

Lauralee Sherwood

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# HUMAN PHYSIOLOGY

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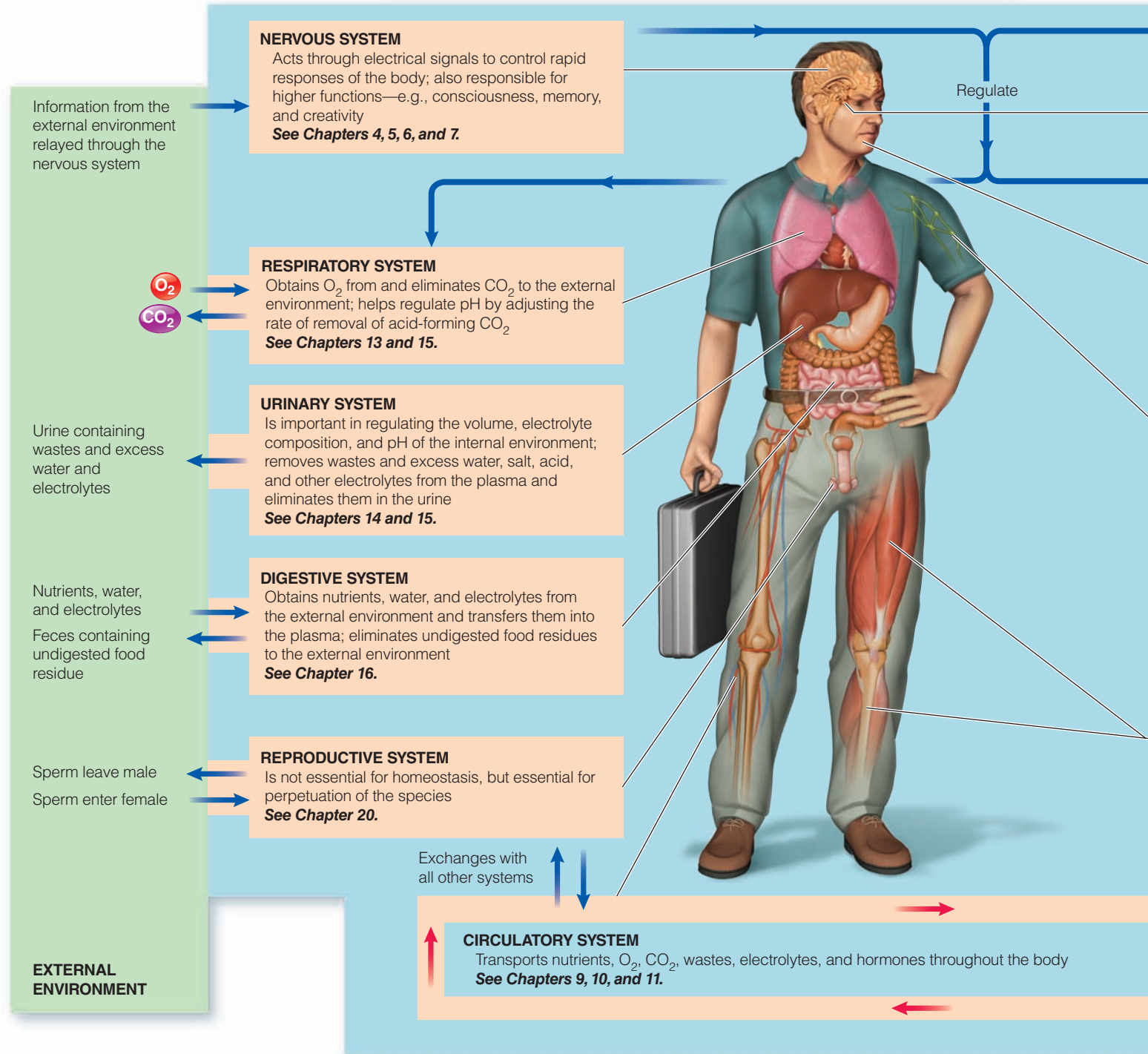
*From Cells to Systems*

Ninth Edition

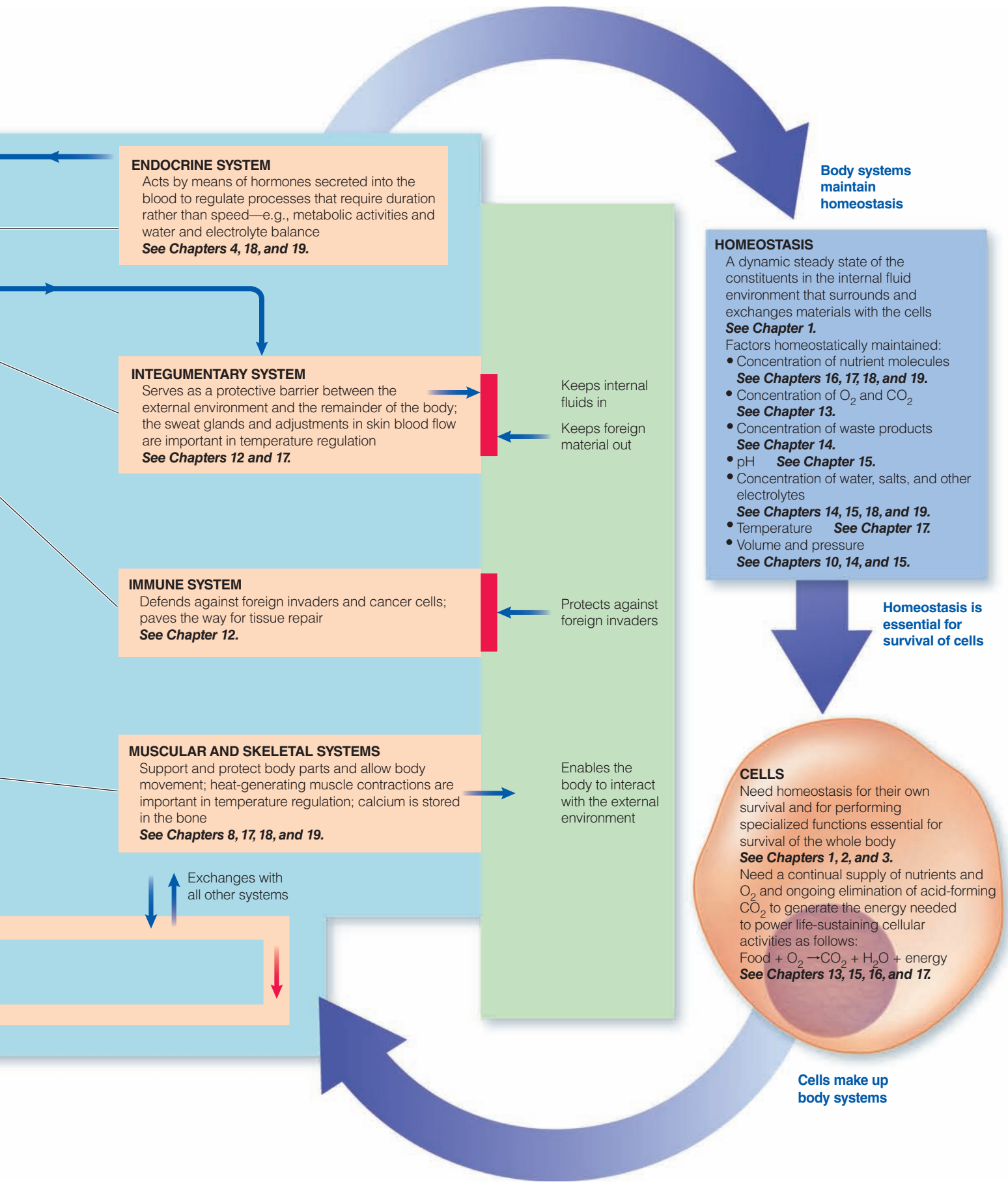


## BODY SYSTEMS

Made up of cells organized according to specialization to maintain homeostasis  
See Chapter 1.



This pictorial homeostatic model is developed in Chapter 1 to show you the relationship among cells, systems, and homeostasis (maintenance of relatively stable conditions in the internal fluid environment that surrounds the cells). The accompanying icon marks special sections at the beginning and end of each chapter that focus on how the topic of the chapter contributes to homeostasis. Together these features will give you a better perspective on homeostasis and the interdependency of body systems.



**ENDOCRINE SYSTEM**  
 Acts by means of hormones secreted into the blood to regulate processes that require duration rather than speed—e.g., metabolic activities and water and electrolyte balance  
**See Chapters 4, 18, and 19.**

**INTEGUMENTARY SYSTEM**  
 Serves as a protective barrier between the external environment and the remainder of the body; the sweat glands and adjustments in skin blood flow are important in temperature regulation  
**See Chapters 12 and 17.**

**IMMUNE SYSTEM**  
 Defends against foreign invaders and cancer cells; paves the way for tissue repair  
**See Chapter 12.**

**MUSCULAR AND SKELETAL SYSTEMS**  
 Support and protect body parts and allow body movement; heat-generating muscle contractions are important in temperature regulation; calcium is stored in the bone  
**See Chapters 8, 17, 18, and 19.**

Exchanges with all other systems

Keeps internal fluids in  
 Keeps foreign material out  
 Protects against foreign invaders  
 Enables the body to interact with the external environment

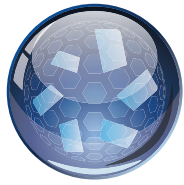
**Body systems maintain homeostasis**

**HOMEOSTASIS**  
 A dynamic steady state of the constituents in the internal fluid environment that surrounds and exchanges materials with the cells  
**See Chapter 1.**  
 Factors homeostatically maintained:  
 • Concentration of nutrient molecules **See Chapters 16, 17, 18, and 19.**  
 • Concentration of O<sub>2</sub> and CO<sub>2</sub> **See Chapter 13.**  
 • Concentration of waste products **See Chapter 14.**  
 • pH **See Chapter 15.**  
 • Concentration of water, salts, and other electrolytes **See Chapters 14, 15, 18, and 19.**  
 • Temperature **See Chapter 17.**  
 • Volume and pressure **See Chapters 10, 14, and 15.**

**Homeostasis is essential for survival of cells**

**CELLS**  
 Need homeostasis for their own survival and for performing specialized functions essential for survival of the whole body  
**See Chapters 1, 2, and 3.**  
 Need a continual supply of nutrients and O<sub>2</sub> and ongoing elimination of acid-forming CO<sub>2</sub> to generate the energy needed to power life-sustaining cellular activities as follows:  
 Food + O<sub>2</sub> → CO<sub>2</sub> + H<sub>2</sub>O + energy  
**See Chapters 13, 15, 16, and 17.**

**Cells make up body systems**



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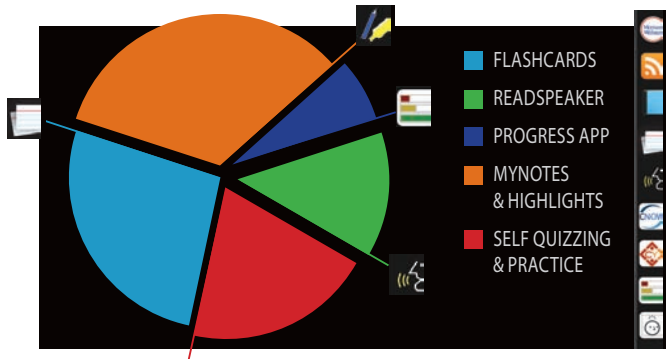
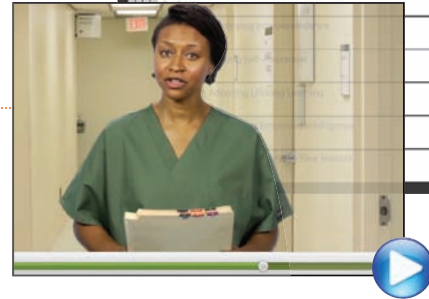
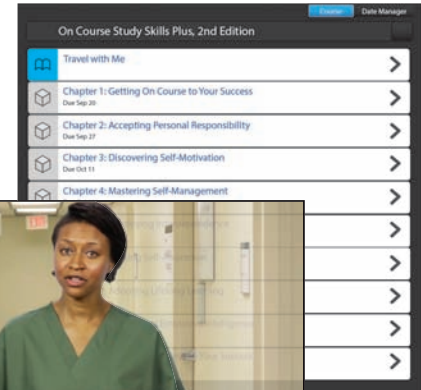
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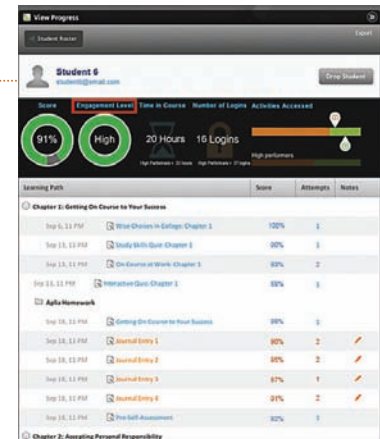


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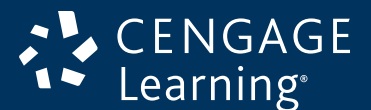
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# Human Physiology

## From Cells to Systems

**Lauralee Sherwood**

Department of Physiology and Pharmacology  
School of Medicine  
West Virginia University



Australia • Brazil • Mexico • Singapore • United Kingdom • United States

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for all that they do for me  
and all that they mean to me:

