CHAPTER 18

The Urinary System
Chapter 18 Learning Outcomes

• 18-1
  • Identify the components of the urinary system, and describe the system's three primary functions.

• 18-2
  • Describe the locations and structural features of the kidneys, trace the path of blood flow to, within, and from a kidney, and describe the structure of the nephron.

• 18-3
  • Discuss the major functions of each portion of the nephron, and outline the processes involved in urine formation.

• 18-4
  • Describe the factors that influence glomerular filtration pressure and the glomerular filtration rate (GFR).
Chapter 18 Learning Outcomes

• 18-5
  • Describe the structures and functions of the ureters, urinary bladder, and urethra, discuss the control of urination, and describe the micturition reflex.

• 18-6
  • Define the terms fluid balance, electrolyte balance, and acid-base balance, discuss their importance for homeostasis, and describe how water and electrolytes are distributed within the body.

• 18-7
  • Explain the basic mechanisms involved in maintaining fluid balance and electrolyte balance.
Chapter 18 Learning Outcomes

- 18-8
  - Explain the buffering systems that balance the pH of the intracellular and extracellular fluids, and identify the most common threats to acid-base balance.

- 18-9
  - Describe the effects of aging on the urinary system.

- 18-10
  - Give examples of interactions between the urinary system and other body systems.
The Urinary System Structures (18-1)

- Two kidneys
  - Produce urine that flows through:
    - Urinary tract
      - Two ureters
      - Urinary bladder
      - Urethra
  - Elimination of urine is urination or micturition
Figure 18-1 The Components of the Urinary System.

- **Kidney**: Produces urine
- **Ureter**: Transports urine toward the urinary bladder
- **Urinary bladder**: Temporarily stores urine prior to elimination
- **Urethra**: Conducts urine to exterior; in males, transports semen as well
Three General Functions of the Urinary System (18-1)

1. *Excretion of organic wastes*

2. *Elimination* of these wastes into the external environment

3. Regulation of blood plasma volume and solute concentration
Homeostatic Functions of the Urinary System (18-1)

- Regulate blood volume and blood pressure
- Regulate plasma ions, such as sodium, potassium, chloride, and calcium
- Aid in stabilization of plasma pH
- Conserve valuable nutrients like glucose and amino acids
- Eliminate wastes like urea and uric acid
1. Name the three primary functions of the urinary system.

2. Identify the components of the urinary system.

3. Define micturition.
Location of the Kidneys (18-2)

- Either side of vertebral column
  - Between last thoracic and 3rd lumbar vertebrae
  - Right is often lower than left
- Retroperitoneal but supported by connective tissue
  - Fibrous capsule covers each kidney
  - Capsule surrounded by adipose tissue
This posterior view of the trunk shows the positions of the kidneys and other components of the urinary system.
A superior view of a section at the level indicated in part (a) shows the kidney’s retroperitoneal position.
Superficial Anatomy of the Kidney (18-2)

- Kidneys are bean shaped
  - Indentation on one side is the **hilum**
    - Exit for ureter and renal vein
    - Entrance for renal artery
  
- **Fibrous capsule**
  - Covers outer surface
  - Lines *renal sinus*, an internal cavity
Sectional Anatomy of the Kidney (18-2)

- **Renal cortex** is outer layer
  - Projects into medulla as renal columns

- **Renal medulla** is inner layer
  - Contains 6–18 cone-shaped **renal pyramids**
  - Tip is called **renal papilla** and projects into renal pelvis

- **Renal lobe**
  - Contains pyramid, overlying cortex and renal columns
Sectional Anatomy of the Kidney (18-2)

- Urine production occurs in **nephrons** of cortex and pyramids of medulla
- Ducts drain urine into a cup-like structure called the **minor calyx**
- 4–5 minor calyces empty into **major calyx**
- Major calyces combine to form the **renal pelvis**
- **Nephron**, functional unit of kidneys in cortex
Figure 18-3 The Structure of the Kidney.

