Compartments

Figure 18-12

- Intracellular fluid (ICF) 60%
- Extracellular fluid (ECF) 40%
- Plasma
- Interstitial fluid
- Bone and dense connective tissue

Minor components:
- Lymph
- CSF
- Synovial fluid
- Serous fluid
- Aqueous humor
- Endolymph
- Perilymph
Ions in Body Fluids

Figure 18-13
18-7 Blood pressure and osmosis are involved in maintaining fluid and electrolyte balance
Fluid Balance

• When the body loses water
  – Plasma volume decreases
  – Electrolyte concentrations rise

• When the body loses electrolytes
  – Water is lost by osmosis

• Regulatory mechanisms are different
Fluid Balance

• Water circulates freely in ECF compartment
  – At capillary beds, hydrostatic pressure forces water out of plasma and into interstitial spaces
  – Water is reabsorbed along distal portion of capillary bed when it enters lymphatic vessels
  – ECF and ICF are normally in osmotic equilibrium:
    • No large-scale circulation between compartments
Fluid Gains and Losses

- Water losses:
  - Body loses about 2500 mL of water each day through urine, feces, and insensible perspiration
  - Fever can also increase water loss
  - Sensible perspiration (sweat) varies with activities and can cause significant water loss (4 L/hr)
Fluid Gains and Losses

- Water gains:
  - About 2500 mL/day
  - Required to balance water loss
  - Through:
    - eating (1000 mL)
    - drinking (1200 mL)
    - *metabolic generation* (300 mL)
<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DAILY INPUT (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content of food</td>
<td>1000</td>
</tr>
<tr>
<td>Water consumed as liquid</td>
<td>1200</td>
</tr>
<tr>
<td>Metabolic water produced during catabolism</td>
<td>300</td>
</tr>
<tr>
<td>Total</td>
<td>2500</td>
</tr>
<tr>
<td>METHOD OF ELIMINATION</td>
<td>DAILY OUTPUT (mL)</td>
</tr>
<tr>
<td>Urination</td>
<td>1200</td>
</tr>
<tr>
<td>Evaporation at skin</td>
<td>750</td>
</tr>
<tr>
<td>Evaporation at lungs</td>
<td>400</td>
</tr>
<tr>
<td>Loss in feces</td>
<td>150</td>
</tr>
<tr>
<td>Total</td>
<td>2500</td>
</tr>
</tbody>
</table>
**Fluid Shifts**

- Are rapid water movements between ECF and ICF
  - In response to an osmotic gradient
    - If ECF osmotic concentration increases:
      - Fluid becomes hypertonic to ICF
      - Water moves from cells to ECF
    - If ECF osmotic concentration decreases:
      - Fluid becomes hypotonic to ICF
      - Water moves from ECF to cells
  - ICF volume is much greater than ECF volume:
    - ICF acts as water reserve
    - Prevents large osmotic changes in ECF
Electrolyte Balance

- Requires rates of gain and loss of each electrolyte in the body to be equal
- Electrolyte concentration directly affects water balance
- Concentrations of individual electrolytes affect cell functions
Electrolyte Balance

• Rules of Electrolyte Balance

1. Most common problems with electrolyte balance are caused by imbalance between gains and losses of sodium ions

2. Problems with potassium balance are less common but more dangerous than sodium imbalance
Electrolyte Balance

• Sodium Balance
  1. Sodium ion uptake across digestive epithelium
  2. Sodium ion excretion in urine and perspiration
Electrolyte Balance

• Sodium Balance
  – Typical Na\(^+\) gain and loss:
    • Is 48–144 mEq (1.1–3.3 g) per day
  – If gains exceed losses:
    • Total ECF content rises
  – If losses exceed gains:
    • ECF content declines
Electrolyte Balance

• Sodium Balance and ECF Volume
  – Changes in ECF Na\(^+\) content:
    • Do not produce change in concentration
    • Corresponding water gain or loss keeps concentration constant
Electrolyte Balance

• Sodium Balance and ECF Volume
  – $Na^+$ regulatory mechanism changes ECF volume:
    • Keeps concentration stable
  – When $Na^+$ losses exceed gains:
    • ECF volume decreases (increased water loss)
    • Maintaining osmotic concentration
Electrolyte Balance