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Peter Marshall

My daughters and sons-in-law,  
Melinda and Mark Marple  
Allison Tadros and Bill Krantz

My grandchildren,  
Lindsay Marple  
Emily Marple  
Alexander Tadros  
Lauren Krantz



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Muscle fibers have alternate pathways for forming ATP. 269  
Fatigue may be of muscle or central origin. 272

Increased  $O_2$  consumption is necessary to recover from exercise. 272

The three types of skeletal muscle fibers differ in ATP hydrolysis and synthesis. 273

Muscle fibers adapt considerably in response to the demands placed on them. 274

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### 8.5 Control of Motor Movement 276


Motor activity can be classified as reflex, voluntary, or rhythmic. 276

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Multiple neural inputs influence motor unit output. 278  
Muscle receptors provide afferent information needed to control skeletal muscle activity. 281  
Skeletal muscle reflexes can be triggered by painful stimulation of the skin. 284

### 8.6 Smooth and Cardiac Muscle 286

Smooth muscle cells are small and unstriated. 288  
Smooth muscle cells are turned on by  $Ca^{2+}$ -dependent phosphorylation of myosin. 288  
Phasic smooth muscle contracts in bursts; tonic smooth muscle maintains tone. 289  
Multiunit smooth muscle is neurogenic. 290  
Single-unit smooth muscle cells form functional syncytia. 291  
Single-unit smooth muscle is myogenic. 291  
Gradation of single-unit smooth muscle contraction differs from that of skeletal muscle. 292  
Smooth muscle can still develop tension yet inherently relaxes when stretched. 293  
Smooth muscle is slow and economical. 293  
Cardiac muscle blends features of both skeletal and smooth muscle. 294

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## Chapter 9 | Cardiac Physiology 297

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### 9.1 Anatomy of the Heart 298

The heart is positioned in the middle of the thoracic cavity. 298  
The heart is a dual pump. 299  
Pressure-operated heart valves ensure that blood flows in the right direction through the heart. 300  
The heart walls are composed primarily of spirally arranged cardiac muscle fibers. 302  
Cardiac muscle fibers are interconnected by intercalated discs and form functional syncytia. 303  
The heart is enclosed by the pericardial sac. 303

## 9.2 Electrical Activity of the Heart 303

Cardiac autorhythmic cells display pacemaker activity. 303

The sinoatrial node is the normal pacemaker of the heart. 305

The spread of cardiac excitation is coordinated to ensure efficient pumping. 307

The action potential of cardiac contractile cells shows a characteristic plateau. 308

A long refractory period prevents tetanus of cardiac muscle. 309

The ECG is a record of the overall spread of electrical activity through the heart. 310

Different parts of the ECG record can be correlated to specific cardiac events. 311

The ECG can detect abnormal heart rates and rhythms and heart muscle damage. 312

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The heart alternately contracts to empty and relaxes to fill. 314

Two normal heart sounds are associated with valve closures. 317

Turbulent blood flow produces heart murmurs. 318

## 9.4 Cardiac Output and Its Control 319

Cardiac output depends on heart rate and stroke volume. 319

Heart rate is determined primarily by autonomic influences on the SA node. 319

Stroke volume is determined by the extent of venous return and by sympathetic activity. 321

Increased end-diastolic volume results in increased stroke volume. 321

Sympathetic stimulation increases the contractility of the heart. 322

High blood pressure increases the workload of the heart. 323

A failing heart cannot pump out enough blood. 324

## 9.5 Nourishing the Heart Muscle 326

The heart receives most of its blood supply through the coronary circulation during diastole. 326

Atherosclerotic coronary artery disease can deprive the heart of essential O<sub>2</sub>. 327

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# Chapter 10 | The Blood Vessels and Blood Pressure 335

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## 10.1 Patterns and Physics of Blood Flow 336

To maintain homeostasis, reconditioning organs receive blood flow in excess of their own needs. 336

Blood flow through a vessel depends on the pressure gradient and vascular resistance. 337

The vascular tree consists of arteries, arterioles, capillaries, venules, and veins. 338

## 10.2 Arteries 339

Arteries serve as rapid-transit passageways to the organs and as a pressure reservoir. 340

Arterial pressure fluctuates in relation to ventricular systole and diastole. 340

Blood pressure can be measured indirectly by using a sphygmomanometer. 341

Mean arterial pressure is the main driving force for blood flow. 341

## 10.3 Arterioles 343

Arterioles are the major resistance vessels. 343

Local control of arteriolar radius is important in determining the distribution of cardiac output. 344

Local metabolic influences on arteriolar radius help match blood flow with the organs' needs. 345

Local histamine release pathologically dilates arterioles. 347

The myogenic response of arterioles to stretch helps tissues autoregulate their blood flow. 348

Arterioles release vasodilating NO in response to an increase in shear stress. 348

Local heat application dilates arterioles and cold application constricts them. 349

Extrinsic control of arteriolar radius is important in regulating blood pressure. 349

The cardiovascular control center and several hormones regulate blood pressure. 350

## 10.4 Capillaries 350

Capillaries are ideally suited to serve as sites of exchange. 351

Water-filled capillary pores permit passage of small, water-soluble substances. 353

Many capillaries are not open under resting conditions. 354

Interstitial fluid is a passive intermediary between blood and cells. 355

Diffusion across capillary walls is important in solute exchange. 355

Bulk flow across the capillary walls is important in extracellular fluid distribution. 356



The lymphatic system is an accessory route for return of interstitial fluid to the blood. 358

Edema occurs when too much interstitial fluid accumulates. 359

### 10.5 Veins 360

Venules communicate chemically with nearby arterioles. 360

Veins serve as a blood reservoir and as passageways back to the heart. 360

Venous return is enhanced by several extrinsic factors. 361

### 10.6 Blood Pressure 365

Blood pressure is regulated by controlling cardiac output, total peripheral resistance, and blood volume. 365

The baroreceptor reflex is a short-term mechanism for regulating blood pressure. 367

Other reflexes and responses influence blood pressure. 369

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Orthostatic hypotension results from transient inadequate sympathetic activity. 374

Circulatory shock can become irreversible. 374

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## Chapter 11 | The Blood 380

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### 11.1 Plasma 381

The hematocrit is the packed cell volume of blood; the rest of the volume is plasma. 381

Plasma water is a transport medium for many inorganic and organic substances. 381

Many of the functions of plasma are carried out by plasma proteins. 381

### 11.2 Erythrocytes 383

Erythrocytes are well designed for their main function of O<sub>2</sub> transport in the blood. 383

The bone marrow continuously replaces worn-out erythrocytes. 384

Erythropoiesis is controlled by erythropoietin from the kidneys. 385

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Anemia can be caused by a variety of disorders. 386

Polycythemia is an excess of circulating erythrocytes. 388

Blood types depend on surface antigens on erythrocytes. 388

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### 11.3 Leukocytes 392

Leukocytes primarily function as defense agents outside the blood. 392

There are five types of leukocytes. 392

Leukocytes are produced at varying rates depending on the body's changing needs. 393

### 11.4 Platelets and Hemostasis 395

Platelets are cell fragments shed from megakaryocytes. 395

Hemostasis prevents blood loss from damaged small vessels. 395

Vascular spasm reduces blood flow through an injured vessel. 395

Platelets aggregate to form a plug at a vessel injury. 395

Clot formation results from a triggered chain reaction involving plasma clotting factors. 397

Fibrinolytic plasmin dissolves clots. 399

Inappropriate clotting produces thromboembolism. 399

Hemophilia is the primary condition that produces excessive bleeding. 400

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### 12.1 Immune System: Targets, Effectors, Components 405

Pathogenic bacteria and viruses are the major targets of the immune system. 405

Leukocytes are the effector cells of the immune system. 405

Immune responses may be either innate and nonspecific or adaptive and specific. 406

### 12.2 Innate Immunity 408

Inflammation is a nonspecific response to foreign invasion or tissue damage. 408

Inflammation is an underlying culprit in many common, chronic illnesses. 412

Nonsteroidal anti-inflammatory drugs and glucocorticoids suppress inflammation. 412

Interferon transiently inhibits multiplication of viruses in most cells. 412

Natural killer cells destroy virus-infected cells and cancer cells on first exposure to them. 413

The complement system punches holes in microorganisms. 413

Newly discovered immune cells straddle innate and adaptive defenses. 415

### 12.3 Adaptive Immunity: General Concepts 415

Adaptive immune responses include antibody-mediated immunity and cell-mediated immunity. 415

An antigen induces an immune response against itself. 416

### 12.4 B Lymphocytes: Antibody-Mediated Immunity 416

The antigens to which B cells respond can be T-independent or T-dependent. 417

Antigens stimulate B cells to convert into plasma cells that produce antibodies. 417

Antibodies are Y shaped and classified according to properties of their tail portion. 417

Antibodies largely amplify innate immune responses to promote antigen destruction. 418

Clonal selection accounts for the specificity of antibody production. 420

Selected clones differentiate into active plasma cells and dormant memory cells. 420

Active immunity is self-generated; passive immunity is “borrowed.” 421

The huge repertoire of B cells is built by reshuffling a small set of gene fragments. 421

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T cells bind directly with their targets. 423

The three types of T cells are cytotoxic, helper, and regulatory T cells. 423

Cytotoxic T cells secrete chemicals that destroy target cells. 423

Helper T cells secrete chemicals that amplify the activity of other immune cells. 425

Regulatory T cells suppress immune responses. 427

T cells respond only to antigens presented to them by antigen-presenting cells. 427

The major histocompatibility complex is the code for self-antigens. 428

The immune system is normally tolerant of self-antigens. 431

Autoimmune diseases arise from loss of tolerance to specific self-antigens. 432

An interplay among immune cells and interferon defends against cancer. 432

A regulatory loop links the immune system with the nervous and endocrine systems. 434

**A Closer Look at Exercise Physiology:** Exercise: A Help or Hindrance to Immune Defense? 435

### 12.6 Immune Diseases 435

Immunodeficiency diseases result from insufficient immune responses. 435

Allergies are inappropriate immune attacks against harmless environmental substances. 436

### 12.7 External Defenses 438

The skin consists of an outer protective epidermis and an inner, connective tissue dermis. 439

Specialized cells in the epidermis produce melanin, keratin, and vitamin D and participate in immune defense. 440

Protective measures within body cavities discourage pathogen invasion into the body. 441

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## Chapter 13 | The Respiratory System 445

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### 13.1 Respiratory Anatomy 446

The respiratory system does not participate in all steps of respiration. 446

The respiratory airways conduct air between the atmosphere and alveoli. 447

The gas-exchanging alveoli are thin-walled air sacs encircled by pulmonary capillaries. 447

The lungs occupy much of the thoracic cavity. 448

A pleural sac separates each lung from the thoracic wall. 449

### 13.2 Respiratory Mechanics 450

Interrelationships among pressures inside and outside the lungs are important in ventilation. 450

The transmural pressure gradient stretches the lungs to fill the larger thoracic cavity. 450

Airway resistance influences airflow rates. 456

Airway resistance is abnormally increased with chronic obstructive pulmonary disease. 457

The lungs' elastic behavior results from elastin fibers and alveolar surface tension. 458

Pulmonary surfactant decreases surface tension and contributes to lung stability. 458

The work of breathing normally requires only about 3% of total energy expenditure. 460

The lungs normally operate about “half full.” 460

Alveolar ventilation is less than pulmonary ventilation because of dead space. 462

Local controls act on bronchiolar and arteriolar smooth muscle to match airflow to blood flow. 465

### 13.3 Gas Exchange 466

Gases move down partial pressure gradients. 466

O<sub>2</sub> enters and CO<sub>2</sub> leaves the blood in the lungs down partial pressure gradients. 468

Factors other than the partial pressure gradient influence the rate of gas transfer. 468

Gas exchange across the systemic capillaries also occurs down partial pressure gradients. 471

### 13.4 Gas Transport 471

Most O<sub>2</sub> in the blood is transported bound to hemoglobin. 471  
The P<sub>O<sub>2</sub></sub> is the primary factor determining the percent hemoglobin saturation. 472  
Hemoglobin promotes the net transfer of O<sub>2</sub> at both the alveolar and the tissue levels. 473  
Factors at the tissue level promote unloading of O<sub>2</sub> from hemoglobin. 474  
Hemoglobin has a much higher affinity for carbon monoxide than for O<sub>2</sub>. 475  
Most CO<sub>2</sub> is transported in the blood as bicarbonate. 476  
Various respiratory states are characterized by abnormal blood-gas levels. 477

### 13.5 Control of Respiration 479

Respiratory centers in the brain stem establish a rhythmic breathing pattern. 479

#### Concepts, Challenges, and Controversies: Effects of Heights and Depths on the Body 480

Ventilation magnitude is adjusted in response to three chemical factors: P<sub>O<sub>2</sub></sub>, P<sub>CO<sub>2</sub></sub>, and H<sup>+</sup>. 481  
Decreased arterial P<sub>O<sub>2</sub></sub> increases ventilation only as an emergency mechanism. 482  
CO<sub>2</sub>-generated H<sup>+</sup> in the brain is normally the main regulator of ventilation. 483  
Adjustments in ventilation in response to changes in arterial H<sup>+</sup> are important in acid–base balance. 484  
Exercise profoundly increases ventilation by unclear mechanisms. 485  
Ventilation can be influenced by factors unrelated to the need for gas exchange. 486  
During apnea, a person “forgets to breathe”; during dyspnea, a person feels “short of breath.” 486

