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As we originally concluded, the study of physiology goes hand-in-hand with consideration of anatomy at multiple levels. While the fundamental focus of this text is physiology, we have strived to include sufficient system, organ, tissue, and cellular anatomy for students to better appreciate the integration of both topics. In short, structure and function are intimately interconnected. Our book is rich with illustrations that we believe add interest and enhance understanding.

Moreover, we have made all of these illustrations available to instructors who adopt the book for use in their classes. We have also increased the use of textbox highlights to provide examples to compel student interest and inquiry. Chapter summaries and sample questions for both the student and instructor, as well as specific websites for each, will increase the utility of the text as well.

As before, our overriding goal with this edition is to provide foundations for undergraduate students in agricultural and biological sciences to be successful in upper-level specialty courses such as nutrition, reproduction, lactation, growth biology, biotechnology, and the like. We also anticipate that this text will provide new graduate students with a readily understandable source for review of basic principles.

We would like to thank our wives (Cathy Akers, 43 years and counting; Dr. Cindy Denbow) for their love, support, and understanding through these long hours of figure making, writing, and editing. We would also like to thank our graduate students, colleagues, and students in our classes for the inspiration, a helping hand, and lots of questions. We would like to especially thank Ms. Sara Robinson for preparing several drawings and Drs. Anthony Capuco, Steve Ellis, Frank Gwazdauskas, Ray Nebel, and Frank Robinson, and Mrs. Cathy Parsons for photographs used in the text.

R. Michael Akers
D. Michael Denbow
In our view, it is virtually impossible to adequately understand or study physiology without consideration of anatomy. While the fundamental focus of this text is physiology, we have strived to include sufficient system, organ, tissue, and cellular anatomy for students to better appreciate the integration of both topics. In short, to appreciate that structure and function are intimately interconnected.

The goal of this book is to provide foundations for undergraduate students in agricultural and biological sciences to be successful in upper-level specialty courses such as nutrition, reproduction, lactation, growth biology, biotechnology, and the like. We also anticipate that this text will provide new graduate students with a readily understandable source for review of basic principles.

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R. Michael Akers
D. Michael Denbow
About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/akers/anatomy

The website includes:

- Review questions
- Powerpoints of all figures from the book for downloading
- Powerpoints of all tables from the book for downloading
Introduction to anatomy and physiology

Although there are many good anatomy and physiology texts that focus on humans, there is a paucity of such options for animals. Since animals have distinct physiological and anatomical differences relative to humans, a human-focused text does not do the study of animals justice. Animals walk on four legs, whereas humans walk on two. Ruminant animals have adaptations to their digestive system that make them unique from humans. The respiratory system of birds differs from that of humans, thus making birds able to fly at high altitudes. The focus of this text will be to emphasize the anatomy and physiology of animals to appreciate their unique physiological systems.

Anatomy and physiology

Anatomy (derived from the Greek words meaning “to cut open”) is the study of the morphology, or structure, of organisms. Thus, strictly speaking, anatomy deals with form rather than function. It can be divided into macroscopic (gross) or microscopic anatomy. Macroscopic anatomy deals with structure that can be seen with the naked eye, whereas microscopic anatomy deals with structure that can only be seen with the aid of a microscope. It is also important to appreciate that it is also much more than simply looking at smears of cells or stained tissue sections. Use of immunocytochemistry, fluorescence-labeled markers, multispectral cameras and sophisticated imaging software, and so on is revolutionizing our understanding of cell and tissue biology. Figure 1.1 provides an example of the ability to localize specific proteins within various cells of the mammary gland.

Macroscopic anatomy can be approached in different ways. Regional anatomy, as the name implies, deals with all the structures, such as nerves, bones, muscles, and blood vessels, in a defined region such as a body part. Global anatomy focuses on the entire animal or human body, covering all systems.