• Potassium Balance
  – 98% of potassium in the human body is in ICF
  – Cells expend energy to recover potassium ions diffused from cytoplasm into ECF
Electrolyte Balance

• Processes of Potassium Balance
  1. Rate of gain across digestive epithelium
  2. Rate of loss into urine
Electrolyte Balance

• Potassium Loss in Urine
  – Is regulated by activities of ion pumps:
    • Along distal portions of nephron and collecting system
    • Na\(^+\) from tubular fluid is exchanged for K\(^+\) in peritubular fluid
  – Is limited to amount gained by absorption across digestive epithelium (about 50–150 mEq or 1.9–5.8 g/day)
18-8 In acid–base balance, buffer systems and respiratory and renal compensation mechanisms regulate hydrogen ions in body fluids.
Acid–Base Balance

• pH of body fluids is altered by
  – Introduction of acids or bases
• Acids and bases may be strong or weak
• Carbonic Acid
  – Is a weak acid
  – In ECF at normal pH:
    • Equilibrium state exists
    • Is diagrammed $\text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^-$
Acid–Base Balance

• The Importance of pH Control
  – pH of body fluids depends on dissolved:
    • Acids
    • Bases
    • Salts
  – pH of ECF:
    • Is narrowly limited, usually 7.35 to 7.45
Acid–Base Balance

- **Acidosis**
  - Physiological state resulting from abnormally low plasma pH
  - Acidemia: plasma pH <7.35

- **Alkalosis**
  - Physiological state resulting from abnormally high plasma pH
  - Alkalemia: plasma pH >7.45
Acid–Base Balance

• Acidosis and Alkalosis
  – Affect all body systems:
    • Particularly nervous and cardiovascular systems
  – Both are dangerous:
    • But acidosis is more common
    • Because normal cellular activities generate acids
Acid–Base Balance

• Carbon Dioxide
  – In solution in peripheral tissues:
    • Interacts with water to form carbonic acid
  – Carbonic acid dissociates to release:
    • Hydrogen ions
    • Bicarbonate ions
• Carbonic Anhydrase (CA)
  – Enzyme that catalyzes dissociation of carbonic acid
  – Found in:
    • Cytoplasm of red blood cells
    • Liver and kidney cells
    • Parietal cells of stomach
    • Other cells
Acid–Base Balance

• \( \text{CO}_2 \) and \( \text{pH} \)
  – Most \( \text{CO}_2 \) in solution converts to carbonic acid:
    • Most carbonic acid dissociates
  – \( P_{\text{CO}_2} \) is the most important factor affecting \( \text{pH} \) in body tissues:
    • \( P_{\text{CO}_2} \) and \( \text{pH} \) are inversely related
Acid–Base Balance

• CO$_2$ and pH
  – When CO$_2$ levels rise:
    • H$^+$ and bicarbonate ions are released
    • pH goes down
  – At alveoli:
    • CO$_2$ diffuses into atmosphere
    • H$^+$ and bicarbonate ions in alveolar capillaries drop
    • Blood pH rises
Figure 18-14
Buffers and Buffer Systems

• **Buffers**
  – Are dissolved compounds that stabilize pH:
    • By providing or removing H⁺
  – Weak acids:
    • Can donate H⁺
  – Weak bases:
    • Can absorb H⁺
Buffers and Buffer Systems

• **Buffer System**
  – Consists of a combination of:
    • A weak acid
    • And the anion released by its dissociation
  – The anion functions as a weak base
  – In solution, molecules of weak acid exist in equilibrium with its dissociation products
Buffers and Buffer Systems

• Three Major Buffer Systems
  – Protein buffer systems:
    • Help regulate pH in ECF and ICF
    • Interact extensively with other buffer systems
  – Carbonic acid–bicarbonate buffer system:
    • Most important in ECF
  – Phosphate buffer system:
    • Buffers pH of ICF and urine
Buffers and Buffer Systems