- Renal corpuscle
- Proximal convoluted tubule
- Distal convoluted tubule
- Collecting duct

A diagrammatic view of a frontal section through the left kidney

- Renal cortex
- Renal medulla
- Renal sinus
- Hilum
- Renal pelvis
- Renal papilla
- Ureter

An enlarged view showing the location and general structure of a nephron

- Major calyx
- Minor calyx
- Renal pyramid
- Renal lobe
- Renal columns
- Fibrous capsule

A frontal section through the left kidney

- Renal cortex
- Renal medulla
- Renal pyramids
- Renal sinus
- Major calyx
- Renal pelvis
- Minor calyx
- Renal papilla

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Blood Supply to the Kidney (18-2)

- Kidneys receive 20–25 percent of cardiac output
- Blood flow starts with **renal artery**
  - ➔ Interlobar artery
  - ➔ **Arcuate artery** (along cortex-medulla boundary)
  - ➔ Cortical radiate artery
  - ➔ Afferent arterioles
  - ➔ Glomerular capillaries
  - ➔ Efferent arterioles
  - ➔ Peritubular capillaries
  - ➔ Cortical radiate vein
  - ➔ Arcuate vein
  - ➔ Interlobar vein
  - ➔ Extends kidney **renal vein**
Blood Supply to the Kidney (18-2)

- Peritubular capillaries follow two possible paths
  1. In cortical nephrons:
     - Blood flows into peritubular capillaries surrounding nephron tubules within the cortex
  2. In juxtamedullary nephrons:
     - Peritubular capillaries flow into vasa recta
     - Vasa recta runs parallel to long nephron loops deep into the medulla
This sectional view of a kidney shows the major arteries and veins; compare with Figure 18-3a.
This enlarged view illustrates the circulation in the cortex.
Further enlargement shows the circulation to a cortical nephron.
Further enlargement shows the circulation to a juxtamedullary nephron.
The Nephron (18-2)

- **Renal corpuscle**
  - *Glomerular (Bowman's) capsule* surrounds glomerular capillaries
  - Filtration occurs from capillaries to capsule

- **Renal tubule**
  - Filtrate flows into *proximal convoluted tubule (PCT)*
  - ➔ *Nephron loop*
  - ➔ *Distal convoluted tubule (DCT)*
  - ➔ *Collecting duct*
  - ➔ *Collecting system*
Functions of the Nephron (18-2)

- **Corpuscle**
  - Filters plasma (minus proteins) into capsule
  - Includes valuable nutrients, ions, and water

- **Tubules**
  1. Reabsorb useful molecules and ions from filtrate back into plasma
  2. Reabsorb >90 percent of water back into plasma
  3. Secrete any wastes missed by filtration
Figure 18-5  A Representative Nephron and the Collecting System.

**NEPHRON**

- Proximal convoluted tubule
- Distal convoluted tubule
- Renal tubule
- Glomerulus
- Efferent arteriole
- Afferent arteriole
- Renal corpuscle
- Nephron loop
- Loop begins
- Loop ends
- Thin descending limb
- Thick ascending limb
- Descending limb
- Ascending limb

**COLLECTING SYSTEM**

- Collecting duct
- Papillary duct
- Minor calyx
- Collecting duct

**KEY**

- Filtrate
- Water reabsorption
- Variable water reabsorption
- Solute reabsorption or secretion
- Variable solute reabsorption or secretion
Renal Corpuscle Contains Filtration Membrane (18-2)

- **Glomerular capsule**
  - Outer layer forms wall of corpuscle
  - Inner layer encloses glomerular capillaries
- **Podocytes**
  - Epithelial cells have foot processes that sit on basement membrane and wrap around capillaries
- Layers separated by *capsular space*
- **Glomerular capillaries**
  - Highly fenestrated or leaky pores in endothelial cells
Figure 18-6 The Renal Corpuscle.

This sectional view illustrates the important structural features of a renal corpuscle.

This cross section through a segment of the glomerulus shows the components of the filtration membrane of the nephron.

This colorized photomicrograph shows the glomerular surface, including individual podocytes and their processes.
This sectional view illustrates the important structural features of a renal corpuscle.
This cross section through a segment of the glomerulus shows the components of the filtration membrane of the nephron.
This colorized photomicrograph shows the glomerular surface, including individual podocytes and their processes.
The Proximal Convoluted Tubule (18-2)

- First segment of renal tubule
- Majority of reabsorption occurs here
  - Epithelium has transport mechanisms for nutrients and ions
  - Molecules are moved from tubule to IF
  - Water follows osmotically
The Nephron Loop (18-2)

- Fluid in descending limb flows toward renal pelvis
  - Epithelium permeable to water, not solutes
- Tubule makes 180-degree turn
- Fluid in ascending limb flows toward renal cortex
  - Epithelium permeable to solutes, not water
- IF of renal medulla has unusually high solute concentration
The Distal Convoluted Tubule (18-2)