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### 14.1 Kidneys: Functions, Anatomy, and Basic Processes 492

The kidneys perform a variety of functions aimed at maintaining homeostasis. 492  
The kidneys form urine; the rest of the urinary system carries it to the outside. 492  
The nephron is the functional unit of the kidney. 493  
The three basic renal processes are glomerular filtration, tubular reabsorption, and tubular secretion. 496

### 14.2 Glomerular Filtration 498

The glomerular membrane is considerably more permeable than capillaries elsewhere. 498

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Glomerular capillary blood pressure is the major force that causes glomerular filtration. 499  
Changes in GFR result mainly from changes in glomerular capillary blood pressure. 500  
The GFR can be influenced by changes in the filtration coefficient. 504  
The kidneys normally receive 20% to 25% of the cardiac output. 504

### 14.3 Tubular Reabsorption 505

Tubular reabsorption is tremendous, highly selective, and variable. 505  
Tubular reabsorption involves transepithelial transport. 505  
Na<sup>+</sup> reabsorption depends on the Na<sup>+</sup>–K<sup>+</sup> ATPase pump in the basolateral membrane. 506  
Aldosterone stimulates Na<sup>+</sup> reabsorption in the distal and collecting tubules. 507  
The natriuretic peptides inhibit Na<sup>+</sup> reabsorption. 509  
Glucose and amino acids are reabsorbed by Na<sup>+</sup>-dependent secondary active transport. 510  
In general, actively reabsorbed substances exhibit a tubular maximum. 510  
Glucose is an actively reabsorbed substance not regulated by the kidneys. 511  
Phosphate is an actively reabsorbed substance regulated by the kidneys. 512  
Active Na<sup>+</sup> reabsorption is responsible for passive reabsorption of Cl<sup>–</sup>, H<sub>2</sub>O, and urea. 512  
In general, unwanted waste products are not reabsorbed. 514

### 14.4 Tubular Secretion 514

Hydrogen ion secretion is important in acid–base balance. 514  
Potassium ion secretion is controlled by aldosterone. 514  
Organic anion and cation secretion hastens elimination of foreign compounds. 516

### 14.5 Urine Excretion and Plasma Clearance 517

Plasma clearance is the volume of plasma cleared of a particular substance per minute. 517  
Clearance rates for inulin and PAH can be used to determine the filtration fraction. 520  
The kidneys can excrete urine of varying concentrations depending on body needs. 520  
Long Henle’s loops establish the vertical osmotic gradient by countercurrent multiplication. 521  
Vasopressin controls variable H<sub>2</sub>O reabsorption in the final tubular segments. 523  
The vasa recta preserve the vertical osmotic gradient by countercurrent exchange. 526  
Water reabsorption is only partially linked to solute reabsorption. 527  
Renal failure has wide-ranging consequences. 527  
Urine is temporarily stored in the bladder, from which it is emptied by micturition. 528

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## Chapter 15 | Fluid and Acid–Base Balance 535

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### 15.1 Balance Concept 536

The internal pool of a substance is the amount of that substance in the ECF. 536

To maintain stable balance of an ECF constituent, its input must equal its output. 536

### 15.2 Fluid Balance 537

Body water is distributed between the ICF and the ECF compartments. 537

Plasma and interstitial fluid are similar in composition, but ECF and ICF differ markedly. 538

Fluid balance is maintained by regulating ECF volume and osmolarity. 538

Control of ECF volume is important in the long-term regulation of blood pressure. 539

Control of salt balance is primarily important in regulating ECF volume. 539

Controlling ECF osmolarity prevents changes in ICF volume. 540

During ECF hypertonicity, cells shrink as H<sub>2</sub>O leaves them. 541

**A Closer Look at Exercise Physiology:** A Potentially Fatal Clash: When Exercising Muscles and Cooling Mechanisms Compete for an Inadequate Plasma Volume 542

During ECF hypotonicity, the cells swell as H<sub>2</sub>O enters them. 543

No water moves into or out of cells during an ECF isotonic fluid gain or loss. 543

Vasopressin control of free H<sub>2</sub>O balance is important in regulating ECF osmolarity. 543

Vasopressin secretion and thirst are largely triggered simultaneously. 545

### 15.3 Acid–Base Balance 547

Acids liberate free hydrogen ions, whereas bases accept them. 547

The pH designation is used to express [H<sup>+</sup>]. 548

Fluctuations in [H<sup>+</sup>] alter nerve, enzyme, and K<sup>+</sup> activity. 549

Hydrogen ions are continually added to the body fluids as a result of metabolic activities. 549

Chemical buffer systems minimize changes in pH by binding with or yielding free H<sup>+</sup>. 550

The H<sub>2</sub>CO<sub>3</sub>:HCO<sub>3</sub><sup>-</sup> buffer pair is the primary ECF buffer for noncarbonic acids. 551

The protein buffer system is primarily important intracellularly. 552

The hemoglobin buffer system buffers H<sup>+</sup> generated from CO<sub>2</sub>. 552

The phosphate buffer system is an important urinary buffer. 552

Chemical buffer systems act as the first line of defense against changes in [H<sup>+</sup>]. 553

The respiratory system regulates [H<sup>+</sup>] by controlling the rate of CO<sub>2</sub> removal. 553

The respiratory system serves as the second line of defense against changes in [H<sup>+</sup>]. 553

The kidneys adjust their rate of H<sup>+</sup> excretion by varying the extent of H<sup>+</sup> secretion. 554

The kidneys conserve or excrete HCO<sub>3</sub><sup>-</sup> depending on the plasma [H<sup>+</sup>]. 555

The kidneys secrete ammonia during acidosis to buffer secreted H<sup>+</sup>. 558

The kidneys are a powerful third line of defense against changes in [H<sup>+</sup>]. 558

Acid–base imbalances can arise from either respiratory or metabolic disturbances. 558

Respiratory acidosis arises from an increase in [CO<sub>2</sub>]. 559

Respiratory alkalosis arises from a decrease in [CO<sub>2</sub>]. 559

Metabolic acidosis is associated with a fall in [HCO<sub>3</sub><sup>-</sup>]. 561

Metabolic alkalosis is associated with an elevation in [HCO<sub>3</sub><sup>-</sup>]. 561

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## Chapter 16 | The Digestive System 565

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### 16.1 General Aspects of Digestion 566

The digestive system performs four basic digestive processes. 566

The digestive tract and accessory digestive organs make up the digestive system. 569

The digestive tract wall has four layers. 570

Regulation of digestive function is complex and synergistic. 571

Receptor activation alters digestive activity through neural and hormonal pathways. 572

### 16.2 Mouth 573

The oral cavity is the entrance to the digestive tract. 573

The teeth mechanically break down food. 574

Saliva begins carbohydrate digestion and helps swallowing, speech, taste, and oral health. 574

Salivary secretion is continuous and can be reflexly increased. 575

Digestion in the mouth is minimal; no absorption of nutrients occurs. 575

### 16.3 Pharynx and Esophagus 575

- Swallowing is a sequentially programmed all-or-none reflex. 576
- During swallowing, food is prevented from entering the wrong passageways. 576
- The pharyngoesophageal sphincter prevents air from entering the digestive tract. 576
- Peristaltic waves push food through the esophagus. 576
- The gastroesophageal sphincter prevents reflux of gastric contents. 578
- Esophageal secretion is entirely protective. 578

### 16.4 Stomach 578

- The stomach stores food and begins protein digestion. 578
- Gastric filling involves receptive relaxation. 579
- Gastric storage takes place in the body of the stomach. 579
- Gastric mixing takes place in the antrum of the stomach. 579
- Gastric emptying is largely controlled by factors in the duodenum. 579

#### A Closer Look at Exercise Physiology: Pregame Meal: What's In and What's Out? 581

- Emotions can influence gastric motility. 582
- The stomach does not actively participate in vomiting. 582
- Gastric digestive juice is secreted by glands located at the base of gastric pits. 582
- Hydrochloric acid is secreted by parietal cells and activates pepsinogen. 584
- Pepsinogen is activated to pepsin, which begins protein digestion. 585
- Mucus is protective. 585
- Intrinsic factor is essential for absorption of vitamin B<sub>12</sub>. 585
- Multiple regulatory pathways influence the parietal and chief cells. 585
- Control of gastric secretion involves three phases. 586
- Gastric secretion gradually decreases as food empties from the stomach into the intestine. 587
- The gastric mucosal barrier protects the stomach lining from gastric secretions. 587
- Carbohydrate digestion continues in the body of the stomach; protein digestion begins in the antrum. 588
- The stomach absorbs alcohol and aspirin but no food. 588

### 16.5 Pancreatic and Biliary Secretions 588

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- The pancreas is a mixture of exocrine and endocrine tissue. 590
- The exocrine pancreas secretes digestive enzymes and an alkaline fluid. 590
- Pancreatic exocrine secretion is regulated by secretin and CCK. 592

- The liver performs various important functions, including bile production. 593
- Bile is continuously secreted by the liver and is diverted to the gallbladder between meals. 595
- Bile salts are recycled through the enterohepatic circulation. 595
- Bile salts aid fat digestion and absorption. 595
- Bile salts stimulate bile secretion; CCK promotes gallbladder emptying. 597
- Bilirubin is a waste product excreted in the bile. 597
- Hepatitis and cirrhosis are the most common liver disorders. 597

### 16.6 Small Intestine 598

- Segmentation contractions mix and slowly propel the chyme. 598
- The migrating motility complex sweeps the intestine clean between meals. 599
- The ileocecal juncture prevents contamination of the small intestine by colonic bacteria. 599
- Small-intestine secretions do not contain any digestive enzymes. 599
- The small-intestine enzymes complete digestion within the brush-border membrane. 599
- The small intestine is remarkably well adapted for its primary role in absorption. 600
- The mucosal lining experiences rapid turnover. 602
- Energy-dependent Na<sup>+</sup> absorption drives passive H<sub>2</sub>O absorption. 603
- Digested carbohydrates and proteins are both absorbed by secondary active transport and enter the blood. 603
- Digested fat is absorbed passively and enters the lymph. 605
- Vitamin absorption is largely passive. 605
- Iron and calcium absorption is regulated. 605
- Most absorbed nutrients immediately pass through the liver for processing. 609
- Extensive absorption by the small intestine keeps pace with secretion. 609
- Biochemical balance among the stomach, pancreas, and small intestine is normally maintained. 609
- Diarrhea results in loss of fluid and electrolytes. 610

### 16.7 Large Intestine 610

- The large intestine is primarily a drying and storage organ. 610

#### Concepts, Challenges, and Controversies: Oral Rehydration Therapy: Sipping a Simple Solution Saves Lives 611

- Haustral contractions slowly shuffle the colonic contents back and forth. 611
- Mass movements propel feces long distances. 612
- Feces are eliminated by the defecation reflex. 612
- Constipation occurs when the feces become too dry. 612
- Intestinal gases are absorbed or expelled. 612
- Large-intestine secretion is entirely protective. 613
- The colon contains myriad beneficial bacteria. 613
- The large intestine absorbs salt and water, converting the luminal contents into feces. 614

## Chapter 17 | Energy Balance and Temperature Regulation 618

### 17.1 Energy Balance 619

Most food energy is ultimately converted into heat in the body. 619

The metabolic rate is the rate of energy use. 619

Energy input must equal energy output to maintain a neutral energy balance. 621

Food intake is controlled primarily by the hypothalamus. 621

Obesity occurs when more kilocalories are consumed than are burned. 624

**A Closer Look at Exercise Physiology:** What the Scales Don't Tell You 625

People suffering from anorexia nervosa have a pathological fear of gaining weight. 627

### 17.2 Temperature Regulation 627

Internal core temperature is homeostatically maintained at 100°F (37.8°C). 627

Heat input must balance heat output to maintain a stable core temperature. 628

Heat exchange takes place by radiation, conduction, convection, and evaporation. 628

Sweating is a regulated evaporative heat-loss process. 630

The hypothalamus integrates a multitude of thermosensory inputs. 630

Shivering is the primary involuntary means of increasing heat production. 630

The magnitude of heat loss can be adjusted by varying the flow of blood through the skin. 632

The hypothalamus simultaneously coordinates heat-production and heat-loss mechanisms. 632

During a fever, the hypothalamic thermostat is “reset” at an elevated temperature. 633

**Concepts, Challenges, and Controversies:** The Extremes of Heat and Cold Can Be Fatal 634

Hyperthermia can occur unrelated to infection. 634

## Chapter 18 | Principles of Endocrinology; The Central Endocrine Glands 638

### 18.1 General Principles of Endocrinology 639

Hormones exert a variety of regulatory effects throughout the body. 640

The effective plasma concentration of a hormone is influenced by the hormone's secretion, peripheral conversion, transport, inactivation, and excretion. 640

The effective plasma concentration of a hormone is normally regulated by changes in the rate of its secretion. 641

Endocrine disorders result from hormone excess or deficiency or decreased target-cell responsiveness. 642

The responsiveness of a target cell can be varied by regulating the number of hormone-specific receptors. 643

### 18.2 Hypothalamus and Pituitary 646

The pituitary gland consists of anterior and posterior lobes. 646

The hypothalamus and posterior pituitary act as a unit to secrete vasopressin and oxytocin. 646