• **Protein Buffer Systems**
  – Depend on amino acids
  – Respond to pH changes by accepting or releasing $H^+$
  – If pH rises:
    • Carboxyl group of amino acid dissociates
    • Acting as weak acid, releasing a hydrogen ion
    • Carboxyl group becomes carboxylate ion
• The Hemoglobin Buffer System
  – CO$_2$ diffuses across RBC membrane:
    • No transport mechanism required
  – As carbonic acid dissociates:
    • Bicarbonate ions diffuse into plasma
    • In exchange for chloride ions (chloride shift)
  – Hydrogen ions are buffered by hemoglobin molecules
Buffers and Buffer Systems

• The Hemoglobin Buffer System
  – Is the only intracellular buffer system with an immediate effect on ECF pH
  – Helps prevent major changes in pH when plasma $P_{CO_2}$ is rising or falling
Buffers and Buffer Systems

• Carbonic Acid–Bicarbonate Buffer System
  – Carbon dioxide:
    • Most body cells constantly generate carbon dioxide
    • Most carbon dioxide is converted to carbonic acid, which
dissociates into $\text{H}^+$ and a bicarbonate ion
  – Is formed by carbonic acid and its dissociation
    products
  – Prevents changes in pH caused by organic acids and
    fixed acids in ECF
Buffers and Buffer Systems

- **Carbonic Acid–Bicarbonate Buffer System**
  1. Cannot protect ECF from changes in pH that result from elevated or depressed levels of \( \text{CO}_2 \)
  2. Functions only when respiratory system and respiratory control centers are working normally
  3. Ability to buffer acids is limited by availability of bicarbonate ions
Buffers and Buffer Systems

• **Phosphate Buffer System**
  – Consists of anion $\text{H}_2\text{PO}_4^-$ (a weak acid)
  – Works like the carbonic acid–bicarbonate buffer system
  – Is important in buffering pH of ICF
Buffers and Buffer Systems

• Limitations of Buffer Systems
  – Provide only temporary solution to acid–base imbalance
  – Do not eliminate H\(^+\) ions
  – Have only a limited supply of buffer molecules
• For homeostasis to be preserved, captured $H^+$ must
  1. Be permanently tied up in water molecules:
     • Through CO$_2$ removal at lungs
  2. Be removed from body fluids:
     • Through secretion at kidney
Maintaining Acid–Base Balance

- Requires balancing H\(^+\) gains and losses
- Coordinates actions of buffer systems with
  - Respiratory mechanisms
  - Renal mechanisms
• Respiratory and Renal Mechanisms
  – Support buffer systems by:
    • Secreting or absorbing H⁺
    • Controlling excretion of acids and bases
    • Generating additional buffers
Maintaining Acid–Base Balance

• Respiratory Compensation
  – Is a change in respiratory rate:
    • That helps stabilize pH of ECF
  – Occurs whenever body pH moves outside normal limits
  – Directly affects carbonic acid–bicarbonate buffer system
• Respiratory Compensation
  
  – Increasing or decreasing the rate of respiration alters pH by lowering or raising the $P_{CO_2}$
  
  – When $P_{CO_2}$ rises:
    • pH falls
    • Addition of CO$_2$ drives buffer system to the right
  
  – When $P_{CO_2}$ falls:
    • pH rises
    • Removal of CO$_2$ drives buffer system to the left
Maintaining Acid–Base Balance

• Renal Compensation
  – Is a change in rates of $H^+$ and $HCO_3^-$ secretion or reabsorption by kidneys in response to changes in plasma pH
  – The body normally generates enough organic and fixed acids each day to add 100 mEq of $H^+$ to ECF
  – Kidneys assist lungs by eliminating any $CO_2$ that:
    • Enters renal tubules during filtration
    • Diffuses into tubular fluid en route to renal pelvis
Acid–Base Disorders

1. Disorders
   – Circulating buffers
   – Respiratory performance
   – Renal function

2. Cardiovascular conditions
   – Heart failure
   – Hypotension

3. Conditions affecting the CNS
   – Neural damage or disease that affects respiratory and cardiovascular reflexes
Acid–Base Disorders