- Has three vital processes
  1. Active secretion of ions, acids, drugs, and toxins
  2. Selective reabsorption of sodium
  3. Selective reabsorption of water
The Juxtaglomerular Complex (18-2)

- Macula densa
  - Epithelial cells of DCT
  - Sit next to afferent arterioles
- Juxtaglomerular cells
  - Smooth muscle cells of afferent arterioles
- Together regulate blood volume and pressure
  - Affected by secretion of erythropoietin and renin
The Collecting System (18-2)

• Many DCTs empty into one **collecting duct**
• Several collecting ducts merge into papillary duct
• Papillary duct empties into minor calyx

• **Functions**
  • Adjusts final filtrate composition
  • Determines final osmotic concentration
  • Determines final volume of urine
Table 18-1 The Functions of the Nephron and Collecting System in the Kidney.

<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; assists in creating the concentration gradient in the renal medulla, enabling the kidney to produce concentrated urine</td>
</tr>
<tr>
<td>Distal convoluted tubule (DCT)</td>
<td>Reabsorption of water and sodium ions; secretion of acids, ammonia, and drugs</td>
</tr>
<tr>
<td>Collecting duct</td>
<td>Reabsorption of water; reabsorption or secretion of sodium, potassium, bicarbonate, and hydrogen ions</td>
</tr>
<tr>
<td>Papillary duct</td>
<td>Conduction of urine to minor calyx</td>
</tr>
</tbody>
</table>
4. How does the position of the kidneys differ from that of most other organs in the abdominal region?

5. Why don't plasma proteins pass into the capsular space of the renal corpuscle under normal circumstances?

6. Damage to which part of the nephron would interfere with the control of blood pressure?
Metabolic Wastes in Urine (18-3)

- Must be excreted to maintain homeostasis
  1. Urea
     - From amino acid breakdown
  2. Creatinine
     - From breakdown of high-energy compound: creatinine phosphate in skeletal muscles
  3. Uric acid
     - From breakdown of RNA
Three Nephron Processes (18-3)

1. Filtration
   - Movement of water and solutes across filtration membrane
   - Occurs exclusively in renal corpuscle

2. Reabsorption
   - Returning water and desirable solutes back to body
   - Occurs primarily at PCT
Three Nephron Processes (18-3)

3. **Secretion**

- Transport of undesirable material missed by filtration
- Occurs primarily at DCT
- **Water, sodium, potassium**
  - Regulated by interaction between nephron loop and collecting duct

**ANIMATION Kidney Function: Reabsorption and Secretion**
Figure 18-7  Physiological Processes of the Nephron.

- **Filtration**: Blood pressure drives filtration through the glomerular capillary, creating filtrate in the capsular space.
- **Reabsorption**: Solute is reabsorbed from the tubular fluid back into the peritubular fluid by transport proteins in the tubular epithelium.
- **Secretion**: Solute is secreted from the peritubular fluid into the tubular fluid by transport proteins in the tubular epithelium.
Table 18-2 Normal Laboratory Values for Solutes in Urine and Plasma

<table>
<thead>
<tr>
<th>Component</th>
<th>Urine</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>IONS (mEq/L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium (Na(^+))</td>
<td>40–220</td>
<td>135–145</td>
</tr>
<tr>
<td>Potassium (K(^+))</td>
<td>25–100</td>
<td>3.5</td>
</tr>
<tr>
<td>Chloride (Cl(^-))</td>
<td>110–250</td>
<td>100–108</td>
</tr>
<tr>
<td>Bicarbonate (HCO(_3)^+)</td>
<td>1–9</td>
<td>20–28</td>
</tr>
</tbody>
</table>

**METABOLITES AND NUTRIENTS (mg/dL)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Urine</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>0.009</td>
<td>70–110</td>
</tr>
<tr>
<td>Lipids</td>
<td>0.002</td>
<td>450–1000</td>
</tr>
<tr>
<td>Amino acids</td>
<td>0.188</td>
<td>40</td>
</tr>
<tr>
<td>Proteins</td>
<td>0.000</td>
<td>6000–8000</td>
</tr>
</tbody>
</table>

**NITROGENOUS WASTES (mg/dL)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Urine</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>1800</td>
<td>8–25</td>
</tr>
<tr>
<td>Creatinine</td>
<td>150</td>
<td>0.6–1.5</td>
</tr>
<tr>
<td>Ammonia</td>
<td>60</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Uric acid</td>
<td>40</td>
<td>2–6</td>
</tr>
</tbody>
</table>
Net Filtration Pressure (18-3)

