

Contents

Section I: Foundations

1 Homeostasis and Integration: The Foundations of Physiology 1

1.1 Introduction 1

Biological adaptations have two levels of explanation: the mechanistic (or proximate) and the evolutionary (or ultimate) 1

Adaptations reflect evolutionary history including cost-benefit trade-offs 2

Physiology is an integrative discipline 3

Physiology is also a comparative discipline, often following the Krogh principle 3

A Closer Look at Adaptation: Geckos on Glass 4

1.2 Methods in Physiology 6

The hypothetico-deductive method is the most widely accepted version of "the scientific method" 6

1.3 Levels of Organization in Organisms 7

Life has the properties of self-organization, self-regulation, self-support and movement, and self-reproduction 7

Cells are progressively organized into tissues, organs, systems, and finally the whole body 8

1.4 Size and Scale among Organisms 10

The larger the organism, the smaller the surface-area-to-volume ratio 10

1.5 Homeostasis: Basic Mechanisms and Enhancements 11

Body cells are in contact with a privately maintained internal environment instead of with the external environment that surrounds organisms 11

Homeostasis is essential for proper cell function, and most cells, as part of an organized system, contribute to homeostasis 12

Animals vary in their homeostatic abilities 13

Negative feedback is the main regulatory mechanism for homeostasis 13

Challenges and Controversies: Can a Planet Have Physiology? 14

Feedback effectors can be antagonistic and can include behaviors as well as internal organs 16

Inadequacies in negative-feedback systems can be improved by anticipation and acclimatization 16

1.6 Regulated Change 17

Some internal processes are not always homeostatic but may be changed by reset and positive-feedback systems 17

Disruptions in regulation can lead to illness and death 19

1.7 Organization of Regulatory and Organ Systems 19

Homeostasis (and other regulation) is hierarchically distributed 19
Organ systems can be grouped according to whole-body contributions 21

Making Connections: How Homeostasis and Integration Contribute to the Body as a Whole 22

Chapter Summary 23

Review, Synthesize, and Analyze 23

Suggested Readings 23

2 Cellular and Molecular Physiology 25

2.1 Introduction 25

Water, other inorganic chemicals, and four types of organic molecules are the universal components of cells 25

All cells have two major subdivisions: the plasma membrane and the cytoplasm 27

Many macromolecular structures need to be flexible to function and to be regulated, and protecting those structures is the basis for many forms of homeostasis 27

Archaeal and bacterial cells have a simpler organization than eukaryotic cells 27

Eukaryotic cells are subdivided into the plasma membrane, nucleus, and cytoplasm 29

2.2 Nucleus, Chromosomes, and Genes 30

DNA contains codes in the form of genes for making RNAs and proteins through the processes of transcription and translation 30

Different genes are expressed in different tissues and organs 30

Alternative splicing of RNA and some "junk" DNA are important in gene expression and evolution 32

Telomeres protect chromosome ends, and their loss is associated with aging 33

2.3 Methodology 33

Molecular Biology and Genomics: Genomics and Evolution 34

Unanswered Questions: Are cloning and genetic engineering ethical? 38

2.4 Ribosomes and Endoplasmic Reticulum 38

The rough endoplasmic reticulum and its ribosomes synthesize proteins for secretion and membrane construction 38

The smooth endoplasmic reticulum packages new proteins in transport vesicles 39

2.5 Golgi Complex 41

Transport vesicles carry their cargo to the Golgi complex for further processing 41

The Golgi complex packages secretory vesicles for release by exocytosis 41

2.6 Lysosomes and Proteasomes 44

Lysosomes digest extracellular material brought into the cell by phagocytosis 44

Lysosomes remove worn out organelles 45

Proteasomes destroy internal proteins 46

2.7 Peroxisomes 46

2.8 Mitochondria and Energy Metabolism 47

Mitochondria are enclosed by two membranes 47

Aerobic metabolism in mitochondria relies on O_2 to convert energy in food into ATP 47

Mitochondrial metabolism can create oxidative stress 53

Mitochondrial densities vary among tissue and organ types such as muscles 54

Phosphagens provide a rapid source for ATP production 55

Oxygen deficiency forces cells to rely on glycolysis and other anaerobic reactions, producing lactate, propionic acid, octopine, or other end products 55

Tolerance of oxygen deficiency varies widely among organisms 56

A Closer Look at Adaptation: Anoxic Animals 57

2.9 Vaults 57

2.10 Cytosol 58

The cytosol is important in intermediary metabolism, ribosomal protein synthesis, and storage of fat and glycogen 58

2.11 Centrosome, Centrioles, and Microtubule Organization 59

2.12 Cytoskeleton: Cell "Bone and Muscle" 59

Microtubules are essential for maintaining asymmetric cell shapes and are important in complex cell movements **59**

Microfilaments are important to cellular contractile systems and as mechanical stiffeners **62**

Intermediate filaments are important in regions of the cell subject to mechanical stress **63**

The cytoskeleton functions as an integrated whole, links other parts of the cell, and contributes to cytosolic "crowding" **64**

2.13 Cell-to-Cell Adhesions 65

The extracellular matrix serves as the biological "glue" **65**

Some cells are directly linked together by specialized cell junctions **65**

Making Connections: How Cellular and Molecular Physiology Contribute to the Body as a Whole 67**Chapter Summary 68****Review, Synthesize, and Analyze 68****Suggested Readings 69****3 Membrane Physiology 70****3.1 Membrane Structure and Composition 70**

The plasma membrane is a fluid lipid bilayer embedded with proteins **70**

The mosaic model and membrane-skeleton fence model describe membrane structure and function **73**

The lipid bilayer forms the basic structural barrier that encloses the cell **73**

The membrane proteins perform a variety of specific membrane functions **73**

The membrane carbohydrates serve as self-identity markers **74**

3.2 Unassisted Membrane Transport 74

Lipid-soluble substances and small polar molecules can passively diffuse through the plasma membrane down their electrochemical gradient **74**

In unassisted membrane transport, particles that can permeate the membrane diffuse passively down their concentration gradient **75**

Ions that can permeate the membrane also conduct passively along their electrical gradient **77**

Osmosis is the net movement of water through a membrane **77**

Osmosis across membranes results between solutions with different concentrations of a nonpenetrating solute **78**

Colligative properties of solutions are dependent solely on the number of dissolved particles **79**

Tonicity refers to the effect the concentration of nonpenetrating solutes in a solution has on cell volume **79**

Unanswered Questions: Is osmosis really the simple diffusion of water down its concentration gradient? **80**

3.3 Assisted Membrane Transport 81

Channel transport is accomplished by protein pores, while carrier-mediated transport generally requires proteins that "flip-flop" **81**

Facilitated diffusion is passive carrier-mediated transport **84**

Active transport is carrier-mediated transport that uses energy and moves a substance against its concentration gradient **84**

With vesicular transport, material is moved into or out of the cell wrapped in membrane **89**

3.4 Intercellular Communication and Signal Transduction 91

Communication between cells is orchestrated by direct contact and by extracellular chemical messengers **91**

Chemical messengers can have multiple, unrelated effects because of the "same key, different locks" principle **93**

Extracellular chemical messengers bring about cell responses primarily by signal transduction **94**

Internal receptors bind lipophilic and gaseous external messengers that enter the cell **94**

Some lipophobic external messengers bind to plasma membrane receptors, which alter ion channels or trigger phosphorylating enzymes (kinases) **94**

A Closer Look at Adaptation: Lighting Up the Night 96

Other lipophobic external messengers bind to plasma membrane receptors, which stimulate second-messenger production, often via G proteins **97**

Pharmacological agents and toxins are often agonists or antagonists affecting communication mechanisms **100**

Molecular Biology and Genomics: Programmed Cell Suicide 101**3.5 Membrane Potential 102**