Most anterior pituitary hormones are tropic. 647

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Hypothalamic releasing and inhibiting hormones help regulate anterior pituitary hormone secretion. 648

Target-gland hormones inhibit hypothalamic and anterior pituitary hormone secretion via negative feedback. 651

### 18.3 Endocrine Control of Growth 652

Growth depends on GH but is influenced by other factors. 652

GH is essential for growth, but it also directly exerts metabolic effects not related to growth. 653

GH mostly exerts its growth-promoting effects indirectly by stimulating insulin-like growth factors. 653

GH, through IGF-I, promotes growth of soft tissues by stimulating hypertrophy and hyperplasia. 654

Bone grows in thickness and in length by different mechanisms, both stimulated by GH. 654

GH secretion is regulated by two hypophysiotropic hormones. 656

Abnormal GH secretion results in aberrant growth patterns. 657

**Concepts, Challenges, and Controversies:** Growth and Youth in a Bottle? 658

Other hormones besides growth hormone are essential for normal growth. 658

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The suprachiasmatic nucleus is the master biological clock. 660

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Melatonin helps keep the body's circadian rhythms in time with the light–dark cycle. 661

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### 19.1 Thyroid Gland 666

The major cells that secrete thyroid hormone are organized into colloid-filled follicles. 666

Thyroid hormone is synthesized and stored on the thyroglobulin molecule. 666

To secrete thyroid hormone, the follicular cells phagocytize thyroglobulin-laden colloid. 668

Thyroid hormone increases the basal metabolic rate and exerts other effects. 668

Thyroid hormone is regulated by the hypothalamus–pituitary–thyroid axis. 669

Abnormalities of thyroid function include both hypothyroidism and hyperthyroidism. 669

A goiter develops when the thyroid gland is overstimulated. 671

### 19.2 Adrenal Glands 672

Each adrenal gland consists of a steroid-secreting cortex and a catecholamine-secreting medulla. 672

The adrenal cortex secretes mineralocorticoids, glucocorticoids, and sex hormones. 672

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# Preface

## Goals, Philosophy, and Theme

I am constantly awestruck at the miraculous intricacies and efficiency of body function. No machine can perform even a portion of natural body function as effectively. My goal in writing physiology textbooks is not only to help students learn about how the body works, but also to share my enthusiasm for the subject matter. Most of us, even infants, have a natural curiosity about how our bodies work. When babies first discover they can control their hands, they are fascinated and spend many hours manipulating them in front of their faces. By capitalizing on students' natural curiosity about themselves, I try to make physiology a subject they can enjoy learning.

Even the most tantalizing subject can be difficult to comprehend if not effectively presented, however. Therefore, this book has a logical, understandable format with an emphasis on how each concept is an integral part of the entire subject. Too often, students view the components of a physiology course as isolated entities; by understanding how each component depends on the others, a student can appreciate the integrated functioning of the human body. The text focuses on the mechanisms of body function from cells to systems and is organized around the central theme of *homeostasis*—how the body meets changing demands while maintaining the internal constancy necessary for all cells and organs to function. The text is written in simple, straightforward language, and every effort has been made to ensure smooth reading through good transitions, common-sense reasoning, and integration of ideas throughout.

This text is designed for undergraduate students preparing for health-related careers, but its approach and depth also are appropriate for other undergraduates. Because this book is intended as an introduction and, for most students, may be their only exposure to a formal physiology text, all aspects of physiology receive broad coverage, yet depth, where needed, is not sacrificed. The scope of this text has been limited by judicious selection of pertinent content that a student can reasonably be expected to assimilate in a one-semester physiology course. Materials were selected for inclusion on a “need to know” basis, so the book is not cluttered with unnecessary detail. Instead, content is restricted to relevant information needed to understand basic physiological concepts and to serve as a foundation for future careers in the health professions. Some controversial ideas and hypotheses are presented to illustrate that physiology is a dynamic, changing discipline.

To keep pace with today's rapid advances in the health sciences, students in the health professions must be able to draw on their conceptual understanding of physiology instead of merely recalling isolated facts that soon may be out of date. Therefore, this text is designed to promote understanding of the basic principles and concepts of physiology rather than memorization of details.

In consideration of the clinical orientation of most students, research methodologies and data are not emphasized, although the material is based on up-to-date evidence. New information based on recent discoveries has been included throughout. Students can be assured of the timeliness and accuracy of the material presented. To make room for new, applicable information, I have carefully trimmed content while clarifying, modifying, and simplifying as needed to make this edition fresh, reader-friendly, and current.

Because the function of an organ depends on the organ's construction, enough relevant anatomy is integrated within the text to make the inseparable relation between form and function meaningful.

## Hallmark Features and Learning Aids

### Implementing the homeostasis theme

*Homeostasis* is the first word in this text, in the caption for the chapter opener photo for Chapter 1, “Introduction to Physiology and Homeostasis,” indicative of the importance placed on homeostasis (see p. 1).

Each chapter begins with **Homeostasis Highlights**, an opening feature that emphasizes the big picture of how the content to come plays a part in homeostasis and functionally fits in with the body as a whole. As an example, see *Homeostasis Highlights* for Chapter 8, “Muscle Physiology,” p. 251.

At the close of each chapter, **Homeostasis: Chapter in Perspective** points out specific ways in which the topic covered in the chapter contributes to homeostasis, returning the reader to this central theme, no matter how far the content appears to be removed from playing a role in maintaining internal constancy, as exemplified by *Homeostasis: Chapter in Perspective* for Chapter 3, “The Plasma Membrane and Membrane Potential,” p. 84.

A unique, easy-to-follow, pictorial homeostatic model showing the relationship among cells, systems, and homeostasis is developed in the introductory chapter (see pp. 14–15) and presented on the inside front cover as a quick reference.

These opening and closing features and the homeostatic model work together to facilitate students' comprehension of the interactions and interdependency of body systems, even though each system is discussed separately.

## Chapter openers

The chapter openers consist of three key components: an eye-catching, informative photo relevant to the chapter; *Chapter at a Glance*, a concise list of contents; and the brief *Homeostasis Highlights* narrative that orients the readers to the homeostatic aspects of the material that follows. Check out the chapter opener for Chapter 13, "The Respiratory System," on p. 445 as an example.

## Pedagogical illustrations

Anatomic illustrations, schematic representations, step-by-step descriptions within process-oriented figures, photographs, tables, and graphs complement and reinforce the written material.

Widespread use of integrated descriptions within figures, including numerous **process-oriented figures with incorporated step-by-step descriptions**, allows visually oriented students to review processes through figures. Check out Figure 5-17, p. 161; Figure 8-11, p. 260; and Figure 11-11, p. 396, for examples.

**Flow diagrams** are used extensively to help students integrate the written information. In the flow diagrams, lighter and darker shades of the same color denote a decrease or increase in a controlled variable, such as blood pressure or the concentration of blood glucose. Physical entities, such as body structures and chemicals, are distinguished visually from actions. Icons of physical entities are incorporated into the flow diagrams. See Figure 15-4, p. 545; Figure 16-12, p. 592; and Figure 20-9, p. 729, for examples.

Most chapters feature one or more **showcase figures**, which are art-enhanced, visually appealing, broad-based foundation figures that draw students' attention to key structural and functional components relevant to the chapter. Examples include the following:

- Figure 2-1, A diagram of cell structures visible under an electron microscope, p. 23
- Figure 14-1, The urinary system, p. 493
- Figure 19-7, Anatomy of and hormonal secretion by the adrenal glands, p. 672

Also, integrated **color-coded figure/table combinations** help students better visualize what part of the body is responsible for what activities. For example, anatomic depiction of the brain is integrated with a table of the functions of the major brain components, with each component shown in the same color in the figure and the table (see Table 5-1, pp. 144–145).

A unique feature of this book is that people depicted in the various illustrations are realistic representatives of a cross-section of humanity. Sensitivity to various races, sexes, and ages should enable all students to identify with the material being presented.

## Analogies

Many analogies and frequent references to everyday experiences are included to help students relate to the physiology

concepts presented. These useful tools have been drawn in large part from my more than four decades of teaching experience. Knowing which areas are likely to give students the most difficulty, I have tried to develop links that help them relate the new material to something with which they are already familiar. As examples, the lymphatic system as an accessory drainage route for interstitial fluid is compared to a storm sewer that picks up and carries away excess rainwater so that it does not accumulate and flood an area (p. 358); and the effect of sildenafil (Viagra) is likened to pushing a pedal on a piano not causing a note to be played but prolonging a played note (p. 734).

## Pathophysiology and clinical coverage



Another effective way to keep students' interest is to help them realize they are learning worthwhile and applicable material. Because many students using this text will have health-related careers, frequent references to pathophysiology and clinical physiology demonstrate the content's relevance to their professional goals. Clinical Note icons flag clinically relevant material, which is integrated throughout the text.

## Boxed features

Two types of boxed features are incorporated within the chapters. **Concepts, Challenges, and Controversies** boxes expose students to high-interest information on such diverse topics as new technologies involving "seeing" with the tongue or the ear (see p. 210); historical highlights, for example, development of vaccinations (see p. 422); body responses to different environments such as those encountered in mountain climbing and deep-sea diving (see pp. 480–481); and in-depth discussions regarding common diseases such as Alzheimer's disease (see pp. 164–165).

**A Closer Look at Exercise Physiology** boxes are included for three reasons: increasing national awareness of the importance of physical fitness, increasing recognition of the value of prescribed therapeutic exercise programs for a variety of conditions, and growing career opportunities related to fitness and exercise. As an example, see the exercise physiology box on p. 542 regarding the importance of acclimatization to exercising in the heat.

## Major section heads and feedforward statements as subsection titles

Major section heads and subsections logically break up large concepts into smaller, manageable chunks. Instead of traditional short topic titles for each subsection (for example, "Glial cells"), feedforward statements alert students to the main point of the subsection to come (for example, "Glial cells support the interneurons physically, metabolically, and functionally"). As an added bonus, the listing of these headings in the **Contents** at the beginning of the book serves as a set of objectives for each chapter.

## Key terms and word derivations

Key terms are defined as they appear in the text. Because physiology is laden with new vocabulary words, many of which are rather intimidating at first glance, word derivations are provided to enhance understanding of new words.

## Review and self-evaluation tools in the text

Students are provided opportunities to review and are encouraged to assess their comprehension in a variety of ways.

**Check Your Understanding Questions** Questions at the end of each major section serve as study breaks for students to test their knowledge before starting the next section. These questions are different than the questions that cover the same content at the end of the chapter. Many of these section questions involve doing something other than copying an answer from a text description, such as drawing and labeling, preparing a chart, predicting based on information provided, and so on. In response to positive feedback regarding the usefulness of this pedagogical tool, which was introduced in the last edition, I have added nearly 100 new Check Your Understanding questions to this edition, bringing them to a total of about 350.

**NEW! Figure Focus Questions** Designed to check and promote student comprehension, focus questions have been added to specific figures throughout the text. To answer these critical thinking questions correctly, the reader must analyze, interpret, infer, and apply the content of 120 key figures. Check out examples of these new questions in Figures 13-20 and 13-21, p. 467; Figure 14-27, p. 525; and Figure 19-2, p. 667.

### NEW! Blooms-Based Organization of Review Exercises

The Review Exercises at the end of each chapter are now organized into categories using the educational tool *Bloom's Taxonomy of Learning Domains* as a guide. Questions are grouped in a hierarchy from lower- to higher-order levels as follows:

- **Reviewing Terms and Facts:** The objective-type questions in this exercise are intended for students to self-test their basic knowledge of the chapter by recalling terms and facts.
- **Understanding Concepts:** With this level, students demonstrate their understanding of the concepts presented by describing, explaining, comparing, stating main ideas, and so on in their own words.
- **Solving Quantitative Exercises:** These problem-solving exercises provide students with an opportunity to practice calculations that enhance their understanding of complex relationships.
- **Applying Clinical Reasoning:** This mini case history challenges students to apply acquired knowledge to a patient's specific symptoms, a situation relevant to the health-profession career goals of most students using this textbook.
- **Thinking at a Higher Level:** This section features thought-provoking problems that encourage students to analyze, synthesize, reorganize, or apply in a different way what they have learned in the chapter.

Answers and explanations for these exercises are available in an appendix and online as described in the next section.

**Study Cards** A tear-out study card is available for each chapter. Each study card presents the major points of the chapter in concise, section-by-section bulleted lists, including cross-references for page numbers, figures, and tables. Students can

carry these handy chapter summaries instead of the book to conveniently review key concepts for exams. The tear-out design lets students more efficiently review material even with the book in hand because they can see the written summary and visual information side-by-side without having to flip pages back and forth. This feature enables students to easily review main concepts before moving on.

## Appendixes and glossary

Most undergraduate physiology texts have a chapter on chemistry, yet physiology instructors rarely teach basic chemistry concepts. Knowledge of chemistry beyond that introduced in secondary schools is not required for understanding this text. Therefore, I provide instead **Appendix A, A Review of Chemical Principles**, as a handy reference for students who need a brief review of basic chemistry concepts that apply to physiology. The following additional review materials are available online at [www.cengagebrain.com](http://www.cengagebrain.com) *Storage, Replication, and Expression of Genetic Information* and *Principles of Quantitative Reasoning*.