• Filtration
  • Result of outward blood pressure, inward blood osmotic pressure, and inward fluid pressure from the capsule

• Glomerular BP
  • Must stay high enough to overcome other two forces

• Serious loss of systemic BP can result in:
  • Loss of filtration, reduction in kidney function
Glomerular Filtration Rate (18-3)

• **GFR**

• Amount of filtrate produced by kidneys/minute
  - Average is 125 mL/min or 180 L/day
  - 99 percent reabsorbed in renal tubules

• **Dependent on:**
  - Maintaining adequate blood flow to kidney
  - Maintaining adequate net filtration pressures
Events at the Proximal Convoluted Tubule (18-3)

• 60–70 percent of filtrate volume is reabsorbed at PCT

• All glucose, amino acids, and other organic nutrients are reabsorbed

• Ionic reabsorption of Na\(^+\), K\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), HCO\(_3\)^–
  • Some are hormonally regulated, like Ca\(^{2+}\) by PTH

• Some secretion occurs here, like H\(^+\)
Events at the Nephron Loop (18-3)

- Filtrate entering loop already has water and solutes removed.
- Nephron loop removes 50 percent of remaining water and 66 percent of remaining sodium and chloride ions.
- Ascending loop actively pumps solutes into IF:
  - Impermeable to water.
  - Creates osmotic gradient.
- Descending loop permeable to water only.
Events at the Nephron Loop (18-3)

• As filtrate moves down the descending loop:
  • Loses water to IF
  • Becomes higher in osmotic concentration

• As filtrate moves up ascending loop:
  • Pumps solutes to IF
  • Becomes lower in osmotic concentration

• What remains are primarily waste products
Events at the Distal Convoluted Tubule (18-3)

- 80 percent of water and 85 percent of solutes have been reabsorbed

- Final adjustments to:
  - Sodium reabsorption
    - Increases in the presence of aldosterone
  - Water reabsorption
    - Increases in the presence of ADH
    - Serves to concentrate filtrate as it passes through collecting duct
The DCT and collecting duct are impermeable to water in the absence of ADH. The result is the production of a large volume of dilute urine.

The DCT and collecting duct are permeable to water in the presence of ADH. The result is the production of a small volume of concentrated urine.

**KEY**
- \( \uparrow \) = Water reabsorption
- \( \downarrow \) = Variable water reabsorption
- \( \downarrow \) = \( \text{Na}^+ / \text{Cl}^- \) transport
- \( \downarrow \) = Antidiuretic hormone (ADH)
Properties of Normal Urine (18-3)

- Once filtrate enters the minor calyx:
  - No other secretion or reabsorption can occur
  - Fluid is now called urine
  - *Concentration* and *composition* vary based on metabolic and hormonal activities
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 ≈ 5 mOsm/L, body fluids ≈ 300 mOsm/L and seawater ≈ 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>
The filtrate produced at the renal corpuscle has the same osmotic concentration as plasma. It has the same composition as blood plasma but does not contain plasma proteins.

In the proximal convoluted tubule (PCT), the active removal of ions and organic nutrients produces a continuous osmotic flow of water out of the tubular fluid. This reduces the volume of filtrate but keeps the solute concentration the same inside and outside the tubule.

Further alterations in the composition of the tubular fluid occur in the DCT and the collecting system. The solute concentration of the tubular fluid can be adjusted through active transport (reabsorption or secretion).

The vasa recta absorbs the solutes and water reabsorbed by the nephron loop and the collecting ducts. By transporting these solutes and water into the bloodstream, the vasa recta maintains the concentration gradient of the renal medulla.
7. A decrease in blood pressure would have what effect on the GFR?

8. If nephrons lacked a nephron loop, what would be the effect on the volume and solute (osmotic) concentration of the urine produced?

9. What effect would low circulating levels of antidiuretic hormone (ADH) have on urine production?
GFR Is Key to Normal Kidney Function (18-4)

• Maintaining net filtration pressure and consistent GFR is necessary for normal kidney function

• GFR is controlled by three mechanisms

  1. *Autoregulation* (or local regulation)
  2. Hormonal regulation
  3. Autonomic regulation
     • Through sympathetic division of ANS
Local Regulation of Kidney Function (18-4)

- Autoregulation of diameters of afferent and efferent arterioles
  - Quick, short-term adjustment of GFR
    - Decrease in GFR triggers:
      - Dilation of afferent arteriole
      - Constriction of efferent arteriole
      - Brings glomerular blood pressure up
      - Increases GFR back to normal
Local Regulation of Kidney Function (18-4)