Anatomical Nomenclature

Directional and Positional Terms

Body Planes

Body Cavities and Membranes

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Anatomy and physiology of domestic animals

Chapter 1

Physiology is the study of the function of living systems. While various systems will be presented separately throughout this book, it must be recognized that all systems work together to maintain the normal functioning of an animal. Therefore, the cardiovascular system does not work in isolation from the respiratory or nervous system, but instead they work in unison to coordinate the distribution of oxygen and removal of carbon dioxide throughout the body. As in anatomy, there are levels of complexity.

Cellular physiology is the study of how cells work. This includes the study of events at the chemical, molecular, and genetic levels. Organ physiology includes the study of specific organs, that is, cardiac or ovarian. Systems physiology includes the study of the functions of specific systems such as the cardiovascular, respiratory, or reproductive systems.

As you study anatomy and physiology, it will become apparent that structure and function have evolved to complement each other. The complementarity of structure and function is an essential concept. At multiple levels, a return to this fundamental idea will hasten your grasp of what sometimes seems to be an overwhelming amount of information and detail. But ultimately, the point is for you to understand how an animal works and to understand limitations. This relationship between form and function is evident beginning at the cellular level. For example, the epithelial cells that line the internal surface of the small intestine have so-called tight junctions that act to restrict the movement of materials into the body from the gastrointestinal tract, whereas the epithelial linings (endothelial cells) of capillaries have modified junctions. The linings of capillaries must be sufficiently porous to allow solutes to move readily in either direction across the capillary wall to nourish the tissue and remove waste products.

As another example, there are structural differences between birds and mammals that allow flight. Birds contain pneumatic bones, that is, bones that are hollow, which are connected to the respiratory system. These bones include the skull, humerus, clavicle, keel, sacrum, and lumbar vertebrae. In addition, the lumbar and sacral vertebrae are fused as an adaptation for flight. This provides yet another example of complementary structure and function.

Levels of organization

The animal body has a complex organization extending from the most microscopic levels up to the macroscopic (Fig. 1.2). Beginning with the smallest microscopic units of stability, the levels of organization are as follows:

Fig. 1.1. Photomicrograph of a developing mammary duct. Taken from a Holstein calf, this tissue section was stained with specific antibodies and fluorescent tags to detect cell nuclei (blue), cytokeratin 18 (red, a marker specific for epithelial cells), CD10 (green, a marker of myoepithelial cells), and Ki67 (yellow, a protein produced in nuclei of cells that are about to divide). The tissue section is from a study to evaluate the effects of the ovary on ontogeny of myoepithelial cells in the bovine mammary gland. Image is courtesy of Dr. Steve Ellis, Clemson University.
Introduction to anatomy and physiology

Chapter 1

pancreas to form part of the digestive system. The pancreas also functions as part of the endocrine system because of the pancreatic islets that produce insulin and glucagon. The organ systems include the integumentary, skeletal, muscular, nervous, endocrine, respiratory, digestive, lymphatic, urinary, and reproductive systems (Fig. 1.3).

- Organismal level. The organismal level, or the whole animal, includes all of the organ systems that work together to maintain homeostasis.

Homeostasis

The 19th-century French physician Claude Bernard (1865) coined the term milieu interieur, which referred to the relatively constant internal environment, that is, extracellular fluid, in which cells live. Walter Cannon (1932), a 20th-century American physiologist, later coined the term homeostasis, meaning “unchanging” internal environment. While the concept of homeostasis is fundamental to understanding physiology, the term is better understood as a relatively steady state that is maintained within an animal despite a wide range of environmental conditions. In this way, various internal conditions, such as plasma glucose, electrolyte concentrations, or body temperature, are maintained within narrow limits through homeostatic mechanisms.

Homeostasis is maintained at all levels of life. Individual cells, for example, control their internal environment via selectively permeable membranes. These membranes will allow selective movement across the membrane based on such factors as pH, size, or whether there is a specific transport system for that compound. Whole animals maintain their internal environment by a host of behavioral and physiological mechanisms. A behavioral method of regulation may include moving from a sunny area to a shady area to decrease body temperature, whereas a physiological method may involve an increase in sweating or panting to accomplish the same goal.