**Appendix B, Text References to Exercise Physiology**, provides an index of all relevant content on this topic.

**Appendix C, Answers**, provides answers to all objective learning activities, including in-chapter *Check Your Understanding* questions and *Figure Focus* questions and end-of-chapter *Reviewing Terms and Facts*, solutions to the *Solving Quantitative Exercises*, and explanations for *Applying Clinical Reasoning* and *Thinking at a Higher Level* exercises. Answers to *Understanding Concepts* questions can be found at [www.cengagebrain.com](http://www.cengagebrain.com).

The **Glossary**, which offers a way to review the meaning of key terminology, includes phonetic pronunciations of the entries.

## Organization

There is no ideal organization of physiologic processes into a logical sequence. In the sequence I chose, most chapters build on material presented in immediately preceding chapters, yet each chapter is designed to stand on its own, allowing the instructor flexibility in curriculum design. This flexibility is facilitated by cross-references to related material in other chapters. The cross-references let students quickly refresh their memory of material already learned or proceed, if desired, to a more in-depth coverage of a particular topic.

The general flow is from introductory background information to cells to excitable tissue (nerve and muscle) to organ systems, with logical transitions from one chapter to the next. For example, Chapter 8, "Muscle Physiology," ends with a discussion of cardiac (heart) muscle, which is carried forward in Chapter 9, "Cardiac Physiology." Even topics that seem unrelated in sequence, such as Chapter 12, "Body Defenses," and Chapter 13, "The Respiratory System," are linked together, in this case by ending Chapter 12 with a discussion of respiratory defense mechanisms.

Several organizational features warrant specific mention. The most difficult decision in organizing this text was placement of the endocrine material. There is merit in placing the chapters on the nervous and the endocrine (hormone-secreting) systems in close proximity because they are the body's two major regulatory systems. However, discussing details of the endocrine system immediately after the nervous system would disrupt the logical flow of material related to excitable tissue. In addition, the endocrine system cannot be covered in the depth its importance warrants if it is discussed before students have the background to understand this system's roles in maintaining homeostasis.

My solution to this dilemma is Chapter 4, "Principles of Neural and Hormonal Communication." This chapter introduces the underlying mechanisms of neural and hormonal action before the nervous system and specific hormones are mentioned in later chapters. It contrasts how nerve cells and endocrine cells communicate with other cells in carrying out their regulatory actions. Building on the different modes of action of nerve and endocrine cells, the last section of this chapter compares, in a general way, how the nervous and endocrine systems differ as regulatory systems. Chapter 5 then begins with the nervous system, providing a good link between Chapters 4 and 5. Chapters 5, 6, and 7 are devoted to the nervous system. Specific hormones are introduced in appropriate chapters, such as hormonal control of the heart and blood vessels in maintaining blood pressure in Chapters 9 and 10 and hormonal control of the kidneys in maintaining fluid balance in Chapters 14 and 15. The body's processing of absorbed energy-rich nutrient molecules is largely under endocrine control, providing a link from digestion (Chapter 16) and energy balance (Chapter 17) to the endocrine system (Chapters 18 and 19). These endocrine chapters pull together the source, functions, and control of specific endocrine secretions and serve as a summarizing and unifying capstone for homeostatic body function. Finally, building on the hormones that control the gonads (testes and ovaries) introduced in the endocrine chapters, the last chapter, Chapter 20, diverges from the theme of homeostasis to focus on reproductive physiology.

Besides the novel handling of hormones and the endocrine system, other organizational features are unique to this book. For example, unlike other physiology texts, the skin is covered in the chapter on defense mechanisms of the body (Chapter 12), in consideration of the skin's recently recognized immune functions. Bone is also covered more extensively in the endocrine chapter than in most undergraduate physiology texts, especially with regard to hormonal control of bone growth and bone's dynamic role in calcium metabolism.

Although there is a rationale for covering the various aspects of physiology in the order given here, it is by no means the only logical way of presenting the topics. Because each chapter is able to stand on its own, especially with the cross-references provided, instructors can vary the sequence of presentation at their discretion. Some chapters may even be omitted, depending on the students' needs and interests and the time constraints of the course. For example, a cursory explanation of the defense role of the leukocytes appears in Chapter 11 on blood, so an instructor can choose to omit the more detailed explanations of immune defense in Chapter 12.

## New to the Ninth Edition

This edition has a new look, new pedagogical features, updates, and numerous revisions to make the book as current, relevant, and accessible to students as possible. Every aspect of the text has been upgraded as the following examples illustrate. For a detailed list of all changes, contact your Cengage Learning sales representative.

### New look

Not only does this edition have fresh colors but the pages are more visually interesting because of creative wrapping of some of the written material around the art for a contemporary look instead of just being wrapped with a traditional, single 90-degree corner. See pp. 111, 245, and 413 for examples.

### New self-check pedagogical tools

Already mentioned, new to this edition are several new or revised self-check features, including the new *Figure Focus* questions, more *Check Your Understanding* questions, and new organization of the end-of-chapter *Review Exercises* into hierarchical learning levels.

### New and revised figures

**New Art** The following exemplify first-time illustrations added in this edition:

- Figure 5-9, Layers of the cerebral cortex, p. 147
- Figure 10-11, Major local chemical and physical means of controlling arteriolar caliber, p. 347
- Figure 16-11, Mechanism of  $\text{NaHCO}_3$  secretion, p. 591

**Revised Art** Examples of extensively revised, newly conceptualized, or reorganized figures include the following:

- Figure 8-1, Characteristics of three types of muscle, p. 252
- Figure 10-26, Skeletal muscle pump enhancing venous return and countering effect of gravity on venous pressure, p. 363
- Figure 16-5, Oropharyngeal and esophageal stages of swallowing, p. 577

**New Photos** More than 50 new photos and replacement photos are incorporated throughout the text, including replacing 45% of the chapter opener photos. For instance, see Chapter 5 opener, a diffusion resonance image (dMRI) scan of the white matter pathways of the brain, p. 133. The following are other examples of content not shown in photos in previous editions:

- Figure 4-7, A micrograph of dendritic spines incorporated into Anatomy of the most common type of neuron, p. 95
- Figure 6-37, A scanning electron micrograph of the tip links between adjacent stereocilia, incorporated into The role of stereocilia in sound transduction, p. 218
- Table 16-3, A scanning electron micrograph of stomach lining showing gastric pits, incorporated into an integrated figure/table featuring The stomach mucosa and the gastric glands, p. 583

## New tables

More new tables that group and consolidate information for easier learning have been added to this edition than ever before, as the following samples demonstrate:

- Table 4-2, Major Neurotransmitters, p. 107
- Table 8-3, Motor Control by CNS, p. 280
- Table 20-4, Stages of Follicular Development, p. 743

## New boxed features

Several old boxes have been retired and two new boxes regarding timely, relevant content have been added: (1) *The Ups (Causes) and Downs (Treatments) of Hypertension*, in consideration of the fact that one third of all adults in the United States have hypertension (see pp. 372–373); and (2) *Still a Big Question: Why Do We Age?*, which focuses on the current theories of aging, in view of the increased graying of America as baby boomers are reaching old age (see pp. 678–679).

## New, updated content

Recent discoveries and hot topics have been incorporated throughout as the following examples illustrate:

- In Chapter 2, inserted a discussion and figure of proteasomes breaking down ubiquitinated proteins into recyclable building blocks (p. 27)
- Among the numerous new topics in Chapter 5 is the glymphatic system, a recently identified glia substitute for the lymphatic system in the brain (p. 137)
- Added a comparison of the trichromatic theory and the opponent-process theory of color vision in Chapter 6 (p. 205)
- In Chapter 9, expanded presentation of cardiac autorhythmicity to include both the membrane clock mechanism and the  $\text{Ca}^{2+}$  mechanism (together, the coupled-clock system) responsible for the pacemaker potential (p. 304)
- Introduced in Chapter 12 newly identified immune cells (innate lymphoid cells [ILCs] and innate response activator [IRA] B cells) that straddle the innate and adaptive immune systems (p. 415)
- Significantly expanded coverage of the microbiota and microbiome in Chapter 16 in light of a torrent of new findings in this hot area of science (pp. 613–614)
- In Chapter 17, updated discussion of brown fat in view of recent studies suggesting that irisin, a newly discovered chemical mediator released from exercising muscles, may promote “browning” of white adipose tissue by stimulating synthesis of uncoupling proteins in mitochondria of white fat cells (p. 632)
- Augmented coverage of the underlying molecular mechanism responsible for the suprachiasmatic nucleus’s circadian oscillations in Chapter 18 by adding the interactions of PER and CRY with CLOCK and BMAL-1 (see p. 660)
- Updated discussion of islets of Langerhans in Chapter 19 to include secretion of amylin in addition to insulin by the beta cells and secretion of ghrelin by newly found epsilon cells (pp. 692 and 689)

- Expanded coverage of clinically related issues, such as adding a new discussion of concussions and chronic traumatic encephalopathy (p. 172)

## Reorganization

Although the focus of each chapter remains the same as previous editions, I moved some content between and within chapters for better grouping of material, as follows:

- Moved the discussion of eicosanoids from Chapter 20 (in association with male accessory sex gland secretions) to Chapter 4, the chapter devoted primarily to neural and hormonal communication and signal transduction. Eicosanoids and cytokines are now more appropriately grouped together and presented in a new section entitled *Introduction to Paracrine Communication* (pp. 118–120)
- Transferred introduction of the JAK/STAT pathway from Chapter 18, where it was treated more as an aside in the discussion of signal transduction by growth hormone and prolactin, to Chapter 4, where the topic more logically fits in with coverage of other means of signal transduction (pp. 116–117)
- Rearranged and grouped together the material within Chapter 5 related to brain waves and the electroencephalogram for better flow and improved clarity (pp. 168–169)
- Based on reviewer input, relocated presentation of specific somatic reflexes, namely the stretch reflex, withdrawal reflex, and crossed extensor reflex, from Chapter 5, Central Nervous System, where these reflexes were covered in conjunction with the spinal cord, to Chapter 8, Muscle Physiology, where they are now included in the section on Control of Motor Movement (pp. 282, 284–286)

## Clearer, more concise coverage

I look at every edition for opportunities to make the writing as clear, concise, well-organized, and relevant for readers as possible. By careful tightening, I was able to shave 22 pages from the text while retaining all essential content and adding more beneficial learning tools and updated content, a win-win for readers.

# New and Enhanced Technology for Instructors and Students

## NEW! MindTap for Human Physiology

MindTap is a personalized, fully digital learning platform of authoritative content, assignments, and services that engages students with interactivity while also offering instructors their choice in the configuration of coursework and enhancement of the curriculum via Web-based applications known as MindApps. MindApps range from ReadSpeaker (which reads the text out loud to students) to Kaltura (allowing you to insert inline video and audio into your curriculum). MindTap is well

beyond an eBook, a homework solution, a digital supplement, a resource center Web site, a course delivery platform, or a Learning Management System. It is the first in a new category—the Personal Learning Experience. MindTap for *Human Physiology* includes an integrated study guide, homework, and clinical case studies, among other valuable learning tools.

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Aplia for *Human Physiology* helps students learn and understand key concepts via focused assignments and active learning opportunities that include randomized, automatically graded questions, exceptional text interaction, and detailed explanations. With Aplia, students move away from just memorizing facts toward a more conceptual understanding of the course materials. In addition, Aplia has a full course management system that can be used independently or in conjunction with other course management systems such as MindTap, D2L, or Blackboard.

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Virtual Physiology Labs enable students to conduct experiments online without expensive equipment. By acquiring data, performing experiments, and using that data to explain physiology concepts, students become involved in the scientific process—they don't just watch or read about it.

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This helpful study tool contains key pieces of art from the book and provides opportunities for students to interact with the material and explain the processes associated with the figures in their own words.

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This full-color atlas (with more than 600 photographs) depicts structures in the same colors as they would appear in real life or in a slide. Labels and color differentiations within each structure are used to facilitate identification of the structure's various components. The atlas includes photographs of tissue and organ slides, the human skeleton, commonly used models, cat dissections, cadavers, some fetal pig dissections, and some physiology materials.

### Fundamentals of Physiology Laboratory Manual

This manual, which may be required by the instructor in courses that have a laboratory component, contains a variety of exercises that reinforce concepts covered in *Human Physiology: From Cells to Systems*, Ninth Edition. These laboratory experiences increase students' understanding of the subject matter in a straightforward manner, with thorough directions to guide them through the process and relevant questions for reviewing, explaining, and applying results.

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*Lauralee Sherwood*





# Introduction to Physiology and Homeostasis

# 1



Oliver Eltinger/Agfotostock

## CHAPTER AT A GLANCE

- 1.1 Introduction to Physiology
- 1.2 Levels of Organization in the Body
- 1.3 Concept of Homeostasis
- 1.4 Homeostatic Control Systems

**Homeostasis (maintaining internal consistency) in action.** Body temperature is maintained as evaporation of sweat cools the body to counterbalance heat gained through exertion on a hot day, and fluid balance is maintained as thirst encourages fluid intake to offset fluid lost in sweat.

## Homeostasis Highlights



**Physiology** focuses on body functions. This book explores how the various components of the human body function to maintain **homeostasis**, the relatively stable conditions inside the body needed for survival. Each chapter begins with *Homeostasis Highlights* to give you a heads up on how the body part under discussion fits in with the big picture of homeostasis. Each chapter concludes with *Homeostasis: Chapter in Perspective*, which points out specific ways in which the topic covered in the chapter contributes to homeostasis.