- Increase in BP causes increase in GFR
- Increase in GFR triggers:
  - Stretch of wall of afferent arteriole
  - Smooth muscle responds by contracting
  - Reduces afferent arteriolar diameter
  - Reduces flow into glomerulus
  - Decreases GFR back to normal
Hormonal Control of Kidney Function (18-4)

• Long-term adjustment of blood pressure and volume stabilizes GFR

• Major hormones
  • Angiotensin II
  • ADH
  • Aldosterone
  • ANP
Renin-Angiotensin System (18-4)

• Decrease in BP, blood volume causes:
  • Release of renin from JGC, which converts angiotensinogen into angiotensin I
  • ACE converts angiotensin I into angiotensin II
    • Causes peripheral vasoconstriction, increases BP
    • Efferent arteriole constriction, increase in GFR
    • Posterior pituitary releases ADH
    • Adrenal glands secrete aldosterone, E, and NE
  • Result is increase in BP and blood volume
Figure 18-10 The Renin-Angiotensin System and Regulation of GFR.

Renin–Angiotensin System

- **Endocrine response**
  - Juxtaglomerular complex increases production of renin.

- **Renin**
  - In the bloodstream triggers formation of angiotensin I, which is then activated to angiotensin II by angiotensin converting enzyme (ACE) in the capillaries of the lungs.

- **Angiotensin II**
  - Triggers increased aldosterone secretion by the adrenal glands.
  - Constricts peripheral arterioles and further constricts the efferent arterioles.

- **Aldosterone**
  - Increases Na^+ retention.

- **Increased fluid consumption**

- **Increased fluid retention**

- **Constriction of venous reservoirs**

- **Increased cardiac output**

- **Increased sympathetic activation**

- **Together, angiotensin II and sympathetic activation stimulate peripheral vasoconstriction.**

**HOMEOSTASIS DISTURBED**
- Decreased blood flow to kidneys

**HOMEOSTASIS RESTORED**
- Normal glomerular filtration rate

**HOMEOSTASIS**
Antidiuretic Hormone (18-4)

- ADH

- Release stimulated by:
  - Angiotensin II
  - Drop in BP
  - Increase in plasma solute concentration

- Results in:
  - Increased water permeability at DCT and collecting duct
  - Stimulates thirst center in hypothalamus
Aldosterone (18-4)

• Release stimulated by:
  • Angiotensin II
  • Increase in K\(^+\) concentration in plasma

• Results in:
  • Reabsorption of Na\(^+\)
  • Secretion of K\(^+\)
  • Occurs at DCT and collecting ducts
Atrial Natriuretic Peptide (18-4)

- ANP

- Release stimulated by:
  - Rise in BP and blood volume in atria of heart

- Results in:
  - Inhibition of renin, aldosterone, ADH
  - Opposite of renin-angiotensin system
  - Decrease in sodium reabsorption
  - Dilation of glomerular capillaries, increasing GFR
Sympathetic Activation (18-4)

• Direct, sudden effect of acute crisis
  • Constriction of afferent arterioles
  • Decreases GFR
  • Can override local effects to stabilize GFR

• Indirect effect
  • Shunts blood away from kidneys to perfuse tissues and organs with higher needs
  • Problematic in strenuous exercise
10. List the factors that affect the glomerular filtration rate (GFR).

11. What effect would increased aldosterone secretion have on the $K^+$ concentration in urine?

12. What is the effect of sympathetic activation on kidney function?
The Ureters (18-5)

- Paired muscular tubes conduct urine to bladder
  - Begins at funnel-shaped renal pelvis
  - Ends at posterior, slightly inferior bladder wall
  - Slitlike ureteral openings prevent backflow

- Wall contains:
  - Transitional epithelium
  - Smooth muscle that undergoes peristalsis
The Urinary Bladder (18-5)

- Hollow muscular organ that stores urine
  - Base has triangular area called trigone, formed by:
    - Two ureteral openings
    - Urethral entrance
    - Contains involuntary internal urethral sphincter
- Wall contains:
  - Transitional epithelium
  - Layers of smooth muscle called detrusor muscle
The Urethra (18-5)

- Extends from *neck* of urinary bladder to exterior of body through:
  - **External urethral orifice**
- Passes through pelvic floor
  - **External urethral sphincter** voluntary, skeletal muscle
- In males, passes through penis
- In females it is very short, anterior to vagina
Figure 18-11a Organs for the Conduction and Storage of Urine.