Membrane potential is a separation of opposite charges across the plasma membrane **102**

Membrane potential is primarily due to differences in the distribution and permeability of key ions **102**

Making Connections: How Membrane Physiology Contributes to the Body as a Whole 108**Chapter Summary 109****Review, Synthesize, and Analyze 110****Suggested Readings 110****4 Neuronal Physiology 111****4.1 Introduction 111**

Excitable cells such as neurons and muscles evolved for rapid signaling, coordination, and movement **111**

Electrical signals are produced by changes in ion movement through ion channels across the plasma membrane **112**

4.2 Graded Potentials 113

The stronger a triggering event, the larger the resultant graded potential **113**

Graded potentials spread by passive current flow and are impeded by resistances **113**

Graded potentials die out over short distances **114**

4.3 Action Potentials 116

During an action potential, the membrane potential rapidly and transiently reverses **116**

Marked changes in membrane permeability and ion movement enhanced by positive feedback lead to an action potential **117**

Unanswered Questions: How do voltage gates actually open and close? **118**

The Na^+/K^+ ATPase pump gradually restores the concentration gradients disrupted by action potentials **120**

Action potentials are propagated from the axon hillock to the axon terminals **121**

Once initiated, action potentials are conducted over the surface of an axon **122**

The refractory period ensures unidirectional propagation of the action potential **124**

The refractory period also limits the frequency of action potentials **125**

Action potentials occur in all-or-none fashion **125**

The strength of a stimulus is coded primarily by the frequency of action potentials **125**

Myelination increases the speed of conduction of action potentials and conserves energy in the process **126**

Insect neurons are coated with a sheath that regulates ion balance **126**

Unanswered Questions: How many animal groups have myelin? **128**

Fiber diameter also influences the velocity of action potential propagation **129**

4.4 Electrical and Chemical Synapses 129

Electrical synapses transfer action potential waveforms through gap junctions **129**

Chemical synapses convert action potentials into organic chemical messengers that are exocytosed into the synaptic gap **130**

4.5 Neuron-to-Neuron Synapses 130

A neurotransmitter carries the signal across a fast synapse and opens a chemically gated channel **130**

Some neurotransmitters excite the postsynaptic neuron, whereas others inhibit the postsynaptic neuron **132**

Each neurotransmitter-receptor combination always produces the same response **133**

Neurotransmitters are quickly removed from the synaptic cleft **133**

Neurotransmitters in slow synapses function through intracellular second-messenger systems **133**

4.6 Neuromuscular Synapses 134

Acetylcholine, a fast excitatory neurotransmitter, links electrical signals in motor neurons with electrical signals in skeletal muscle cells **134**

Acetylcholinesterase terminates acetylcholine activity at the neuromuscular junction **136**

4.7 Synapses and Integration 136

The grand postsynaptic potential depends on the sum of the activities of all presynaptic inputs **136**

Action potentials are initiated at the axon hillock because it has the lowest threshold **138**

Neuropeptides act primarily as neuromodulators **138**

Presynaptic inhibition or facilitation can selectively alter the effectiveness of a given presynaptic input **140**

Retrograde messengers travel "backward" and also modulate synaptic function **141**

Neurons are linked to each other through convergence and divergence to form complex nerve pathways **141**

4.8 Neural Signaling and External Agents 142

Synthetic and natural toxins can alter resting potentials and action potentials **142**

Drugs, natural toxins, and pollutants can modify synaptic transmission between neurons **142**

Molecular Biology and Genomics: Neurotoxins in War and Peace 143

Challenges and Controversies: Synaptic Solutions to Pet Problems 144

The neuromuscular junction is vulnerable to several chemical agents and diseases **144**

Temperature and pressure also influence action potentials and synapses **145**

Making Connections: How Neuronal Physiology Contributes to the Body as a Whole 145

Chapter Summary 146

Review, Synthesize, and Analyze 146

Suggested Readings 147

Section II: Whole-Body Regulation and Integration

5 Nervous Systems 148

5.1 Evolution of Nervous Systems 148

Nervous systems evolved from simple reflex arcs to centralized brains with distributed, hierarchic regulation **148**

Sponges have no nerves but can respond to stimuli using electrical signals **150**

Nerve nets are the simplest nervous systems and are found in most animals **150**

Unanswered Questions: How did nervous systems evolve? **152**

Simple ganglia and nerve rings evolved for more complex behavior **152**

A true CNS first evolved with bilateral symmetry **152**

True brains evolved at the anterior end of complex animals **154**

Cephalopod brains have complex structures supporting complex behaviors **154**

Vertebrate brain size varies up to 30-fold for a given body size **155**

Relative brain size may be explained by the expensive-tissue hypothesis **156**

Some nervous systems exhibit plasticity **156**

5.2 The Vertebrate Nervous System: Overview and Peripheral System 156

The three classes of neurons are afferent neurons, efferent neurons, and interneurons **157**

The efferent division of the vertebrate PNS controls the activities of various effector organs **158**

The sympathetic and parasympathetic branches of the autonomic system innervate most visceral organs to control essential visceral functions **158**

The sympathetic system dominates in times of "fight or flight" **159**

The parasympathetic system dominates in times of "rest and digest" **159**

Dual innervation gives precise, antagonistic control **161**

An autonomic nerve pathway consists of a two-neuron chain **162**

Parasympathetic postganglionic fibers release acetylcholine; sympathetic ones release norepinephrine **162**

The adrenal medulla, an endocrine gland, is a modified part of the sympathetic nervous system **164**

Several different receptor types are available for each autonomic neurotransmitter **164**

Many regions of the central nervous system are involved in the control of autonomic activities **165**

The vertebrate somatic system controls skeletal muscles **166**

Motor neurons are the final common pathway **166**

5.3 The Vertebrate Nervous System: Central System 167

Glial cells support the interneurons physically, metabolically, and functionally **167**

The delicate central nervous tissue is well protected **169**

The brain floats in its own special cerebrospinal fluid **169**

A highly selective blood-brain barrier carefully regulates exchanges between the blood and brain **169**

The brain depends on delivery of oxygen and glucose by the blood **170**

Brains of virtually all vertebrates display a degree of plasticity **171**

Neurogenesis is a normal function of several regions of the brain **171**

Challenges and Controversies: Strokes: Not Always a Deadly Domino Effect 172

Challenges and Controversies: Neural Plasticity: A Song for All Seasons 173

Mammalian neural tissue is susceptible to neurodegenerative disorders **173**

5.4 Brain Evolution in Vertebrates 174

Newer, more sophisticated regions of the vertebrate brain are piled on top of older, more primitive regions **174**

5.5 Spinal Cord 176

The spinal cord retains an inherent segmental organization characteristic of many nonvertebrates **176**

The white matter of the spinal cord is organized into tracts **176**

Each horn of the spinal cord gray matter houses a different type of neuronal cell body **177**

Spinal nerves contain both afferent and efferent fibers **177**

Many reflex responses and patterned movements in vertebrates are integrated in the spinal cord **180**

Activity of command fibers elicits a fixed action pattern **182**

5.6 Brainstem and Cerebellum 183

The cerebellum is important in balance as well as in coordination of movement **184**

5.7 Basal Nuclei, Thalamus, Hypothalamus, and Limbic System 184

The basal nuclei play an important inhibitory role in motor control **184**

Challenges and Controversies: Is the Cerebellum a "Smith Predictor"? 185

The thalamus is a sensory relay station and is important in motor control **186**

The hypothalamus regulates many homeostatic functions **186**

The limbic system plays a key role in animal motivation and memory **187**

The amygdala processes and learns inputs that give rise to the sensation of fear **187**

The limbic system and higher cortex participate in the control of basic behavioral patterns **188**

Motivated behaviors are goal directed **188**

Norepinephrine, dopamine, and serotonin are neurotransmitters in pathways for emotion and behavior **189**