Homeostatic regulatory mechanisms

Elaborate regulatory mechanisms exist to maintain homeostasis. Homeostasis is maintained by the actions of the nervous and endocrine systems that communicate changes in the internal and external environment. The two systems work in conjunction to make relatively rapid or slow changes, respectively. The nervous system responds to immediate, short-term needs, as seen in a reflex arc in which an animal withdraws its foot after stepping on a sharp object. In contrast, the endocrine system generally elicits responses that last...
Anatomy and physiology of domestic animals

Chapter 1

Regulation within the body occurs in different settings and involves the coordinated action of both the nervous and endocrine systems. Such regulation occurs, for example, during prolonged stress where there is release of norepinephrine, epinephrine, and corticosteroids from the paired adrenal glands. This results in an increase in blood pressure and a change in blood flow such that there is an increase to the skeletal muscle and a decrease to the digestive tract.

Fig. 1.3. Organ systems. The body consists of 11 major organ systems that are shown above along with examples of their components.

a. Integumentary system: Forms the external covering of the body providing protection, preventing desiccation, supplying sensory information about the environment and synthesizing vitamin D.

b. Skeletal system: Functions in support, protection, and movement. Also important in blood cell formation and mineral storage.

c. Muscular system: Functions in movement, maintains posture, and generates heat.

d. Nervous system: Through its functions of sensory input, integration, and motor output, it quickly helps the animal interact with the internal and external environment.

e. Endocrine system: Collectively, all the endocrine-secreting cells; these produce hormones that help maintain the internal environment.

f. Cardiovascular system: Includes blood vessels and the heart, which function to carry nutrients and waste throughout the body.

g. Lymphatic system: Returns excess interstitial fluid to the blood and contains phagocytic cells involved in immunity.

h. Respiratory system: Provides oxygen and eliminates CO₂.

i. Digestive system: Assimilation, breakdown, and absorption of nutrients. Provides important immunological barrier against external environment.

j. Urinary system: Eliminates nitrogenous wastes, maintains fluid and electrolyte balance, and has an endocrine function.

k. Reproductive system: Functions to produce offspring.

hours or days such as the release of insulin in response to a rise in blood glucose levels.

When regulation occurs at either the cellular, tissue, organ, or organ system level, it is termed autoregulation. For example, the presence of tryptophan in the small intestine will cause the local release of cholecystokinin (CCK) that will cause the pancreas to secrete enzymes. Extrinsic regulation, on the other hand, involves the coordinated action of both the nervous and endocrine systems. Such regulation occurs, for example, during prolonged stress where there is release of norepinephrine, epinephrine, and corticosteroids from the paired adrenal glands. This results in an increase in blood pressure and a change in blood flow such that there is an increase to the skeletal muscle and a decrease to the digestive tract.
The factor being regulated is the variable. The regulatory mechanisms involve a receptor, a control center, and an effector. The receptor is a neuron that senses a change in the environment, called a stimulus. In response to the stimulus, the receptor carries an afferent (away) signal to the control center. The control center has a set point around which the variable is maintained. When the input signal is outside of the range of the set point, an appropriate response is elicited to correct the variable. An efferent (toward) signal is then sent to the effector. The effector induces a change in the controlled variable to bring it back to the set point (Fig. 1.4).

Feedback systems

Homeostatic regulatory mechanisms consist of either negative or positive feedback systems. Negative feedback systems are far more common than positive feedback systems.

Negative feedback system

In negative feedback systems, the control system initiates changes that counteract the stimulus (Fig. 1.5). This either reduces or eliminates the stimulus, thereby reestablishing the variable near its set point to maintain homeostasis. Using body temperature regulation as an example, every animal has a set point for body temperature, with the control center residing in the hypothalamus, a region of the brain. When the body temperature of an animal rises, possibly due to exposure to the sun, the warmth receptors located in the skin and hypothalamus sense a rise in temperature and send a signal to the hypothalamus. The hypothalamus compares these signals to the set point and then activates appropriate heat loss mechanisms to decrease body temperature toward the set point. As a result of the heat loss mechanisms, body temperature is returned to the set-point value, and homeostasis is maintained.