- Peritoneum
- Urinary bladder
- Pubic symphysis
- Prostate gland
- External urethral sphincter
- Urethra
- Left ureter
- Rectum
- External urethral orifice

Male
Figure 18-11b Organs for the Conduction and Storage of Urine.

- Rectum
- Right ureter
- Uterus
- Peritoneum
- Urinary bladder
- Pubic symphysis
- Vagina
- Urethra
- External urethral sphincter
- Female
Figure 18-11c Organs for the Conduction and Storage of Urine.

- Ureter
- Ligaments
- Detrusor muscle
- Ureteral openings
- Trigone
- Internal urethral sphincter
- External urethral sphincter
- Neck
- Prostate gland
- Urethra

Urinary bladder in male
The Micturition Reflex and Urination (18-5)

- Reflex pathway
  - Increased urine volume triggers stretch receptors in wall
  - Activates afferent fibers to sacral spinal cord
  - Activates parasympathetic pathway back to bladder wall
  - Activates interneurons relaying information to CNS

- Contraction
  - Elevates pressure, forces internal sphincter to open
Figure 18-12 The Micturition Reflex.

If convenient, the individual voluntarily relaxes the external urethral sphincter.

The afferent fibers stimulate neurons involved with:
- a local pathway,
- and a central pathway

Projection fibers from thalamus, deliver sensation to the cerebral cortex.

An interneuron relays sensation to the thalamus.

Parasympathetic preganglionic motor fibers in pelvic nerves.

Postganglionic neurons in Intramural ganglia stimulate detrusor muscle contraction.

Voluntary relaxation of the external urethral sphincter causes relaxation of the internal urethral sphincter.

Urination occurs
13. What is responsible for the movement of urine from the kidneys to the urinary bladder?

14. An obstruction of a ureter by a kidney stone would interfere with the flow of urine between what two structures?

15. Control of the micturition reflex depends on the ability to control which muscle?
Fluid, Electrolyte, and pH Balance (18-6)

• Topic integrates information from multiple chapters
• Key to proper treatment of multiple diseases and conditions
  • Water balance is essential to maintain enzyme function
  • Electrolyte balance is essential to maintain excitable tissue function
  • pH balance is essential to maintain normal chemical reactions, cell structure, and function
Three Interrelated Factors in Homeostasis (18-6)

• For balance of all factors, intake must equal output

1. Fluid balance
   • Movement between ECF and ICF driven by osmosis

2. Electrolyte balance
   • Creates osmotic gradients

3. Acid-base balance
   • H⁺ ion balance establishes normal pH
Basics of Body Fluid Compartments (18-6)

• Water is 50–60 percent of body weight

• Fluid compartments
  • Intercellular fluid (ICF)
  • Extracellular fluid (ECF)
Intracellular Fluid (18-6)

• Is largest compartment
  • 27 percent of total in adult females, 33 percent in males
  • Contains high $\text{K}^+$, $\text{Mg}^{2+}$, $\text{HPO}_4^{2-}$
  • Also contains a lot of negatively charged proteins
    • Exerts primary osmotic pressure
Extracellular Fluid (18-6)

- Major subdivisions
  - Plasma 4.5 percent of total in males and females
  - Interstitial fluid (IF) 18 percent in females, 21.5 percent in males
  - Contains high Na\(^+\), Cl\(^-\), HCO\(_3\)^-
  - Plasma has proteins
    - Exert osmotic pressure
  - IF has few proteins
The body composition (by weight, averaged for both sexes) and major body fluid compartments of a 70-kg individual. For technical reasons, it is extremely difficult to determine the precise size of any of these compartments; estimates of their relative sizes vary widely.
The Composition of the Human Body.

**Adult males**
- Intracellular fluid (ICF): 33%
- Interstitial fluid (ECF): 21.5%
- Plasma: 4.5%
- Solids: 40% (organic and inorganic materials)
- Other body fluids: ≤1%

**Adult females**
- Intracellular fluid (ICF): 27%
- Interstitial fluid (ECF): 18%
- Plasma: 4.5%
- Solids: 50% (organic and inorganic materials)
- Other body fluids: ≤1%

A comparison of the body compositions of adult males and females, ages 18–40 years.
Figure 18-14 Ions in Body Fluids.