5.8 Mammalian Cerebral Cortex 189

The cerebral cortex is an outer shell of gray matter covering an inner core of white matter **189**

The cerebral cortex is organized into layers and functional columns **189**
 The four pairs of lobes in the cerebral cortex are specialized for different activities **189**
 The parietal lobes are responsible for somatosensory processing **192**
 The primary motor cortex located in the frontal lobes controls the skeletal muscles **192**
 The higher motor areas are important in motor control **192**
 The cerebral hemispheres have some degree of specialization **194**
 Avian intelligence evolved differently than mammalian intelligence **194**

5.9 Learning, Memory, and Sleep **194**

Memory comes in two forms—declarative and procedural—and is laid down in stages **195**
 Memory traces are present in multiple regions of the brain **196**
 Short-term and long-term memory involve different molecular mechanisms **197**
 Short-term memory involves transient changes in synaptic activity **197**

Molecular Biology and Genomics: A Smarter Rodent **201**

Long-term memory involves formation of new, permanent synaptic connections **201**
 Complex memories and learning may reside in neuronal networks **203**
 Sleep is a nearly universal phenomenon, and has two states in birds and mammals **203**
 The function of sleep is unclear **204**
 The term *consciousness* refers to a subjective awareness of the world and self **205**

Making Connections: How Nervous Systems Contribute to the Body as a Whole **205**

Chapter Summary **206**

Review, Synthesize, and Analyze **207**

Suggested Readings **207**

6 Sensory Physiology **208**

6.1 Evolution and Roles of Senses **208**

Sensory cells have ion channels and receptor proteins with specific modalities **208**
 Animal senses can be classified into three roles: sensing the external environment, the internal environment, and body motion and position **209**
 Perception is not reality **210**
 Unanswered Questions: Do fish perceive pain? **210**

6.2 Receptor Cell Physiology **211**

Receptors have differential sensitivities to various stimuli **211**
 A stimulus alters the receptor's permeability, leading to a graded receptor potential **211**
 Receptor potentials may initiate action potentials in the afferent neuron **212**
 Receptors may fire continuously or adapt slowly or rapidly to sustained stimulation **213**
 Each somatosensory pathway is "labeled" according to modality and location **215**
 Acuity is influenced by receptive field size and filtered by lateral inhibition **215**

6.3 Mechanoreception: Touch, Pressure, and Proprioception **217**

Animal integuments may have both touch and pressure receptors **217**
 Proprioceptors in the muscles, tendons, and joints give information on limb position and motion **218**
 The statocyst is the simplest organ that can monitor an animal's position in space **218**
 The lateral line system of amphibians and fish detects motion in the surrounding water **218**
 The vestibular apparatus of vertebrates detects position and motion of the head and is important for equilibrium and coordination of head, eye, and body movements **219**

6.4 Mechanoreception: Ears and Hearing **224**

Fishes hear with lateral lines and otolith organs, aided by the gas bladder in some species **224**

Many terrestrial vertebrates and insects receive sound initially with a tympanic membrane, aided by other external features in some groups **225**

Sound is characterized by its intensity (loudness), pitch (tone), and timbre (quality) **225**

The external ear and middle ear convert airborne sound waves into fluid vibrations in the inner ear **227**

The cochlea of the inner ear contains the organ of Corti, the sense organ for hearing **229**

Hair cells in the organ of Corti transduce fluid movements into neural signals **229**

Pitch discrimination depends on the region of the basilar membrane that vibrates **231**

Loudness discrimination depends on the amplitude of vibration **231**

Molecular Biology and Genomics: The Smell and Taste of Evolution **232**

The auditory cortex is mapped according to tone **232**

Insect ears are derived from the respiratory tracheal system **232**

6.5 Chemoreception: Taste and Smell **233**

Taste and smell have numerous roles such as sensing food, kin, mates, and direction **233**

Taste sensation is coded by patterns of activity in various taste receptors **233**

Mammalian taste is based on five (and perhaps more) primary tastes **234**

The olfactory receptors in the nose are specialized endings of renewable afferent neurons **236**

Various parts of an odor are detected by different olfactory receptors and sorted into "smell files" **237**

Odor discrimination is coded by patterns of activity in the olfactory bulb glomeruli **238**

The olfactory system adapts quickly, and odorants are rapidly cleared **238**

The vomeronasal organ detects pheromones **238**

6.6 Photoreception: Eyes and Vision **239**

Light detection uses universal photopigments in ciliary or rhabdomeric receptor cells **239**

Dedicated light-sensing organs range from simple eyespots to complex eyes **239**

The vertebrate eye is a fluid-filled sphere enclosed by three specialized tissue layers **240**

Molecular Biology and Genomics: The Eyes Have It **241**

The amount of light entering many vertebrate eyes is controlled by the iris **241**

The cornea and lens refract the entering light to focus the image on the retina **242**

Accommodation increases the strength of the lens for near vision **244**

Light must pass through several retinal layers in vertebrates before reaching the photoreceptors **245**

Phototransduction by opsin and retinene in retinal cells converts light stimuli into neural signals **247**

Rods provide indistinct gray vision at night, whereas cones provide sharp color vision during the day **248**

The sensitivity of eyes can vary markedly through dark and light adaptation **250**

Color vision depends on the ratios of stimulation of the various cone types **251**

Color discrimination abilities vary greatly among types of animals **251**

Unanswered Questions: Why did whales lose the blues? **252**

Some animals can see ultraviolet and/or polarized light **252**

Visual information is separated and modified within the visual pathway before it is integrated into a perceptual image of the visual field by the vertebrate cortex **253**

The thalamus and visual cortices elaborate the visual message **253**

Visual input goes to other areas of the vertebrate brain not involved in vision perception **255**

Cephalopod camera eyes have light-sensing cells on top of neural cells **255**

Compound eyes of arthropods and some annelids and bivalves consist of multiple image-forming units **256**

Phototransduction in rhabdomeric eyes uses rhodopsin but otherwise differs from that in vertebrate eyes **258**

6.7 Thermoreception 258

Warmth and cold thermoreceptors give information about the temperature of the environment near the body **258**

Infrared thermoreceptors give pit vipers the ability to detect prey and desirable thermal habitats **259**

6.8 Nociception: Pain 260

Stimulation of mammalian nociceptors elicits two types of pain signals **260**

A Closer Look at Adaptation: Why Are Hot Spices Hot? 261

The mammalian brain has a built-in analgesic system **261**

6.9 Electoreception and Magnetoreception 261

Electoreception can be passive or active, and can be used for navigation, prey detection, and communication **261**

Electric organs use specialized electrocytes to generate electric organ discharges **263**

Some animals can detect magnetic fields for long-range navigation, possibly by magnetic induction, magnetic minerals in receptors, or magnetochemical reactions **264**

Making Connections: How Senses Contribute to the Body as a Whole 266**Chapter Summary 266****Review, Synthesize, and Analyze 267****Suggested Readings 267****7 Endocrine Systems 268****7.1 Introduction: Principles of Endocrinology 268**

Hormones are chemically classified into three categories: peptides and proteins, amines, steroids **268**

The mechanisms of hormone synthesis, storage, and secretion vary according to the class of hormone **270**

Hydrophilic hormones are transported dissolved in the plasma, whereas lipid-soluble hormones are almost always transported bound to plasma proteins **271**

Hormones exert a variety of regulatory effects throughout the body **272**

Hormones produce their effects by altering intracellular proteins through ion fluxes, second messengers, and transcription factors **273**

By stimulating genes, lipophilic hormones promote synthesis of new proteins **274**

Hormone actions are greatly amplified at the target cell **275**

Endocrine-disrupting chemicals can mimic the effects of native hormones **275**

The effective plasma concentration of a hormone is normally regulated by changes in its rate of secretion **275**