• **Respiratory Acid–Base Disorders**
  – Result from imbalance between:
    • $\text{CO}_2$ generation in peripheral tissues
    • $\text{CO}_2$ excretion at lungs
  – Cause abnormal $\text{CO}_2$ levels in ECF
• **Metabolic Acid–Base Disorders**
  – Result from:
    • Generation of organic or fixed acids
    • Conditions affecting $\text{HCO}_3^-$ concentration in ECF
<table>
<thead>
<tr>
<th>DISORDER</th>
<th>PH (NORMAL = 7.35–7.45)</th>
<th>GENERAL CAUSES</th>
<th>TREATMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respiratory acidosis</td>
<td>Decreased (below 7.35)</td>
<td>Generally caused by hypoventilation and CO₂ buildup in tissues and blood</td>
<td>Improve ventilation—in some cases, with bronchodilation and mechanical assistance</td>
</tr>
<tr>
<td>Metabolic acidosis</td>
<td>Decreased (below 7.35)</td>
<td>Caused by buildup of metabolic acid, impaired H⁺ excretion at kidneys, or bicarbonate loss in urine or feces</td>
<td>Administration of bicarbonate (gradual) with other steps as needed to correct primary cause</td>
</tr>
<tr>
<td>Respiratory alkalosis</td>
<td>Increased (above 7.45)</td>
<td>Generally caused by hyperventilation and reduction in plasma CO₂ levels</td>
<td>Reduce respiratory rate, allow rise in P CO₂</td>
</tr>
<tr>
<td>Metabolic alkalosis</td>
<td>Increased (above 7.45)</td>
<td>Usually caused by prolonged vomiting and associated acid loss</td>
<td>For pH below 7.55, no treatment; pH above 7.55 may require administration of ammonium chloride</td>
</tr>
</tbody>
</table>
18-9 Age-related changes affect kidney function and the micturition reflex
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 disease, and other CNS problems
  – In males, urinary retention may develop if enlarged prostate gland compresses the urethra and restricts urine flow
Age-Related Changes

• A gradual decrease of total body water content with age
• A net loss in body mineral content in many people over age 60 as muscle mass and skeletal mass decrease
• Increased incidence of disorders affecting major systems with increasing age
18-10 The urinary system is one of several body systems involved in waste excretion
Excretion

• Integument
  – Sweat
• Respiration
  – Carbon dioxide
• Digestive
  – Feces
The Urinary System in Perspective

FIGURE 18-15
Functional Relationships Between the Urinary System and Other Systems
The Integumentary System assists in elimination of water and solutes, especially sodium and chloride ions, with sweat glands; keratinized epidermis prevents excessive fluid loss through skin surface; epidermis produces vitamin D$_3$, important for the renal production of calcitriol.
The Skeletal System provides some protection for kidneys and ureters; pelvis protects urinary bladder and proximal portion of urethra.

The Urinary System conserves calcium and phosphate needed for bone growth.
The Nervous System adjusts renal blood pressure; monitors distension of urinary bladder and controls urination.
The Endocrine System’s hormones aldosterone and ADH adjust rates of fluid and electrolyte reabsorption in kidneys.

The Urinary System releases renin when local blood pressure declines, and erythropoietin (EPO) when renal oxygen levels decline.
The Cardiovascular System delivers blood to capillaries, where filtration occurs; accepts fluids and solutes reabsorbed during urine production.

The Urinary System releases renin to elevate blood pressure and erythropoietin (EPO) to accelerate red blood cell production.
The Lymphoid System provides specific defenses against urinary tract infections

The Urinary System eliminates toxins and wastes generated by cellular activities; acid pH of urine provides nonspecific defense against urinary tract infections
The Respiratory System assists in the regulation of pH by eliminating carbon dioxide.

The Urinary System assists in the elimination of carbon dioxide; provides bicarbonate buffers that assist in pH regulation.
The Digestive System absorbs water needed to excrete wastes at kidneys; absorbs ions needed to maintain normal body fluid concentrations; liver removes bilirubin.

The Urinary System excretes toxins absorbed by the digestive tract; excretes bilirubin and nitrogenous wastes produced by the liver; calcitrol production by kidneys aids calcium and phosphate absorption along digestive tract.
The Muscular System provides some protection for urinary organs with muscle layers of the trunk; sphincter muscles close the urethral opening.

The Urinary System removes waste products of protein metabolism; assists in regulation of calcium and phosphate.
The Reproductive System’s secretions by male accessory organs may have antibacterial action that prevents urethral infections.

The Urinary System carries semen in the male urethra.