**INTRACELLULAR FLUID**
- **Cations:** Na⁺, K⁺, Mg²⁺
- **Anions:** HCO₃⁻, Cl⁻, SO₄²⁻, PO₄³⁻, Proteins

**PLASMA**
- **Cations:** Na⁺, K⁺, Ca²⁺
- **Anions:** Cl⁻, HCO₃⁻, PO₄³⁻, SO₄²⁻, Org. acid

**INTERSTITIAL FLUID**
- **Cations:** Na⁺, K⁺, Ca²⁺
- **Anions:** Cl⁻, HCO₃⁻, PO₄³⁻, SO₄²⁻, Org. acid

**KEY**
- Cations: Na⁺, K⁺, Ca²⁺, Mg²⁺
- Anions: HCO₃⁻, Cl⁻, SO₄²⁻, PO₄³⁻, Org. acid, Proteins

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16. Identify the three interrelated processes essential to stabilizing body fluid volumes.

17. List the major component(s) of the intracellular fluid (ICF) and the extracellular fluid (ECF).
Fluid Balance (18-7)

- Water moves continuously
  - Across capillary endothelium, serous membranes, synovial membranes, CSF, eye humors, peri- and endolymph of inner ear
- 2.5 L/day lost insensibly and sensibly
- Gains are 40 percent from food, 48 percent drink, 12 percent metabolic generation
**Table 18-4 Water Balance**

<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><strong>Total</strong></td>
<td><strong>2500</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method of Elimination</th>
<th>Daily Output (mL)</th>
</tr>
</thead>
<tbody>
<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><strong>Total</strong></td>
<td><strong>2500</strong></td>
</tr>
</tbody>
</table>
Fluid Shifts (18-7)

- Water movement between ECF and ICF
- Occurs due to changes in osmotic concentration (osmolarity) of ECF
  - If ECF osmolarity increases, water leaves cells
  - If ECF osmolarity decreases, water moves into cells
- Movement progresses until equilibrium reached
Electrolyte Balance (18-7)

• Loss of balance results in:
  • Loss of water balance
  • Loss of cell function
    • $\text{Ca}^{2+}$ and $\text{K}^{+}$ imbalances affect cardiac muscle tissue
    • $\text{Na}^{+}$ and $\text{K}^{+}$ major contributors to osmolarity of ICF and ECF
Sodium Balance (18-7)

• Created between $\text{Na}^+$ absorption from gut and excretion by kidneys
  • Regulated by aldosterone and ANP

• Excess dietary salt results in additional water absorption from gut, raising blood volume and BP

• Imbalance of $\text{Na}^+$ is most common cause of electrolyte imbalances
Potassium Balance (18-7)

- Most K\(^+\) is in cells
- ECF low K\(^+\) content a balance between absorption from gut and excretion by kidneys
  - Regulated by aldosterone
- Problems with K\(^+\) balance less common, but much more dangerous
  - Disrupts membrane potentials in excitable tissues
18. Define a fluid shift.

19. How would eating a meal high in salt content affect the amount of fluid in the intracellular fluid compartment (ICF)?

20. What effect would being in the desert without water for a day have on your blood osmotic concentration?
Acid-Base Balance (18-8)

• Normal ECF pH range 7.35–7.45
  • Imbalances result in:
    • Unstable cell membranes
    • Denaturation of proteins, including enzymes
    • CNS, cardiac tissue fail
    • Vasodilation results in drop of BP
  • Below 7.35 is acidosis
  • Above 7.45 is alkalosis
Acids in the Body (18-8)

- Carbonic acid (H$_2$CO$_3$) most abundant, but dissociates in reversible reaction

\[
\text{carbonic anhydrase}
\]

\[
\begin{align*}
\text{CO}_2 + \text{H}_2\text{O} & \rightleftharpoons \text{H}_2\text{CO}_3 \\
\text{carbon dioxide} & \text{water} & \text{carbonic acid} \\
& & \text{hydrogen ion} & \text{bicarbonate ion}
\end{align*}
\]

- CO$_2$ and H$^+$ concentrations are proportional
- P$_{CO2}$ and pH are inversely proportional

- Other metabolic sources of acids
  - Lactic acid, ketoacids
When carbon dioxide levels rise, more carbonic acid forms, additional hydrogen ions and bicarbonate ions are released, and the pH goes down.