The effective plasma concentration of a hormone can be influenced by the hormone's transport, metabolism, and excretion **277**

The responsiveness of a target cell to its hormone can be varied by regulating the number of its hormone-specific receptors **277**

Endocrine disorders are attributable to hormonal excess, hormonal deficiency, or decreased responsiveness of the target cells **278**

7.2 Nonvertebrate Endocrinology 279

Molting is the process of replacing one exoskeleton with another **280**

The quantity of JH released determines the quality of the molt **281**

Pheromones are used in mating and colonial interactions **281**

7.3 Vertebrate Endocrinology: Central Endocrine Glands 281

Biological clocks involve the pineal gland and the suprachiasmatic nuclei **282**

All eukaryotic cells, including all those within an animal, express clock genes **283**

The biological clock must be synchronized with environmental cues **283**

The pituitary gland descends from the hypothalamus and consists of two or three lobes **283**

Molecular Biology and Genomics: Clocks and Genes 284

The hypothalamus and posterior pituitary form a neurosecretory system that secretes vasopressin and oxytocin **285**

The anterior pituitary secretes six established hormones, many of which are tropic **286**

Hypothalamic releasing and inhibiting hormones that regulate secretion in the anterior pituitary are delivered to it by the hypothalamic-hypophyseal portal system **288**

Target gland hormones inhibit hypothalamic and anterior pituitary hormone secretion via negative feedback **290**

7.4 Endocrine Control of Growth and Development in Vertebrates 291

Growth depends on growth hormone but is influenced by other factors as well **291**

Growth hormone exerts metabolic effects not related to growth **292**

Indirect effects of growth hormone are exerted through insulin-like growth factors **292**

Growth hormone/IGF-I promote growth of soft tissues by stimulating hyperplasia and hypertrophy **293**

Growth hormone secretion is regulated by two hypophysiotropic hormones and influenced by a variety of other factors **294**

Prolactin has a wide range of growth-related effects, including lactogenesis **296**

A Closer Look at Adaptation: Brood Patch Development: Some Have It, Others Don't! 297**7.5 Thyroid Gland 297**

The major thyroid hormone secretory cells are organized into colloid-filled follicles **298**

Thyroid hormone is synthesized and stored on the thyroglobulin molecule **298**

Molecular Biology and Genomics: Crosstalk between the Pituitary and Hypothalamus 300

To secrete thyroid hormone, the follicular cells phagocytize thyroglobulin-laden colloid **300**

For the most part, both T_4 and T_3 are transported bound to specific plasma proteins **300**

Most of the secreted T_4 is converted into T_3 outside the thyroid **301**

Thyroid hormone is the primary determinant of overall metabolic rate and exerts other effects as well **301**

Thyroid hormone is regulated by the hypothalamus-pituitary-thyroid axis **303**

Abnormalities of thyroid function include both hypothyroidism and hyperthyroidism **303**

7.6 Adrenal Glands 304

In most vertebrates, the adrenal gland consists of a steroid-secreting cortex intermingled with chromaffin tissue **304**

The adrenal cortex secretes mineralocorticoids, glucocorticoids, and sex hormones **304**

Glucocorticoids exert metabolic effects and have an important role in adaptation to stress **305**

Glucocorticoid secretion is directly regulated by the hypothalamic-pituitary-adrenal axis **307**

The adrenal cortex secretes both male and female sex hormones in both sexes **307**

The adrenal cortex may secrete too much or too little of any of its hormones **308**

The catecholamine-secreting adrenal medulla is a modified sympathetic ganglion **308**

Sympathetic stimulation of the adrenal medulla is solely responsible for epinephrine release **308**

Epinephrine reinforces the sympathetic nervous system in "fight-or-flight" short-term stress, and exerts additional metabolic effects **308**

Epinephrine and norepinephrine vary in their affinities for the different adrenergic receptor types **309**

The stress response is a generalized, nonspecific pattern of neural and hormonal reactions to any situation that threatens homeostasis **310**

The multifaceted stress response is coordinated by the hypothalamus **310**

Activation of the stress response by chronic psychosocial stressors may be harmful **311**

7.7 Endocrine Control of Fuel Metabolism in Vertebrates 312

Fuel metabolism includes anabolism, catabolism, and interconversions among energy-rich organic molecules **312**

Because food intake is intermittent, nutrients must be stored for use between meals, primarily as adipose tissue **314**

Glucose is homeostatically regulated to supply the brain and to prevent damaging processes at high concentrations **315**

Metabolic fuels are stored during the absorptive state and are mobilized during the postabsorptive state **315**

Lesser energy sources are tapped as needed **316**
 The pancreatic hormones, insulin and glucagon, are most important in regulating fuel metabolism **316**
 Insulin lowers blood levels of glucose, amino acids, and fatty acids, and promotes their storage **317**
 The primary stimulus for increased insulin secretion is an increase in blood glucose concentration **319**
 Glucagon in general opposes the actions of insulin **320**
 Glucagon secretion is increased during the postabsorptive state **320**
 Insulin and glucagon work as a team to maintain blood glucose and fatty acid levels **320**
 Epinephrine, cortisol, growth hormone, and thyroid hormone also exert direct metabolic effects **320**
 The symptoms of diabetes mellitus are characteristic of an exaggerated postabsorptive state **322**

7.8 Endocrine Control of Calcium Metabolism in Vertebrates **323**

Plasma calcium must be closely regulated to prevent changes in neuromuscular excitability **323**
 Control of Ca^{2+} metabolism includes regulation of both calcium homeostasis and Ca^{2+} balance **324**
 Parathyroid hormone raises free plasma calcium levels by its effects on bone, kidneys, and intestine **324**
 Bone continuously undergoes remodeling **324**

PTH raises plasma Ca^{2+} by withdrawing Ca^{2+} from the bone **326**
 The immediate effect of PTH is to promote the transfer of Ca^{2+} from bone fluid into plasma **326**
 PTH's chronic effect is to promote localized dissolution of bone to release Ca^{2+} into plasma **326**
 PTH acts on the kidneys to conserve Ca^{2+} and to eliminate PO_4^{3-} **326**
 PTH indirectly promotes absorption of Ca^{2+} and PO_4^{3-} by the intestine **327**
 The primary signal for regulating PTH secretion is the plasma concentration of free Ca^{2+} **327**
 Calcitonin lowers the plasma Ca^{2+} concentration, but may not be essential **327**
 Vitamin D is actually a hormone that increases calcium absorption in the intestine **329**
 Phosphate metabolism is controlled by the same mechanisms that regulate Ca^{2+} metabolism **330**
 Disorders in Ca^{2+} metabolism may arise from abnormal levels of parathyroid hormone or vitamin D **330**

Making Connections: How the Endocrine System Contributes to the Body as a Whole **332**

Chapter Summary **333**

Review, Synthesize, and Analyze **334**

Suggested Readings **334**

Section III: Support and Movement

8 Muscle Physiology **335**

8.1 Introduction **335**

Three types of muscle create a wide range of movements **335**

8.2 Skeletal Muscle **336**

Skeletal muscle consists of muscle fibers lying parallel to each other **336**
 Myosin forms the thick filaments **338**
 Actin, along with tropomyosin and troponin, forms the thin filaments **338**

Molecular Biology and Genomics: What Are the Functions of Titin? **339**

8.3 Molecular Basis of Skeletal Muscle Contraction **341**

During contraction, cycles of cross-bridge binding and bending pull the thin filaments closer together between the stationary thick filaments, causing shortening of the sarcomeres **341**
 Complete shortening is accomplished by repeated cycles of cross-bridge binding and bending **342**
 Calcium is the link between excitation and contraction **342**
 Removal of calcium is the key to muscle relaxation **346**

Beyond the Basics: Conversion of Muscle into Meat **347**

Contractile activity far outlasts the electrical activity that initiated it **347**