Positive feedback system

In response to a stimulus, the animal elicits regulatory mechanisms that augment or exaggerate the effect. This creates a regulatory cycle in which the response...
causes an augmentation of the stimulus, which further increases the response. While positive feedback systems are rare, there are situations where they prove beneficial. In the case of blood clotting, an injured blood vessel secretes factors that attract platelets to that site. These platelets secrete factors that attract more platelets, and thus a positive cascade begins to occur. While this is beneficial in preventing the loss of blood, if left unchecked, the clotting process would continue until all the blood in the body was clotted, resulting in death.

Childbirth is another classic example of a positive feedback system. Near the time of parturition, oxytocin is produced by the fetus, which, along with prostaglandins, initiates uterine contractions. The uterine contractions cause the hypothalamus of the mother to release more oxytocin, causing greater uterine contractions. Thus, a positive feedback loop is initiated.

Anatomical nomenclature

As with any field of science, anatomy has its own language. It is necessary to know this language to describe structures and events in a precise and accurate manner. When trying to describe the location of the femur, simply saying that it is “in the back leg and located before the tibia and fibula” will not suffice.

Directional and positional terms

Anatomical terms are used to describe an animal that is in its normal anatomical position. In the case of humans, who are biped (i.e., walk on two legs), this means standing with the arms hanging by the side and the palms rotated forward. For animals that are quadruped (i.e., walk on four legs), anatomical position entails standing on all four limbs.

Positional and directional terms are presented in Table 1.1. The use of such terms allows for more precision while using fewer words to describe body structures. For example, one might say, “The knee is located on the front leg approximately halfway between the trunk and the hoof.” With directional and positional terms, one can say, “The knee is located distal to the humerus and proximal to the radius and ulna, in the middle of the front leg.”

These terms can have different meanings when referring to humans as opposed to animals. While dorsal and posterior mean toward the back or spinal column in humans, dorsal means toward the spinal cord in a quadruped, while posterior means toward the tail.

Body planes

When talking about anatomical locations, it is necessary to take into account the three-dimensional nature of an animal. The body can be sectioned, or cut, in all three planes. Knowing which plane one is observing when looking at a cross section gives knowledge of the location of various structures. Looking at anatomical planes has become common in the many television crime and medical mystery shows that show images from various magnetic resonance imaging (MRI) scans. Using the horse as an example, the terms are further depicted in Figure 1.7.

A sagittal plane divides the body into right and left parts along the longitudinal axis (Table 1.2; Fig. 1.7). If the plane is exactly along the midline of the longitudinal axis, it is said to be a median, or midsagittal, plane. Any sagittal plane other than the midsagittal is said to be a parasagittal (para = near) plane.

A frontal (dorsal) plane runs longitudinally and passes through the body parallel to its dorsal surface and at a right angle to the median plane. In other words, it divides an animal into a dorsal and ventral portion and runs parallel to the ground. In humans, such a plane runs perpendicular to the ground.
Table 1.1. Directional and positional terms.