When carbon dioxide levels fall, carbonic acid dissociates into carbon dioxide and water. This removes H+ ions from solution and increases the pH.
Buffers (18-8)

- Weak acids donate $H^+$; weak bases absorb $H^+$

- **Buffer system**
  - Combination of $H^+$ and an anion

- Three key buffer systems
  1. Protein buffer systems
  2. Carbonic acid–bicarbonate buffer system
  3. Phosphate buffer system
Protein Buffer Systems (18-8)

• Regulate pH in ICF and ECF

• If pH rises:
  • —COOH group acts as weak acid
    • Dissociates from amino acid and releases a H⁺

• If pH drops:
  • —NH₂ group acts as weak base
    • Picks up a free H⁺
Carbonic Acid–Bicarbonate Buffer System (18-8)

- Regulates pH in ECF

- \[\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{HCO}_3^-\]

- Metabolic acids release \(\text{H}^+\), lowering pH
  - Is picked up by \(\text{HCO}_3^-\) and drives above formula to left
  - \(\text{P}_{\text{CO}_2}\) rises, respiratory system excretes \(\text{CO}_2\)
  - pH rises
    - Formula is driven to the right
Phosphate Buffer System (18-8)

- Primary buffer system of ICF

\[ \text{H}_2\text{PO}_4^- \rightleftharpoons \text{H}^+ + \text{HPO}_4^{2-} \]

dihydrogen phosphate \hspace{1cm} hydrogen ion \hspace{1cm} monohydrogen phosphate
Maintaining Acid-Base Balance (18-8)

- Buffer systems can tie up excess $H^+$
  - Temporary and limited
- Respiratory and renal mechanisms contribute
  - Secrete or absorb $H^+$
  - Control excretion of acids and bases
  - Generate additional buffers
Respiratory Compensation of pH (18-8)

- Accomplished by altering respiration rate
  - Low $P_{CO_2}$ results in rise in pH
    - Respiration is suppressed
    - Carbonic acid formula driven to right, conserving $CO_2$
    - Lowers pH
  - High $P_{CO_2}$ results in lower pH
    - Respiration is stimulated
    - Carbonic acid formula driven to left, blowing off $CO_2$
    - Raises pH
Renal Compensation of pH (18-8)

• Only way to truly eliminate H⁺

• Tubules can:
  • Conserve H⁺ and eliminate HCO₃⁻ when pH is high
  • Eliminate H⁺ and conserve HCO₃⁻ when pH is low
Acid-Base Disorders (18-8)

- Respiratory disorders
  - Caused by changes in CO$_2$ in ECF

- Metabolic disorders
  - Caused by overproduction of acids
  - Alteration in HCO$_3^-$ concentrations
<table>
<thead>
<tr>
<th>Disorder</th>
<th>pH (normal)</th>
<th>Remarks</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Respiratory acidosis</strong></td>
<td>Decreased</td>
<td>Most common acid-base disorder; 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></td>
<td>(below 7.35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Metabolic acidosis</strong></td>
<td>Decreased</td>
<td>Second most common acid-base disorder; 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></td>
<td>(below 7.35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Respiratory alkalosis</strong></td>
<td>Increased</td>
<td>Relatively uncommon acid-base disorder; generally caused by hyperventilation and reduction in plasma CO₂ levels</td>
<td>Reduce respiratory rate, allow rise in P\text{CO}_2</td>
</tr>
<tr>
<td></td>
<td>(above 7.45)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Metabolic alkalosis</strong></td>
<td>Increased</td>
<td>Severe cases relatively rare; 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>
<tr>
<td></td>
<td>(above 7.45)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
21. Identify the body's three major buffer systems.

22. What effect would a decrease in the pH of body fluids have on the respiratory rate?

23. How would a prolonged fast affect the body's pH?
Age-Related Changes in the Renal System (18-9)

1. Decline in number of functional nephrons

2. Reduction in GFR

3. Reduction in sensitivity to ADH and aldosterone

4. Problems with micturition reflex
   - Sphincters weaken
   - CNS loss of control over sphincters
   - Prostate enlargement in males restricts urine flow
Age-Related Changes in the Renal System (18-9)

5. Gradual decrease in total body water content

6. Net loss of body mineral content

7. Increase incidence of disorders in other systems impacting fluid, electrolyte, and pH balance
24. What effect does aging have on the GFR?
25. After age 40, does total body water content increase or decrease?
The renal system excretes wastes but so do other systems

- Integumentary system through sweat
- Respiratory system removes CO$_2$
- Digestive system through excretion of bile
Figure 18-16

SYSTEM INTEGRATOR

For all systems, the urinary system excretes waste products and maintains normal body fluid pH and ion composition.
Checkpoint (18-10)

26. What organ systems make up the body's excretory system?

27. Identify the role the urinary system plays for all other body systems.