8.4 Skeletal Muscle Mechanics **348**

A Closer Look at Adaptation: Muscles Evolved for Speed **349**

Muscle organs are groups of muscle fibers bundled together by connective tissue, often attached to skeletal elements in antagonistic pairs **349**
 Contractions of a whole muscle can be of varying strength **350**
 The number of fibers contracting within a vertebrate muscle depends on the extent of motor unit recruitment **350**
 The frequency of stimulation can influence the tension developed by each vertebrate skeletal muscle fiber **351**
 Twitch summation results from a sustained elevation in cytosolic calcium **352**
 Arthropod muscle tension is controlled by gradation of contraction within a motor unit **353**
 There is an optimal muscle length at which maximal tension can be developed on a subsequent contraction **353**
 Muscle tension is transmitted to skeletal elements as the contractile component tightens the series-elastic component **355**

The two primary types of contraction are isotonic and isometric **355**
 The velocity of shortening is related to the load **356**
 Skeletons include endoskeletons, exoskeletons, and hydrostatic skeletons **356**

Interactive units of skeletal muscles, tendons, skeletons, and joints form lever systems **357**

Elastic storage structures can greatly increase the efficiency and speed of locomotion **357**

8.5 Skeletal Muscle Metabolism and Fiber Types **358**

Muscle fibers have alternate pathways for forming ATP **359**
 Fatigue may be of muscle or central origin **361**
 Increased oxygen consumption is necessary to recover from activity **362**

Although muscles can accomplish work, much of the energy is converted to heat **362**

There are three types of skeletal muscle fibers, which differ in ATP hydrolysis and synthesis **362**

Molecular Biology and Genomics: Myosin Family Genetics **364**

Muscle fibers adapt considerably in response to the demands placed on them **365**

Unanswered Questions: What signals trigger changes in muscle mass and fiber type? **366**

8.6 Adaptations for Flight: Continuous High Power at High Contraction Frequencies **366**

Asynchronous muscle contractions are characterized by a nearly constant myoplasmic Ca^{2+} concentration **367**

8.7 Control of Motor Movement **368**

Multiple motor inputs influence vertebrate motor unit output **368**
 Muscle spindles and the Golgi tendon organs provide afferent information essential for controlling skeletal muscle activity **370**

8.8 Smooth Muscle and Cardiac Muscle **373**

Smooth and cardiac muscle share some basic properties with skeletal muscle **373**

Smooth muscle cells are small and unstriated **373**

Smooth muscle cells are turned on by Ca^{2+} -dependent phosphorylation of myosin **375**

Phasic smooth muscle contracts in bursts of activity; tonic smooth muscle maintains an ongoing level of contraction **376**

Multiunit smooth muscle is neurogenic **377**

Single-unit smooth muscle cells form functional syncytia **378**

Single-unit smooth muscle is myogenic **378**

Gradation of single-unit smooth muscle contraction differs considerably from that of skeletal muscle **379**

Smooth muscle activity can be modified by the autonomic nervous system **379**
 Smooth muscle can still develop tension, yet inherently relaxes when stretched **380**
 Smooth muscle is slow and economical, especially in latch and catch types **381**
 Cardiac muscle is striated but also has some smooth-muscle characteristics **382**

Section IV: Self-Maintenance

9 Circulatory Systems **385**

9.1 Evolution of Circulation **385**

Circulatory systems evolved to overcome the limits of diffusion **385**
 Circulatory systems have up to three distinct components: fluid, pump, and vessels **385**

Circulatory systems can be open or closed **386**

9.2 Circulatory Fluids and Cells **387**

Plasma is an aqueous medium for inorganic ions, gases, and numerous organic solutes **387**

Plasma proteins carry out many of the functions of plasma **388**
 Lipoprotein complexes carry energy lipids and structural lipids for biosynthesis **389**

Respiratory pigments carry oxygen **391**

Erythrocytes serve primarily to transport oxygen **391**

Unanswered Questions: Why are erythrocytes in birds and mammals so different? **391**

Hemoglobins and erythrocytes have additional transport functions **392**

Hemopoietic tissues continuously replace worn-out erythrocytes **392**

Erythropoiesis in mammals and probably other vertebrates is controlled by erythropoietin from the kidneys **392**

Leukocytes are key components of vertebrate immune systems **393**

Thrombocytes and platelets function in clotting **393**

9.3 Circulatory Fluids: Hemostasis **394**

Vascular spasm reduces blood flow through an injured vessel **395**

Platelets aggregate to form a plug at a vessel defect by positive feedback **395**

A triggered chain reaction and positive feedback involving clotting factors in the plasma results in blood coagulation **395**

The clotting cascade may be triggered by the intrinsic pathway or the extrinsic pathway **397**

Unanswered Questions: Why is mammalian clotting so complex? **397**

Fibrinolytic plasmin dissolves clots and prevents inappropriate clot formation **398**

Hemocytes and hemolymph proteins provide hemostasis in arthropods **399**

A Closer Look at Adaptation: Vampires and Medicine **400**

9.4 Circulatory Pumps: Evolution **400**

Pumping mechanisms include flagella, extrinsic skeletal muscles, peristaltic muscular pumps, and hearts (chamber muscle pumps) **400**
 Many animals have primary hearts aided by auxiliary pumps **401**

Arthropod systemic hearts are dorsally located and have many valved openings **402**

Vertebrate systemic hearts evolved from a two-chambered to a four-chambered structure **402**

Avian and mammalian hearts are dual pumps **402**

Heart valves ensure that the blood flows in the proper direction through the heart **403**

Vertebrate heart walls are composed primarily of spirally arranged cardiac muscle fibers interconnected by intercalated discs **405**

9.5 Circulatory Pumps: Heart Electrical Activity **406**

Pacemaker cells have channels that cyclically move them to "firing" threshold **407**

The sinoatrial node is the normal pacemaker of the vertebrate heart **407**

The spread of cardiac excitation is coordinated to ensure efficient pumping **408**

The action potential of contractile cardiac muscle cells shows a characteristic plateau **409**

Making Connections: How Muscle Physiology Contributes to the Body as a Whole **382**

Chapter Summary **383**

Review, Synthesize, and Analyze **383**

Suggested Readings **383**

Ca^{2+} entry from the ECF induces a much larger Ca^{2+} release from the sarcoplasmic reticulum **409**

Tetanus of cardiac muscle is prevented by a long refractory period **410**

9.6 Circulatory Pumps: Heart Mechanics and the Cardiac Cycle **412**

Hearts alternately contract in systole to empty and relax in diastole to fill **412**

9.7 Circulatory Pumps: Cardiac Output and Its Control **414**

Cardiac output is a product of heart rate and stroke volume **414**

Heart rate is determined primarily by antagonistic regulation of autonomic influences on the SA node **415**

Stroke volume is determined by the extent of venous return and by sympathetic activity **416**

Increased end-diastolic volume intrinsically results in increased stroke volume **417**

The contractility of the heart and venous return are increased by sympathetic stimulation **417**

The heart receives most of its own blood supply through the coronary circulation **418**

9.8 Circulatory Pathways and Vessels: Hemodynamics and Evolution **419**

Blood flow varies directly with the pressure gradient and inversely with resistance **419**

Unanswered Questions: How could a brachiosaur pump blood to its brain? **420**

Circulatory fluids transport materials in a parallel manner, especially in closed systems **421**

Circulatory fluids are driven by pressure and can transmit useful force **422**

9.9 Circulatory Pathways and Vessels: Open Circulation **422**

9.10 Circulatory Pathways and Vessels: Closed Circulation **425**

Parallel and series flow are both important for reconditioning the blood **425**

The vertebrate vascular system evolved from one circuit to two separate circuits **425**