## 1.1 Introduction to Physiology

Look at Figure 1-1. The activities described are a sampling of the body processes that occur all the time just to keep us alive. We usually take these life-sustaining activities for granted and do not really think about “what makes us tick,” but that’s what physiology is about. **Physiology** is the study of the functions of living things. Specifically, we will focus on how the human body works.

### Physiology focuses on mechanisms of action.

Two approaches are used to explain events that occur in the body; one emphasizes the *purpose* of a body process and the other emphasizes the underlying *mechanism* by which this process occurs. In response to the question “Why do I shiver when I am cold?” one answer would be “to help my body warm up, because shivering generates heat.” This approach, which explains body functions in terms of meeting a bodily need, emphasizes *why* body processes occur. Physiologists, however, explain *how* processes occur in the body. They view the body as a machine whose mechanisms of action can be explained in terms of cause-and-effect sequences of physical and chemical processes—the same types of processes that occur throughout the universe. A physiologist’s explanation of shivering is that when temperature-sensitive nerve cells detect a fall in body temperature, they signal the area in the brain responsible for temperature regulation. In response, this brain area activates nerve pathways that ultimately bring about involuntary, oscillating muscle contractions (that is, shivering).

### Structure and function are inseparable.

Physiology is closely related to **anatomy**, the study of the structure of the body. Physiological mechanisms are made possible by the structural design and relationships of the various body parts that carry out each of these functions. Just as the functioning of an automobile depends on the shapes, organization, and interactions of its various parts, the structure and function of the human body are inseparable. Therefore, as we tell the story of how the body works, we provide sufficient anatomic background for you to understand the function of the body part being discussed.

Some structure–function relationships are obvious. For example, the heart is well designed to receive and pump blood, the teeth to tear and grind food, and the hingelike elbow joint to permit bending of the arm. In other situations, the interdependence of form and function is more subtle but equally important. Consider the interface between air and blood in the lungs as an example: The respiratory airways, which carry air from the outside into the lungs, branch extensively when they reach the lungs. Tiny air sacs cluster at the ends of the huge number of airway branches. The branching is so extensive that the lungs contain about 300 million air sacs. Similarly, the vessels carrying blood into the lungs branch extensively and form dense networks of small vessels that encircle each air sac (see **Figure 13-2**, p. 448). Because of this

structural relationship, the total surface area forming an interface between the air in the air sacs and the blood in the small vessels is about the size of one side of a volleyball court. This tremendous interface is crucial for the lungs’ ability to efficiently carry out their function: the transfer of needed oxygen ( $O_2$ ) from the air into the blood and the unloading of the waste product carbon dioxide ( $CO_2$ ) from the blood into the air. The greater the surface area available for these exchanges, the faster  $O_2$  and  $CO_2$  can move between the air and the blood. This large functional interface packaged within the confines of your lungs is possible only because both the air-containing and blood-containing components of the lungs branch extensively.

### Check Your Understanding 1.1

1. Define *physiology*.
2. The nutrient-absorbing intestinal cells have a multitude of fingerlike projections in contact with the digested food (see **Figure 16-20**, p. 602). Based on your knowledge of structure–function relationships, explain the functional advantage of this structural feature. (Answers are in Appendix C.)

## 1.2 Levels of Organization in the Body

We now turn to how the body is structurally organized into a total functional unit, from the chemical level to the whole body (**Figure 1-2**). These levels of organization make possible life as we know it.

### The chemical level: Various atoms and molecules make up the body.

Like all matter, both living and nonliving, the human body is a combination of specific *atoms*, which are the smallest building blocks of matter. The most common atoms in the body—oxygen, carbon, hydrogen, and nitrogen—make up approximately 96% of the total body chemistry. These common atoms and a few others combine to form the *molecules* of life, such as proteins, carbohydrates, fats, and nucleic acids (genetic material, such as deoxyribonucleic acid, or DNA). These important atoms and molecules are the inanimate raw ingredients from which all living things arise. (See Appendix A for a review of this chemical level.)

### The cellular level: Cells are the basic units of life.

The mere presence of a particular collection of atoms and molecules does not confer the unique characteristics of life. Instead, these nonliving chemical components must be arranged and packaged in precise ways to form a living entity. The **cell**, the fundamental unit of both structure and function in a living being, is the smallest unit capable of carrying out the processes associated with life. Cell physiology is the focus of Chapter 2.

**During the minute that it will take you to read this page:**

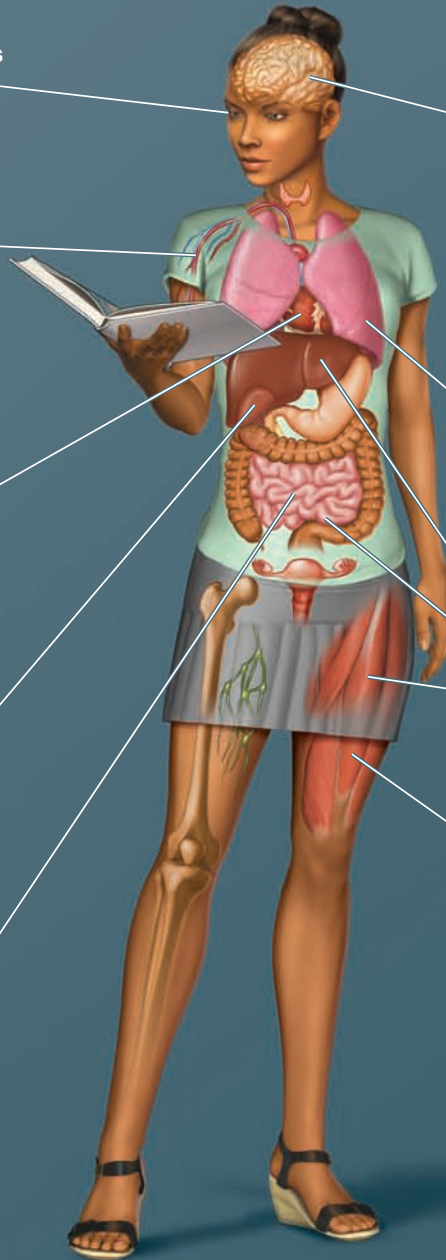
Your eyes will convert the image from this page into electrical signals (nerve impulses) that will transmit the information to your brain for processing.

Approximately 150 million old red blood cells will die and be replaced by newly produced ones.

Your heart will beat 70 times, pumping 5 liters (about 5 quarts) of blood to your lungs and another 5 liters to the rest of your body.

More than 1 liter of blood will flow through your kidneys, which will act on the blood to conserve the “wanted” materials and eliminate the “unwanted” materials in the urine. Your kidneys will produce 1 mL (about a thimbleful) of urine.

Your digestive system will be processing your last meal for transfer into your bloodstream for delivery to your cells.



Besides receiving and processing information such as visual input, your brain will provide output to your muscles to help maintain your posture, move your eyes across the page as you read, and turn the page as needed. Chemical messengers will carry signals between your nerves and muscles to trigger appropriate muscle contraction.

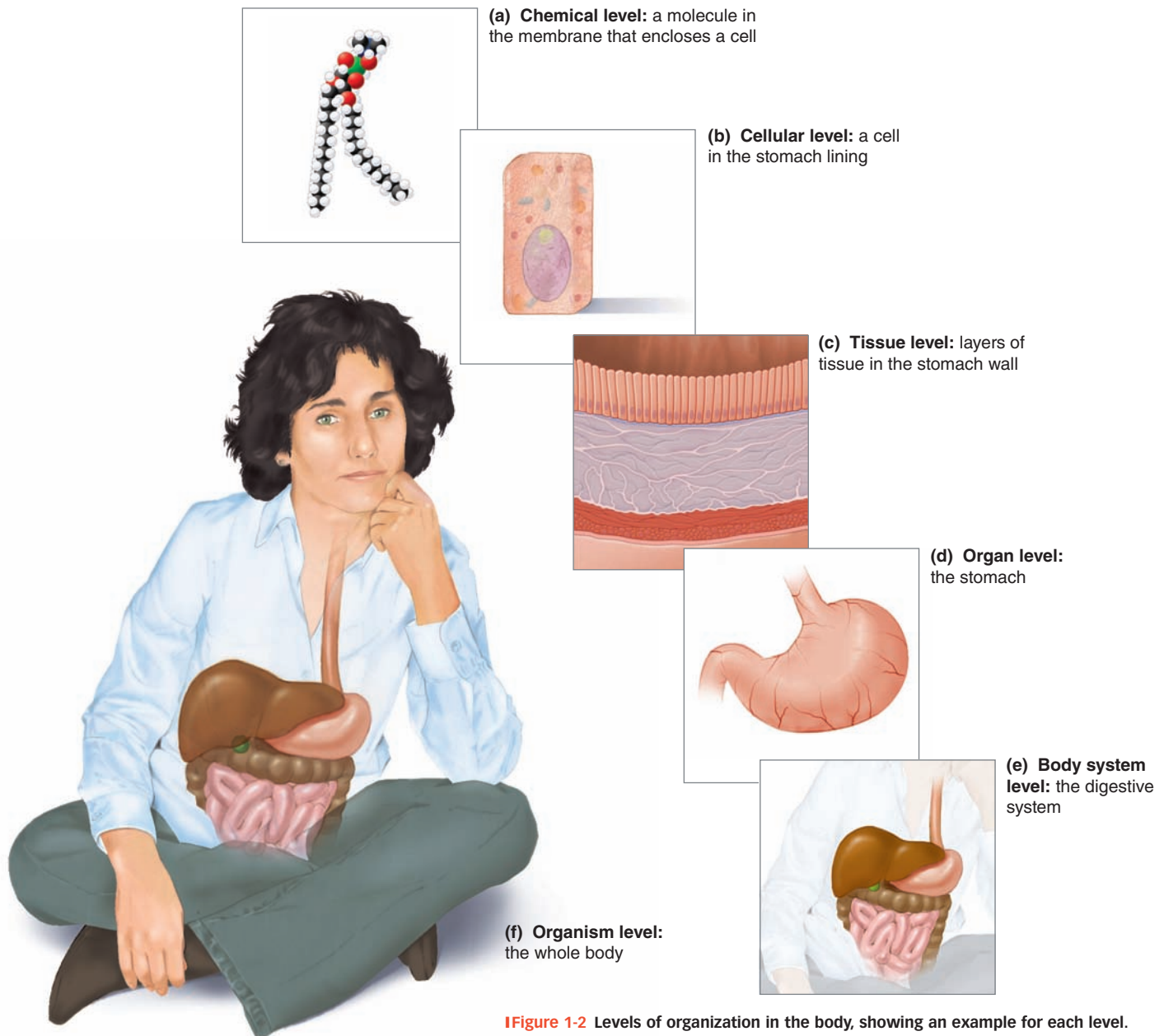
You will breathe in and out about 12 times, exchanging 6 liters of air between the atmosphere and your lungs.

Your cells will consume 250 mL (about a cup) of oxygen and produce 200 mL of carbon dioxide.

You will use about 2 calories of energy derived from food to support your body’s “cost of living,” and your contracting muscles will burn additional calories.

**IFigure 1-1 A glimpse at your body functions.**

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**Figure 1-2** Levels of organization in the body, showing an example for each level.

An extremely thin, oily, complex barrier, the *plasma membrane*, encloses the contents of each cell and controls movement of materials into and out of the cell. Thus, the cell's interior contains a combination of atoms and molecules that differs from the mixture of chemicals in the environment surrounding the cell. Given the importance of the plasma membrane and its associated functions for carrying out life processes, Chapter 3 is devoted entirely to this structure.

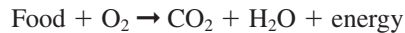
**Organisms** are independent living entities. The simplest forms of independent life are single-celled organisms such as bacteria and amoebas. Complex multicellular organisms, such as trees and humans, are structural and functional aggregates of trillions of cells (*multi* means “many”). In the simpler multicellular forms of life—for example, a sponge—the cells of the organism are all similar. However, more complex organisms, such as humans, have many kinds of cells, such as muscle cells, nerve cells, and gland cells.

Each human organism begins when an egg and sperm unite to form a single new cell, which multiplies and forms a growing mass through myriad cell divisions. If cell multiplication were the only process involved in development, all body cells would be essentially identical, as in the simplest multicellular life-forms. However, during development of complex multicellular organisms such as humans, each cell also **differentiates**, or becomes specialized to carry out a particular function. As a result of cell differentiation, your body is made up of about 200 specialized types of cells.

**Basic Cell Functions** All cells, whether they exist as solitary cells or as part of a multicellular organism, perform certain basic functions essential for their own survival, including the following:

1. Obtaining food (nutrients) and  $O_2$  from the environment surrounding the cell.

2. Performing chemical reactions that use nutrients and O<sub>2</sub> to provide energy for the cells, as follows:



3. Eliminating to the cell's surrounding environment CO<sub>2</sub> and other by-products, or wastes, produced during these chemical reactions.

4. Synthesizing proteins and other components needed for cell structure, for growth, and for carrying out particular cell functions. For example, **enzymes** are specialized proteins that speed up particular chemical reactions in the body.