Molecular Biology and Genomics: From Three to Four **428**

9.11 Circulatory Vessels: Arteries **429**

Arteries are wide with low total cross-sectional area and store and release pressure for high-velocity delivery **429**

Mean arterial pressure is the main driving force for blood flow **432**

9.12 Circulatory Vessels: Arterioles **432**

Arterioles are the major resistance vessels and can be dilated or constricted **432**

Local (intrinsic) influences on arteriolar radius help match blood flow with the tissues' "selfish" needs **434**

Extrinsic sympathetic control of arteriolar radius is important in the regulation of both blood flow during activity and arterial blood pressure **435**

The medullary cardiovascular control center, other brain regions, and hormones regulate blood flow and pressure **437**

9.13 Circulatory Vessels: Capillaries **437**

Capillary anatomy increases diffusion rates by minimizing distance ΔX while maximizing surface area A and the diffusion coefficient D of Fick's law **437**

Blood composition and perfusion regulation enhance capillary-tissue concentration gradients ΔC **439**

Capillary anatomy increases time for diffusion by slowing blood flow due to a high total cross-sectional area **441**

Interstitial fluid is a passive intermediary between the blood and cells **442**

Bulk flow across the capillary wall is important in extracellular fluid distribution **442**

9.14 Circulatory Vessels: Lymphatic System **444**

The lymphatic system is an accessory route by which interstitial fluid can be returned to the blood **444**

The lymphatic system is important for immune functions and fat transport **445**

9.15 Circulatory Vessels: Venules and Veins **445**

Veins serve as a blood reservoir as well as passageways back to the heart **445**

Venous return is enhanced by a number of extrinsic factors **446**

9.16 Integrated Cardiovascular Function **448**

Proper gas and heat transport is the first priority and regulation of mean arterial pressure is the second priority of the cardiovascular system **448**

Gas transport and blood pressure are monitored by arterial sensors and regulated in part by the cardiovascular control center **449**

The baroreflex is the most important mechanism for short-term regulation of blood pressure during rest or low activity **449**

Regulation of gas transport and blood pressure are coordinated during locomotor activity by higher brain centers **450**

Blood pressure regulation must integrate both short-term and long-term influences **453**

Making Connections: How Circulation Contributes to the Body as a Whole **455**

Chapter Summary **455**

Review, Synthesize, and Analyze **456**

Suggested Readings **457**

10 Defense Systems **458**

10.1 Evolution of Defense Systems **458**

Animal defenses target external as well as internal threats including pathogenic bacteria, viruses, parasites, and cancer **459**

Immune responses can be either innate or acquired **459**

Immune responses use pattern-recognition receptors to distinguish "self" from "nonself" **460**

Immune cells communicate with cytokines and by direct contact **460**

Some animals behaviorally acquire defense components from other organisms **460**

10.2 Innate Immune Systems in Nonvertebrates **461**

Barrier tissues are the first line of defense, using passive and active mechanisms **461**

Phagocytotic cells and inflammatory responses are the major form of cell-mediated second lines of defense **461**

Antimicrobial and other defensive peptides of barrier tissues and immune cells are common noncellular second lines of defense **463**

Opsonin proteins "tag" invaders for destruction by phagocytotic cells **463**

10.3 Immune Systems in Vertebrates: Overview **464**

Active immune responses are regulated by feedback systems with sensors, integrators, and effectors that are primarily leukocytes and proteins **464**

Leukocytes of innate and acquired immunity are found in circulation and localized in tissues **464**

10.4 Innate Immunity in Mammals **465**

Barrier tissues form passive walls and can have active mechanisms to kill or remove invaders **466**

Inflammation in part is triggered by histamine released by mast cells **467**

The complement system punches holes in microorganisms directly, acts as opsonins, works with antibodies, and augments inflammation **469**

NSAIDs and glucocorticoid drugs suppress the inflammatory response **470**

Natural killer cells destroy virus-infected cells and cancer cells on first exposure to them **471**

Interferon transiently inhibits multiplication of viruses in most cells **471**

10.5 Acquired Immunity in Mammals: Overview **472**

Acquired immunity includes antibody-mediated and cell-mediated responses **472**

Lymphoid tissues store, produce, and/or process lymphocytes **472**

An antigen induces an immune response against itself **473**

10.6 Acquired Immunity in Mammals: B-Lymphocytes **474**

The antigens to which B cells respond can be T-independent or T-dependent **474**

Antigens stimulate B cells to convert into plasma cells that produce antibodies **474**

Antibodies are Y-shaped and classified according to properties of their tail portion **474**

Antibodies largely amplify innate immune responses to promote antigen destruction **475**

Clonal selection accounts for the specificity of antibody production **476**

Selected clones differentiate into active plasma cells and dormant memory cells **476**

The huge repertoire of B cells is built by recombination of a small set of gene fragments **479**

Active immunity is self-generated; passive immunity is "borrowed" **480**

10.7 Acquired Immunity in Mammals: T-Lymphocytes **480**

T cells bind directly with their targets and effector cells via immunosynapses **480**

The three types of T cells are cytotoxic T cells, helper T cells, and regulatory T cells **480**

Cytotoxic T cells secrete chemicals that destroy target cells **481**

Helper T cells secrete chemicals that amplify the activity of other immune cells **482**

T-lymphocytes respond only to antigens presented to them by antigen-presenting cells **482**

The major histocompatibility complex (MHC) is the code for self-antigens **483**

The immune system is normally tolerant of self-antigens **485**

Immune surveillance against cancer cells involves an interplay among immune cells and interferon **486**

A regulatory loop links the immune system with the nervous and endocrine systems **488**

10.8 Acquired Immunity in Other Animals **489**

Unanswered Questions: How did the acquired immune system arise in jawed vertebrates? **489**

Sharks generate diverse B and T cells with a lower diversity but a greater number of gene fragments than mammals **489**

Lamprey lymphocytes shuffle ancient PRR genes to generate variable receptors and antibody-like proteins **489**

Some arthropods and mollusks have immunity mechanisms resembling vertebrate acquired processes **489**

Molecular Biology and Genomics: An Accidental Origin for Acquired Immunity? **490**

Making Connections: How Defense Systems Contribute to the Body as a Whole **491**

Chapter Summary **491**

Review, Synthesize, and Analyze **492**

Suggested Readings **492**

11 Respiratory Systems **493**

11.1 Gas Demands: General Problems and Evolutionary Solutions **493**

External respiration involves up to four major steps of transport and exchange **493**

Gas diffusion follows Fick's law for partial pressure gradients **494**

External respiratory processes must meet the demands of size, metabolism, and habitat **496**

Gas exchange may be increased by respiratory organs, bulk transport, and diffusion-enhancing proteins **497**

Breathing as a form of bulk transport can be tidal or flow-through **498**

11.2 Water Respirers 498

Water is a more difficult medium than air for gas exchange **498**

The limitations of diffusion in water are overcome with gills and other external thin, high-surface-area structures, internal circulation, and flow-through breathing **499**

Breathing muscles in water provide rapid and often flow-through transport **501**

Countercurrent blood flow enhances gas pressure gradients in fishes **502**

Aquatic respiratory systems can perform numerous nonrespiratory functions **502**

11.3 Air Respirers: Overview and Nonvertebrates 502

Air breathers may have less efficient exchange surfaces and breathing mechanisms, and their exchange surfaces must be protected from drying out **502**

Land slugs and snails use skin, mantle tissue, or lungs **503**

Arachnids use book lungs or tracheae **503**

In insects, internal air-filled tubes—tracheae—supply oxygen directly to the tissues **504**

11.4 Air Respirers: Vertebrates 504**Challenges and Controversies: Why Are There No Large Insects? 505**

The first air-breathing vertebrates were bimodal **505**

Frog lungs may be simple or moderately folded and are inflated by positive pressure **506**

Reptiles and mammals have respiratory systems ranging from simple to elaborately folded chambers inflated by negative pressure **507**

Mammalian airways terminate in alveoli, which are involved in both ventilation and gas exchange **508**

A pleural sac separates each lung from the thoracic wall **510**

Mammalian lungs are inflated and deflated tidally by cyclical changes in intra-alveolar pressure generated indirectly by respiratory muscles **510**

Ventilation and gas exchange are separated in avian respiratory systems due to air sacs and parabronchi with air capillaries **511**

Flow-through breathing plus crosscurrent blood flow enhances gas exchange in birds **514**

Unanswered Questions: Soaring birds from Saurischian

dinosaurs? **515**

Aerial respiratory systems can perform numerous nonrespiratory functions **515**

11.5 Breathing: Respiratory Mechanics in Mammals 517

Interrelationships among atmospheric, intra-alveolar, and intrapleural pressures are important in respiratory mechanics of mammals **517**

The lungs are normally stretched to fill the larger thorax **517**

Intrapleural and lung pressures decrease during inhalation and increase during exhalation **519**

Respiratory diseases often increase airway resistance **519**

Elasticity in mammalian lungs depends on connective tissue and alveolar surface tension, which is reduced by surfactant **520**

11.6 Breathing: Lung Volumes in Mammals 521

Changes in lung volumes are important for analyzing different respiratory efforts, disease states, aerobic activity capacities, and species differences **521**

Alveolar ventilation is less than pulmonary ventilation because of the presence of dead space **523**

11.7 Breathing: Flow-Through versus Tidal Respirers 526

Dead-space volumes are lower in fishes but higher in birds compared to mammals **526**

The work of normal breathing requires as little as 2% of total energy expenditure in some mammals to as much as 50% in some fishes **527**

Flow-through ventilation yields a greater oxygen uptake than tidal breathing **527**

11.8 Gas Exchange at Vertebrate Respiratory Organs and Body Tissues 527

Lung air has a lower partial pressure of oxygen than atmospheric air **527**

O₂ enters and CO₂/HCO₃⁻ leaves the capillaries in the lungs or gills passively down partial pressure or concentration gradients **529**

Factors other than the partial pressure gradient influence the rate of gas transfer **529**

Gas exchange across the systemic capillaries also occurs down partial pressure gradients **530**

11.9 Circulatory Transport and Gas Exchange 530

Most O₂ in many animal circulatory systems is transported bound to hemoglobins, hemocyanins, and other metal-containing respiratory pigments **530**

A Closer Look at Adaptation: Life in the Cold: The Hemoglobinless Icefish 532

Myoglobin stores oxygen in aerobic muscle and may facilitate diffusion from the blood to the mitochondria **533**

Neurons contain neuroglobin, while fibroblasts contain cytoglobin **533**

The P_{O₂} is the primary factor determining the percent hemoglobin saturation **533**

Cooperativity among hemoglobin subunits allows for effective delivery of oxygen **533**

Evolutionary adaptation results in different hemoglobin P₅₀ values **535**

By acting as a storage depot, respiratory pigments promote the net transfer of O₂ from the respiratory surfaces to the circulatory fluid **536**

Increased CO₂, acidity, temperature, and organic phosphates shift the O₂-Hb dissociation curve to the right, favoring unloading **537**

Filling of the gas bladder is aided by the Root effect **539**

Most CO₂ is transported in the blood as bicarbonate **540**

Various respiratory states are characterized by abnormal blood gas levels **542**

Other unusual respiratory states such as apnea are not necessarily pathological **543**

A Closer Look at Adaptation: High Fliers and Deep Divers 544**11.10 Control of Respiration 546**

Spiracles that control tracheal ventilation in insects are regulated intrinsically and extrinsically for both gas exchange and evaporation control **546**

Extrinsic and intrinsic controls act on the smooth muscle of mammalian airways and arterioles to maximally match ventilation to perfusion **546**

Respiratory centers in the vertebrate brain stem establish a rhythmic breathing pattern **547**

Molecular Biology and Genomics: HIF to the Rescue 549

The magnitude of ventilation is adjusted in response to three chemical factors: P_{O₂}, P_{CO₂}, and H⁺ **550**

Feedback monitoring of blood gases and H⁺ occurs both peripherally and centrally **550**

Decreased arterial P_{O₂} increases ventilation more strongly in fish than in air breathers **550**

Carbon dioxide-generated H⁺ in the brain is normally the main regulator of ventilation in air breathers **551**

Adjustments in ventilation in response to changes in arterial H⁺ are important in acid-base balance **553**

Activity profoundly increases ventilation, possibly due to anticipatory mechanisms **553**

Making Connections: How Respiratory Systems Contribute to the Body as a Whole 554**Chapter Summary 554****Review, Synthesize, and Analyze 555****Suggested Readings 556****12 Excretory Systems 557****12.1 Evolution of Excretory Systems 557**

Selective excretion is crucial to internal fluid homeostasis and involves several systems **557**

Nitrogen metabolism creates special stresses and produces three major end products: ammonia, urea, and uric acid **558**

Excretory organs have transport epithelia, which typically use Na⁺/K⁺ ATPases **561**

12.2 Renal Excretory Organs: Overview 563

Renal tubules produce urine using the processes of filtration, secretion, reabsorption, and osmoconcentration **563**

The major renal organs are protonephridia, meso- and metanephridia, and Malpighian tubules **563**

Carbohydrate and protein are both absorbed by secondary active transport and enter the blood **696**

Vitamin absorption is largely passive **699**

Most absorbed nutrients immediately pass through the liver for processing **699**

Extensive absorption by the small intestine keeps pace with secretion **701**

Biochemical balance among the stomach, pancreas, and small intestine is normally maintained **701**

Diarrhea results in loss of fluid and electrolytes **701**

14.8 Hindgut/Large Intestine **701**

The hindgut of insects actively transports nutrients and may house symbionts **701**

Molecular Biology and Genomics: Big Bugs Have Little Bugs... **702**

The vertebrate hindgut or large intestine consists of the colon, cecum, and rectum or cloaca **702**

The large intestine serves as a temporary storage site for excreta, functions in electrolyte and fluid balance, and harbors microbes for fermentation and production of volatile fatty acids **702**

Diet composition governs variation in structure of the large intestine **703**

Haustral contractions prolong the retention of digesta **703**

Postgastric fermentation is not as efficient as pregastric fermentation in obtaining nutrients **704**

Mass movements propel colonic contents long distances **704**

Feces are eliminated by the defecation reflex **704**

Large-intestine secretion is protective in nature **705**

The large intestine converts the luminal contents into feces **705**

14.9 Ruminant Digestion **705**

The rumen is divided into separate compartments **705**

The abomasum is similar in function to the stomachs of nonruminants **707**

Motility of the ruminant stomach is predominantly regulated by central nervous system reflex mechanisms **707**

Rumination is the regurgitation, remastication, and reswallowing of ingesta **707**

The environment of the rumen fosters the growth of anaerobic microbes **707**

Nutrients for the host ruminant are generated by anaerobic microbes **708**

Rumen microbes synthesize vitamins for their host and detoxify some ingested toxins **710**

Some ruminants are selective in what they eat, whereas others simply graze the available forage **710**

14.10 Overview of the Gastrointestinal Hormones **711**

Making Connections: How Digestive Systems Contribute to the Body as a Whole **712**

Chapter Summary **712**

Review, Synthesize, and Analyze **713**

Suggested Readings **714**

15 Energy Balance and Thermal Physiology **715**

15.1 Introduction: Thermodynamics and Life **715**

Life follows the laws of thermodynamics **715**

To compensate for entropy, animals require input of food energy, most of which is ultimately converted to heat output **716**

15.2 Energy Balance: General Principles **717**

Energy input must equal energy output, which is measured as metabolic rates of basal metabolism, activity, diet-induced thermogenesis, and production **717**