5. Largely controlling the exchange of materials between the cell and its surrounding environment.

6. Moving materials internally from one part of the cell to another, with some cells also being able to move themselves through their surrounding environment.

7. Being sensitive and responsive to changes in the surrounding environment.

8. In the case of most cells, reproducing. Exceptions are nerve cells and muscle cells, which lose the ability to reproduce soon after they are formed. This is the reason strokes, which result in lost nerve cells in the brain, and heart attacks, which cause death of heart muscle cells, can be so devastating.

Because all cells are remarkably similar in the ways they carry out these basic functions, they share many common characteristics despite their specialization.

**Specialized Cell Functions** In multicellular organisms, each cell also performs a specialized function, which is usually a modification or elaboration of a basic cell function. Here are a few examples:

- By taking special advantage of their protein-synthesizing ability, the gland cells of the digestive system secrete digestive enzymes that break down ingested food.

- Certain kidney cells can selectively retain the substances needed by the body while eliminating unwanted substances in the urine because of their highly specialized ability to control exchange of materials between the cell and its environment.

- Muscle contraction, which involves selective movement of internal structures to generate tension in the muscle cells, is an elaboration of the inherent ability of these cells to produce intracellular movement (*intra* means “within”).

- Capitalizing on the basic ability of cells to respond to changes in their surrounding environment, nerve cells generate and transmit to other body regions electrical impulses that relay information

about changes to which the nerve cells are responsive. For example, nerve cells in the ear can relay information to the brain about sounds in the body's surroundings.

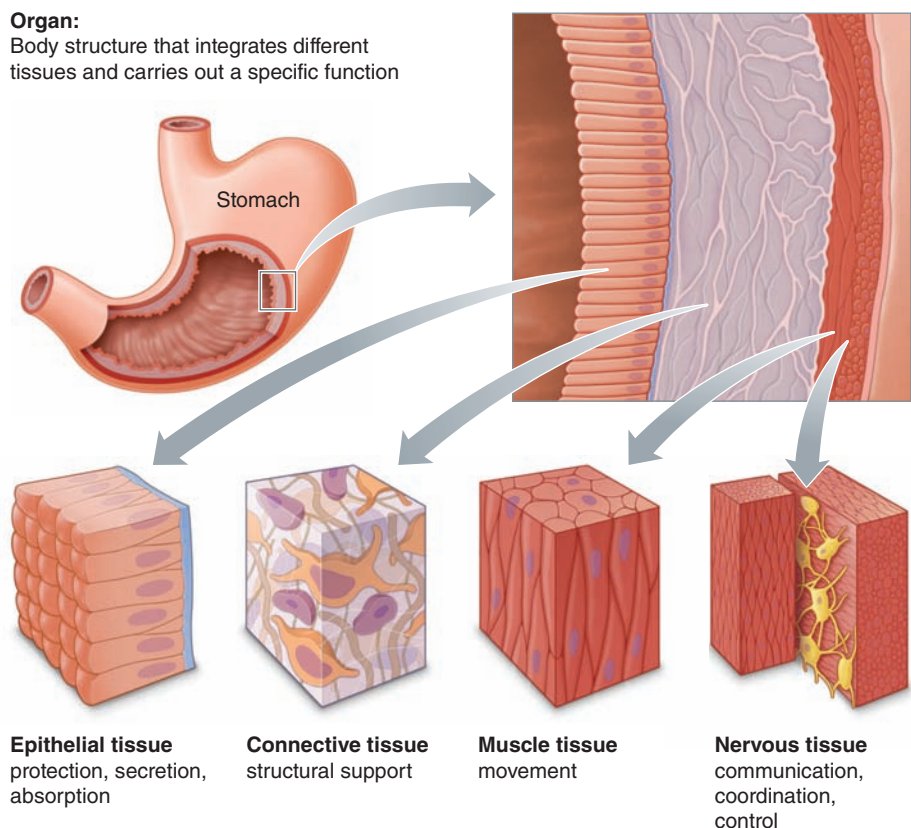
Each cell performs these specialized activities in addition to carrying on the unceasing, fundamental activities required of all cells. The basic cell functions are essential for survival of individual cells, whereas the specialized contributions and interactions among the cells of a multicellular organism are essential for survival of the whole body.

Just as a machine does not function unless all its parts are properly assembled, the cells of the body must be specifically organized to carry out the life-sustaining processes of the body as a whole, such as digestion, respiration, and circulation. Cells are progressively organized into tissues, organs, body systems, and finally the whole body.

### The tissue level: Tissues are groups of cells of similar specialization.

Cells of similar structure and specialized function combine to form **tissues**, of which there are four *primary types*: muscle, nervous, epithelial, and connective (Figure 1-3). Each tissue consists of cells of a single specialized type, along with varying amounts of extracellular material (*extra* means “outside of”).

- **Muscle tissue** consists of cells specialized for contracting, which generates tension and produces movement. The three types of muscle tissue include *skeletal muscle*, which moves the skeleton; *cardiac muscle*, which pumps blood out of the heart;



**Figure 1-3** The stomach as an organ made up of all four primary tissue types.

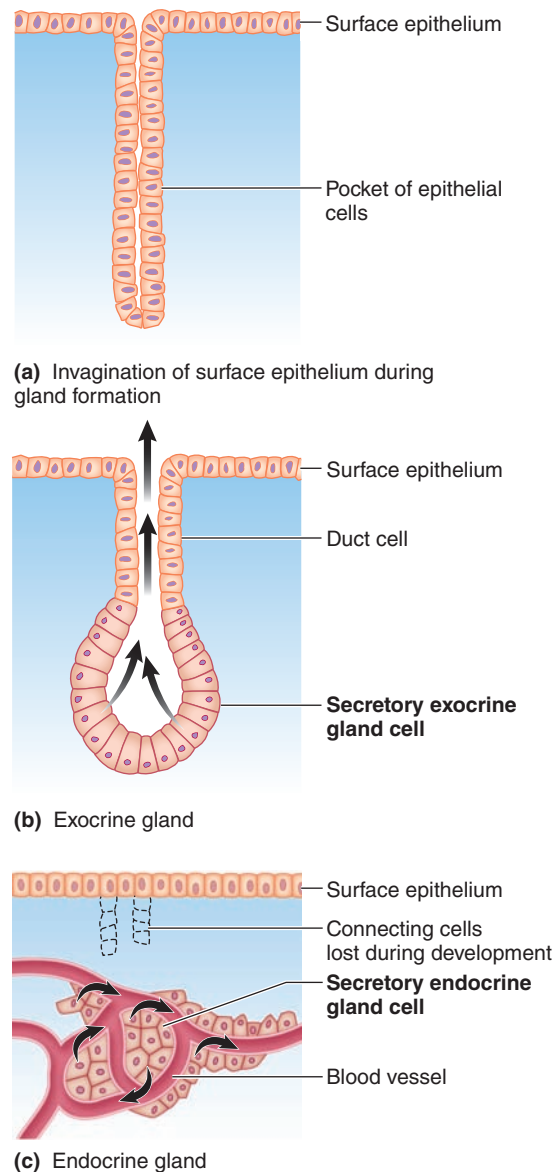
and *smooth muscle*, which controls movement of contents through hollow tubes and organs, such as movement of food through the digestive tract.

- **Nervous tissue** consists of cells specialized for initiating and transmitting electrical impulses, sometimes over long distances. These electrical impulses act as signals that relay information from one part of the body to another. Such signals are important in communication, coordination, and control in the body. Nervous tissue is found in the brain, spinal cord, nerves, and special sense organs.

- **Epithelial tissue** consists of cells specialized for exchanging materials between the cell and its environment. Any substance that enters or leaves the body must cross an epithelial barrier. Epithelial tissue is organized into two general types of structures: *epithelial sheets* and *secretory glands*. Epithelial sheets are layers of tightly joined cells that cover and line various parts of the body. For example, the outer layer of the skin is epithelial tissue, as is the lining of the digestive tract. In general, epithelial sheets serve as boundaries that separate the body from its surroundings and from the contents of cavities that open to the outside, such as the digestive tract lumen. (A **lumen** is the cavity within a hollow organ or tube.) Only selective transfer of materials is possible between regions separated by an epithelial barrier. The type and extent of controlled exchange vary depending on the location and function of the epithelial tissue. For example, the skin can exchange little between the body and outside environment, making it a protective barrier. By contrast the epithelial cells lining the small intestine of the digestive tract are specialized for absorbing nutrients that have come from outside the body.

**Glands** are epithelial tissue derivatives specialized for secreting. **Secretion** is the release from a cell, in response to appropriate stimulation, of specific products that have been produced by the cell. Glands are formed during embryonic development by pockets of epithelial tissue that dip inward from the surface and develop secretory capabilities. The two categories of glands are *exocrine* and *endocrine* (Figure 1-4). During development, if the connecting cells between the epithelial surface cells and the secretory gland cells within the depths of the pocket remain intact as a duct between the gland and the surface, an exocrine gland is formed. **Exocrine glands** secrete through ducts to the outside of the body (or into a cavity that opens to the outside) (*exo* means “external”; *crine* means “secretion”). Examples are sweat glands and glands that secrete digestive juices. If, in contrast, the connecting cells disappear during development and the secretory gland cells are isolated from the surface, an endocrine gland is formed. **Endocrine glands** lack ducts and release their secretory products, known as *hormones*, internally into the blood (*endo* means “internal”). For example, the pancreas secretes insulin into the blood, which transports this hormone to its sites of action throughout the body. Most cell types depend on insulin for taking up glucose (sugar).

- **Connective tissue** is distinguished by having relatively few cells dispersed within an abundance of extracellular material. As its name implies, connective tissue connects, supports, and



**Figure 1-4 Exocrine and endocrine glands.** (a) Glands form during development from pocketlike invaginations of surface epithelial cells. (b) Exocrine gland cells release their secretory product through a duct to the outside of the body (or to a cavity in communication with the outside). (c) Endocrine gland cells release their secretory product (a hormone) into the blood.

**FIGURE FOCUS:** *Milk-secreting glands are surrounded by musclelike cells that squeeze out the milk in response to oxytocin secreted into the blood when a baby breast-feeds. Are milk-secreting glands exocrine or endocrine? Is oxytocin secreted by an exocrine or endocrine gland? (Answers are in Appendix C.)*

anchors various body parts. It includes such diverse structures as the loose connective tissue that attaches epithelial tissue to underlying structures; tendons, which attach skeletal muscles to bones; bone, which gives the body shape, support, and protection; and blood, which transports materials from one part of the body to another. Except for blood, the cells within connective tissue produce specific structural molecules that they release into the extracellular spaces between the cells. One such molecule is the rubber band–like protein fiber *elastin*; its presence facilitates the stretching and recoiling of structures

such as the lungs, which alternately inflate and deflate during breathing.

Muscle, nervous, epithelial, and connective tissue are the primary tissues in a classical sense—that is, each is an integrated collection of cells with the same specialized structure and function. The term *tissue* is also often used, as in clinical medicine, to mean the aggregate of various cellular and extracellular components that make up a particular organ (for example, lung tissue or liver tissue).

### The organ level: An organ is a unit made up of several tissue types.

**Organs** consist of two or more types of primary tissue organized to perform particular functions. The stomach, an example of an organ, is made up of all four primary tissue types (see **Figure 1-3**). The tissues of the stomach function collectively to store ingested food, move it forward into the rest of the digestive tract, and begin the digestion of protein. The stomach is lined with epithelial tissue that restricts the transfer of harsh digestive chemicals and undigested food from the stomach lumen into the blood. Epithelial gland cells in the stomach include exocrine cells, which secrete protein-digesting juices into the lumen, and endocrine cells, which secrete a hormone that helps regulate the stomach's exocrine secretion and muscle contraction. The stomach wall contains smooth muscle tissue, whose contractions mix ingested food with the digestive juices and push the mixture out of the stomach and into the intestine. The stomach wall also contains nervous tissue, which, along with hormones, controls muscle contraction and gland secretion. Connective tissue binds together all these various tissues.

### The body system level: A body system is a collection of related organs.

Groups of organs are further organized into **body systems**. Each system is a collection of organs that perform related functions and interact to accomplish a common activity essential for survival of the whole body. For example, the digestive system consists of the mouth, pharynx (throat), esophagus, stomach, small intestine, large intestine, salivary glands, exocrine pancreas, liver, and gallbladder. These digestive organs cooperate to break food down into small nutrient molecules that can be absorbed into the blood for distribution to all cells.

The human body has 11 systems: circulatory, digestive, respiratory, urinary, skeletal, muscular, integumentary, immune, nervous, endocrine, and reproductive (**Figure 1-5**). Chapters 4 through 20 cover the details of these systems.

### The organism level: The body systems are packaged into a functional whole body.

Each body system depends on the proper functioning of other systems to carry out its specific responsibilities. The whole body of a multicellular organism—a single, independently living individual—consists of the various body systems structurally and functionally linked as an entity that is separate from its sur-

rounding environment. Thus, the body is made up of living cells organized into life-sustaining systems.

The different body systems do not act in isolation from one another. Many complex body processes depend on the interplay among multiple systems. For example, regulation of blood pressure depends on coordinated responses among the circulatory, urinary, nervous, and endocrine systems. Even though physiologists may examine body functions at any level from cells to systems (as indicated in the title of this book), their ultimate goal is to integrate these mechanisms into the big picture of how the entire organism works as a cohesive whole.

Currently, researchers are hotly pursuing several approaches for repairing or replacing tissues or organs that can no longer adequately perform vital functions because of disease, trauma, or age-related changes. (See the boxed feature on pp. 10 and 11, **Concepts, Challenges, and Controversies**. Each chapter has similar boxed features that explore in greater depth high-interest information on such diverse topics as environmental impact on the body, aging, ethical issues, discoveries regarding common diseases, and historical perspectives.)

We next focus on how the different body systems normally work together to maintain the internal conditions necessary for life.

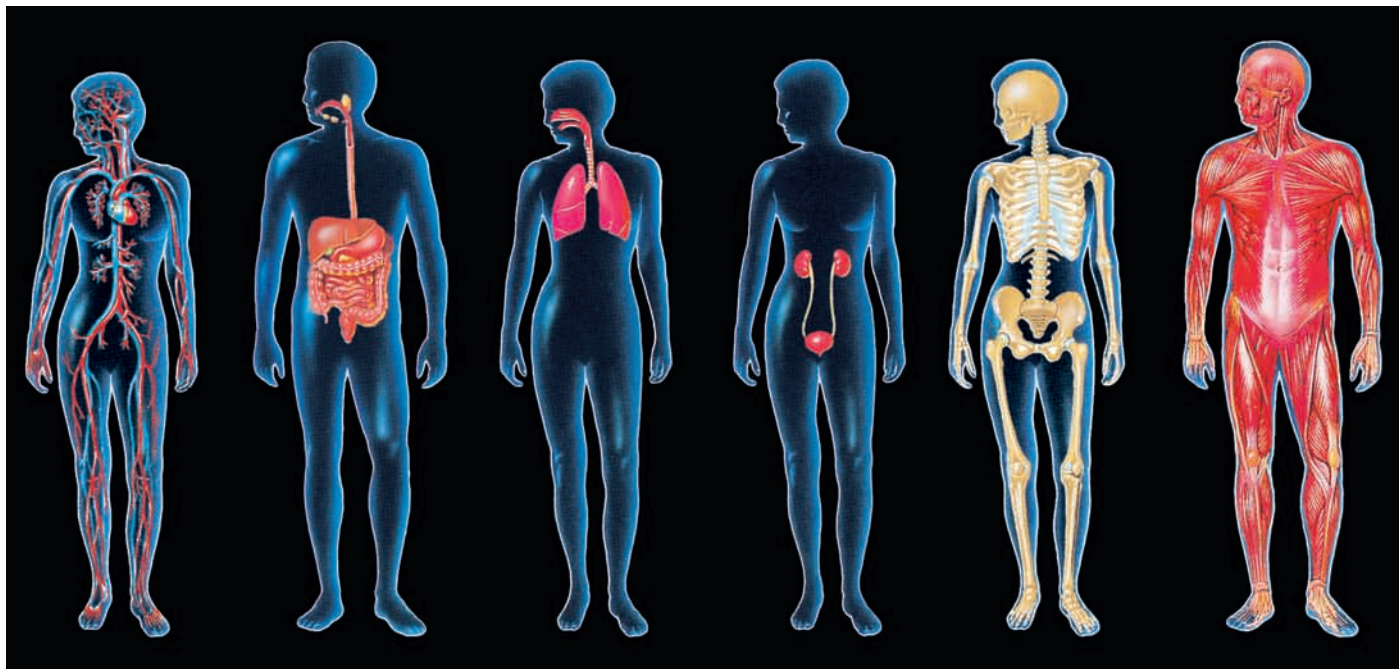
#### Check Your Understanding 1.2

1. List and describe the levels of organization in the body.
2. State the basic cell functions.
3. Name the four primary types of tissue and give an example of each.

## 1.3 Concept of Homeostasis

If each cell has basic survival skills, why can't the body cells live without performing specialized tasks and being organized according to specialization into systems that accomplish functions essential for the whole organism's survival? The cells in a multicellular organism cannot live and function without contributions from the other body cells because most cells are not in direct contact with the external environment. The **external environment** is the surrounding environment in which an organism lives. A single-celled organism such as an amoeba obtains nutrients and O<sub>2</sub> directly from its immediate external surroundings and eliminates wastes back into those surroundings. A muscle cell or any other cell in a multicellular organism has the same need for life-supporting nutrient and O<sub>2</sub> uptake and waste elimination; yet, the muscle cell is isolated from the external environment surrounding the body. How can it make vital exchanges with the external environment with which it has no contact? The key is the presence of a watery internal environment. The **internal environment** is the fluid that surrounds the cells and through which they make life-sustaining exchanges.





**Circulatory system**  
heart, blood vessels,  
blood

**Digestive system**  
mouth, pharynx,  
esophagus, stomach,  
small intestine, large  
intestine, salivary  
glands, exocrine  
pancreas, liver,  
gallbladder

**Respiratory system**  
nose, pharynx, larynx,  
trachea, bronchi, lungs

**Urinary system**  
kidneys, ureters,  
urinary bladder,  
urethra

**Skeletal system**  
bones, cartilage,  
joints

**Muscular system**  
skeletal muscles

**Figure 1-5** Components of the body systems.

## Body cells are in contact with a privately maintained internal environment.

The fluid collectively contained within all body cells is called **intracellular fluid (ICF)**. The fluid outside the cells is called **extracellular fluid (ECF)**. Note that the ECF is outside the cells but inside the body. Thus, the ECF is the internal environment of the body. You live in the external environment; your cells live in the body's internal environment.

ECF is made up of two components: the **plasma**, the fluid portion of the blood, and the **interstitial fluid**, which surrounds and bathes the cells (*inter* means “between”; *stitial* means “that which stands”) (Figure 1-6).

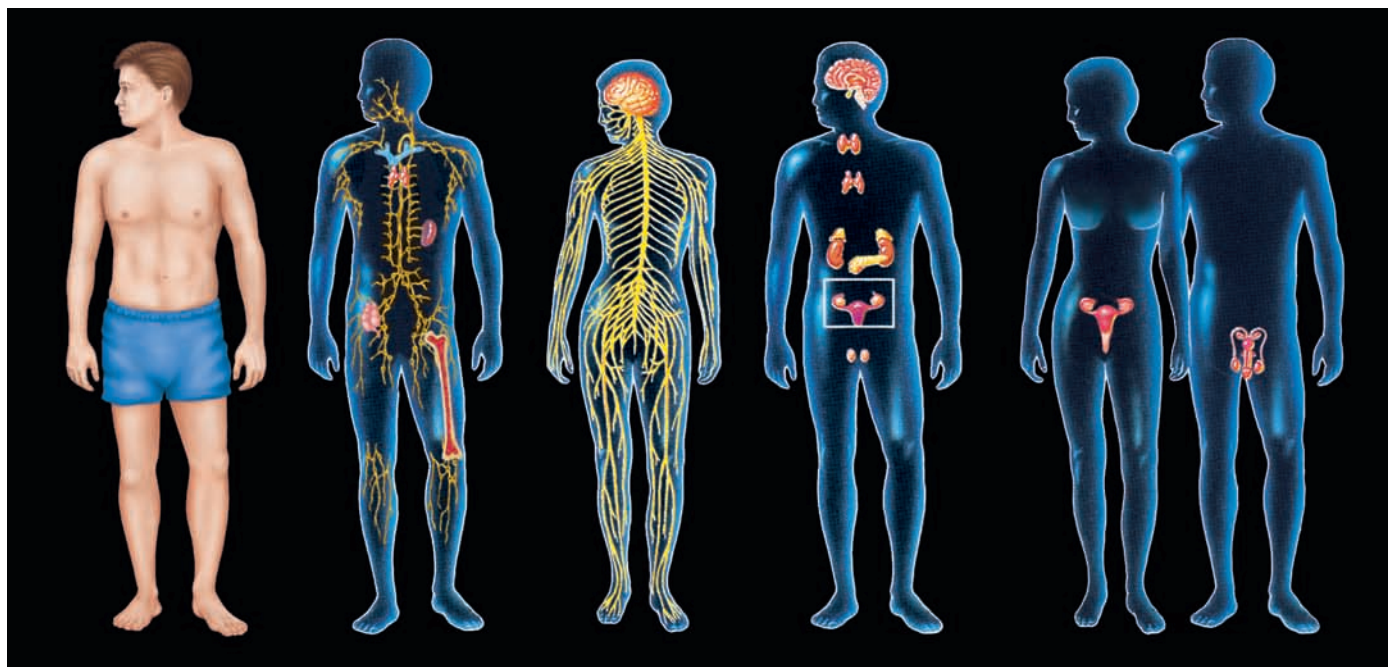
No matter how remote a cell is from the external environment, it can make life-sustaining exchanges with its surrounding fluid. Particular body systems accomplish the transfer of materials between the external environment and the internal environment so that the composition of the internal environment is appropriately maintained to support the life and functioning of the cells. The digestive system transfers the nutrients required by all body cells from the external environment into the plasma, and the respiratory system transfers  $O_2$  from the external environment into the plasma. The circulatory system distributes these nutrients and  $O_2$  throughout the body. Materials are thoroughly mixed and exchanged between the plasma and the interstitial fluid across the capillaries, the smallest and thinnest of blood vessels. As a result, the nutrients and  $O_2$  originally obtained from the

external environment are delivered to the interstitial fluid, from which the body cells pick up these needed supplies. Similarly, wastes produced by the cells are released into the interstitial fluid, picked up by the plasma, and transported to the organs that specialize in eliminating these wastes from the internal environment to the external environment. The lungs remove  $CO_2$  from the plasma and blow out this waste, and the kidneys remove other wastes for elimination in the urine.

Thus, a body cell takes in essential nutrients from its watery surroundings and eliminates wastes into these same surroundings, just as an amoeba does. The main difference is that each body cell must help maintain the composition of the internal environment so that this fluid continuously remains suitable to support the existence of all body cells. In contrast, an amoeba does nothing to regulate its surroundings.

## Body systems maintain homeostasis, a dynamic steady state in the internal environment.

Body cells can live and function only when the ECF is compatible with their survival; thus, the chemical composition and physical state of this internal environment must be maintained within narrow limits. As cells take up nutrients and  $O_2$  from the internal environment, these essential materials must constantly be replenished. Likewise, wastes must constantly be removed from the internal environment so that they do not reach toxic



**Integumentary system**  
skin, hair, nails

**Immune system**  
lymph nodes, thymus, bone marrow, tonsils, adenoids, spleen, appendix, and, not shown, white blood cells, gut-associated lymphoid tissue, skin-associated lymphoid tissue

**Nervous system**  
brain, spinal cord, peripheral nerves, and, not shown, special sense organs

**Endocrine system**  
all hormone-secreting tissues, including hypothalamus, pituitary, thyroid, adrenals, endocrine pancreas, gonads, kidneys, pineal, thymus, and, not shown, parathyroids, intestine, heart, skin, adipose tissue

**Reproductive system**  
*Male:* testes, penis, prostate gland, seminal vesicles, bulbourethral glands, associated ducts  
*Female:* ovaries, oviducts, uterus, vagina, breasts

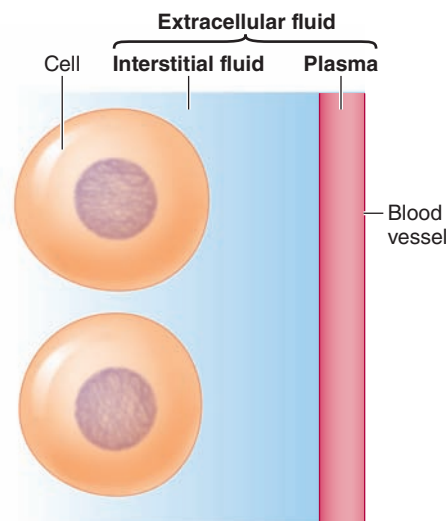
levels. Other aspects of the internal environment important for maintaining life, such as temperature, also must be kept relatively constant. Maintenance of a relatively stable internal environment is termed **homeostasis** (*homeo* means “similar”; *stasis* means “to stand or stay”).

The functions performed by each body system contribute to homeostasis, thereby maintaining within the body the environment required for the survival and function of all cells. Cells, in turn, make up body systems. This is the central theme of physiology and of this book: *Homeostasis is essential for the survival of each cell, and each cell, through its specialized activities as part of a body system, helps maintain the internal environment shared by all cells* (Figure 1-7, p. 12).

The internal environment must be kept relatively stable, but this does not mean that its composition, temperature, and other characteristics are absolutely unchanging. Both external and internal factors continuously threaten to disrupt homeostasis. When any factor starts to move the internal environment away from optimal conditions, the body systems initiate appropriate counter-reactions to minimize the change. For example, when you’re exposed to a cold environmental temperature (an external factor), your body temperature tends to fall. In response, the temperature control center in your brain initiates compensatory measures, such as shivering, to raise your body temperature to normal. By contrast, when you exercise, your working muscles produce extra heat (an internal factor) that tends to increase your body temperature. In response, the temperature control

center brings about sweating and other compensatory measures to reduce your body temperature to normal.

Thus, homeostasis is not a rigid, fixed state but a dynamic steady state in which changes that occur are minimized by compensatory physiological responses. The term *dynamic* refers to each homeostatically regulated factor being marked by continuous change, whereas *steady state* implies that these changes do



**Figure 1-6** Components of the extracellular fluid (internal environment).