Energy of production determines net energy balance **719**

BMR and SMR are regulated in part by thyroid hormones **720**

BMR and SMR scale with body mass **720**

Increased muscle activity is the factor that can most increase metabolic rate, as indicated by metabolic scope **720**

Challenges and Controversies: A Universal Scale of Life? **722**

Diet-induced thermogenesis occurs after eating in most animals **722**

15.3 Energy Balance: Regulation **724**

Some adult animals maintain long-term neutral energy balance, while others undergo regulated periods of positive or negative energy balance **724**

Food intake in mammals is controlled primarily by the hypothalamus in response to numerous inputs **724**

Leptin and insulin are signals of long-term energy balance **725**

Molecular Biology and Genomics: Discovering the Obesity Gene **726**

Effectors for energy balance are mechanisms to regulate eating and expenditures **728**

Different energy-balance set points among species result from evolutionary adaptations to different food supplies **729**

15.4 Thermal Physiology: General Principles **730**

Temperature alters rates of chemical reactions and denatures macromolecules **730**

Biomolecules can be altered to work optimally at different temperatures **731**

The thermal adaptation strategies of animals depend on their primary source of heat **733**

Heat exchange between the body and the environment takes place by radiation, conduction, convection, and evaporation **734**

Heat gain versus heat loss determines core body temperature, with mechanisms to gain external heat, retain internal heat, generate more internal heat, and lose excess heat **735**

15.5 Ectothermy **736**

Body temperatures of ectotherms may follow the environment, or may be regulated by heat gains, retention, and losses **736**

Some ectotherms can compensate biochemically for changes in body temperatures **737**

Ectotherms survive extreme cold by metabolic dormancy and by either freeze avoidance or freeze tolerance **739**

Ectotherms may survive temporary extreme heat with the heat shock response **740**

15.6 Endothermy and Homeothermy **740**

Challenges and Controversies: What Is the Maximum Temperature for Life? **741**

Unanswered Questions: How, when, and why did endothermy evolve? **741**

Birds and mammals maintain a consistent internal core temperature (homeothermy) **741**

To maintain a stable core temperature, heat gains must balance heat loss, with mechanisms to gain, retain, generate, and lose excess heat **743**

The hypothalamus and/or spine integrates a multitude of thermosensory inputs from both the core and the surface of the body **748**

To regulate core temperature homeostatically, the hypothalamus simultaneously coordinates heat production, heat loss, and heat conservation mechanisms **748**

During a fever, the hypothalamic thermostat is "reset" to an elevated temperature, which can be beneficial **750**

15.7 Heterothermy **750**

Regional heterotherms heat only some parts of their bodies **750**

Temporal heterotherms maintain high body temperatures only for certain time periods **750**

Some colonial heterotherms create homeothermic "superorganisms" **752**

15.8 Thermal Physiology and Climate Change **752**

Arctic regions have warmed the most, and climate is becoming more extreme **752**

A Closer Look at Adaptation: The Naked Mole Rat—Mammalian Hive Ectotherm **753**

Animal physiology, behavior, and genes are already being affected by warming trends **754**

Making Connections: How Energy Balance and Thermal Adaptations Contribute to the Body as a Whole **754**

Chapter Summary **755**

Review, Synthesize, and Analyze **755**

Suggested Readings **756**

Section V: Reproduction

16 Reproductive Systems 757

16.1 Introduction: Reproductive Processes 757

Animals may reproduce asexually or sexually 757

Animals may reproduce by *r*-selected, *K*-selected, or intermediate ecological strategies 758

Animals may reproduce physiologically by oviparity, ovoviviparity, or viviparity 758

Animals use various strategies to ensure breeding at the appropriate time 760

16.2 Reproductive Systems and Genetics 761

The reproductive system of vertebrates includes the hypothalamus, gonads, and reproductive tract 761

Reproductive systems in insects include the neuroendocrine organs, gonads, and reproductive tract 764

Reproductive cells each contain a half set of chromosomes 765

Gametogenesis occurs by meiosis, resulting in genetically unique sperm and ova 765

The sex of an individual is determined by the combination of sex chromosomes or by environmental stimuli 766

An unfertilized egg can develop into a male or female in parthenogenesis 767

Sex differentiation in mammals depends on the presence or absence of Y-chromosome masculinizing determinants during critical periods of embryonic development 767

16.3 Male Reproductive Physiology 770

Testes in most mammals descend into the scrotum to become external 770

The scrotal location of the testes provides a cooler environment essential for temperature-sensitive spermatogenesis in mammals 770

Unanswered Questions: Why can't sperm develop at core body temperatures? 770

The testicular Leydig cells secrete masculinizing testosterone during the breeding season 771

Spermatogenesis yields an abundance of highly specialized, mobile sperm 773

Throughout their development, vertebrate sperm remain intimately associated with Sertoli cells 775

LH and FSH from the anterior pituitary control testosterone secretion and spermatogenesis 776

Gonadotropin-releasing hormone activity increases at puberty 777

The ducts of the reproductive tract store and concentrate sperm and increase their fertility 778

The accessory sex glands contribute the bulk of the semen 778

Prostaglandins are ubiquitous, locally acting chemical messengers 779

The penis in many vertebrates is both erectile and extendible 779

16.4 Mating 780

The male sex act is characterized by erection and ejaculation 780

Erection is accomplished by penis vasocongestion 781

Ejaculation includes emission and expulsion 782

The female sex act is similar to the male sex act 783

Oxytocin has several roles in mating and other social interactions 783

16.5 Female Reproductive Physiology 783

Complex cycling characterizes female reproductive physiology in many vertebrates, including estrous cycles in most mammals 783

Concepts and Controversies: Environmental Estrogens: Bad News for Reproduction 785

The steps of gametogenesis are the same in both sexes, but the timing and outcome differ sharply 786

The ovarian cycle of mammals consists of alternating follicular and luteal phases 788

The follicular phase is characterized by the development of maturing follicles 788

The luteal phase is characterized by the presence of a corpus luteum and secretion of progesterone 790

The estrous cycle is regulated by complex hormonal interactions among the hypothalamus, anterior pituitary, and ovarian endocrine units 790

The uterine changes that occur during the estrous cycle reflect hormonal changes during the ovarian cycle 794

Fluctuating concentrations of estrogens and progesterone produce cyclic changes in cervical mucus 794

The reproductive cycles of nonviviparous vertebrates are fundamentally similar but have some unique differences 794

A Closer Look at Adaptation: A Rut for One Season 795

Sexual maturity events in mammalian females are similar to those in males 798

16.6 Fertilization and Implantation 799

The oviduct is the site of fertilization 799

Sperm may compete among males 801

The mammalian blastocyst implants in the endometrium through the action of its trophoblastic enzymes 801

The placenta is the organ of exchange between maternal and fetal blood 803

Modes of placentation differ among species 803

Hormones secreted by the corpus luteum and placenta play a critical role in maintaining pregnancy 804

Maternal body systems respond to the increased demands of gestation 805

16.7 Parturition and Lactation 805

Changes during late gestation prepare for parturition 805

The factors that trigger the onset of parturition are only partially understood 806

Parturition is accomplished by a positive-feedback cycle 809

Lactation requires multiple hormonal inputs 809

Mammary gland feeding is advantageous to both the infant and the parent 812

Molecular Biology and Genomics: Prolactin: A Key with Many Locks in Females and Males 813

The end is a new beginning 813

Making Connections: How Reproductive Systems Contribute to the Body as a Whole 814

Chapter Summary 814

Review, Synthesize, and Analyze 815

Suggested Readings 816

Answers to Check Your Understanding Questions A-1

Online Reviews Offered at CengageBrain.com:

A Review of Chemical Principles

Storage, Replication, and Expression of Genetic Information

Glossary A-15

Index A-33