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<tr>
<th>Term</th>
<th>Meaning</th>
<th>Example</th>
</tr>
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<tr>
<td>Dorsal</td>
<td>Toward the back; also, below the proximal ends of the carpus and tarsus, dorsal means toward the head (i.e., dorsal replaces cranial)</td>
<td>The vertebral column is dorsal to the sternum.</td>
</tr>
<tr>
<td>Ventral</td>
<td>Toward the belly</td>
<td>The udder is ventral to the tail.</td>
</tr>
<tr>
<td>Cranial</td>
<td>Toward the head</td>
<td>The neck is cranial to the tail.</td>
</tr>
<tr>
<td>Caudal</td>
<td>Toward the tail</td>
<td>The tail is caudal to the head.</td>
</tr>
<tr>
<td>Rostral</td>
<td>Part of the head closer to the nose</td>
<td>The beak is rostral to the ear.</td>
</tr>
<tr>
<td>Proximal</td>
<td>Near the trunk or origin of the limb</td>
<td>The elbow is proximal to the ankle.</td>
</tr>
<tr>
<td>Distal</td>
<td>Farther from the trunk</td>
<td>The ankle is distal to the elbow.</td>
</tr>
<tr>
<td>Palmar</td>
<td>Below the proximal ends of the carpus, palmar replaces caudal</td>
<td>The dewclaws are on the palmar surface of the forelimb.</td>
</tr>
<tr>
<td>Plantar</td>
<td>Below the proximal ends of the tarsus, planar replaces caudal</td>
<td>The dewclaws of the hind limb are on the plantar surface of the foot.</td>
</tr>
<tr>
<td>Medial</td>
<td>Toward the longitudinal axis (midline)</td>
<td>The sternum is medial to the limbs.</td>
</tr>
<tr>
<td>Lateral</td>
<td>Away from the longitudinal axis</td>
<td>The scapula lies lateral to the spine.</td>
</tr>
<tr>
<td>Superficial</td>
<td>Nearer the body surface</td>
<td>The skin is superficial to the ribs.</td>
</tr>
<tr>
<td>Deep</td>
<td>Farther from the body surface</td>
<td>The heart is deep to the ribs.</td>
</tr>
<tr>
<td>Axial and abaxial</td>
<td>Restricted to the digits, these terms indicate position relative to the longitudinal axis of the limb; axial and abaxial are closer and further to the longitudinal axis, respectively</td>
<td>The lateral edge of the hoof is abaxial to the phalanges.</td>
</tr>
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Table 1.2. Body planes.

<table>
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<th>Orientation of Plane</th>
<th>Plane</th>
<th>Description</th>
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<td>Perpendicular to long axis</td>
<td>Transverse</td>
<td>Divides the body into cranial and caudal parts; also crosses an organ or limb at a right angle to its long axis</td>
</tr>
<tr>
<td>Parallel to long axis</td>
<td>Median (midsagittal)</td>
<td>Divides body into equal right and left halves</td>
</tr>
<tr>
<td></td>
<td>Sagittal</td>
<td>Divides body into unequal right and left halves</td>
</tr>
<tr>
<td></td>
<td>Frontal (dorsal)</td>
<td>Longitudinal plane passing through the body parallel to dorsal surface and at right angles to the median plane</td>
</tr>
</tbody>
</table>

A transverse plane runs perpendicular to the long axis of the structure. A transverse plane can divide an animal into a cranial and caudal half, or it can divide a limb into a proximal and distal section.

Body cavities and membranes

A median view of an animal will reveal two cavities, the dorsal and ventral. The dorsal cavity protects the brain and spinal cord and contains the cranial cavity within the skull, and the vertebral, or spinal, cavity that is found within the vertebral column. The brain and the spinal cord are continuous; therefore, the cranial and vertebral cavities are also continuous.

When looking down the longitudinal axis, the trunk of the animal can be divided into three cavities. The thoracic cavity is surrounded by the ribs and muscles of the chest. It can be further subdivided into the pleural cavities, each of which houses a lung, and the mediastinum, which is located medially between the lungs and contains the pericardial cavity. The mediastinum also houses the esophagus and trachea.

The abdominopelvic cavity is separated from the thoracic cavity by the diaphragm. The abdominopelvic cavity has two components: the abdominal cavity that contains, among others, the stomach, intestines, spleen, and liver, as well as the more caudal pelvic cavity. The pelvic cavity is surrounded by the bones of the pelvis, and contains the bladder, part of the reproductive organs, and rectum.

The walls of the ventral body cavities, as well as the surface of the visceral organs, are covered by a thin, double-layer membrane called the serosa, or serous membrane. The portion of the serosa lining the body cavity is called the parietal (parie = wall) serosa, while the portion lining the organ is the visceral serosa.

The best way to visualize the relationship between the two layers of the serosa is to imagine pushing your
fist into an inflated balloon. The layer of the balloon closest to your fist would be equivalent to the visceral serosa, while that part of the balloon on the outside would represent the parietal serosa. The two serosal membranes each secrete serosal fluid into the space between the two layers. This fluid acts as a lubricant to reduce the friction between the parietal and visceral serosa as they slide across one another. This is important when one considers how often the heart beats or the lungs inflate, during which time the visceral and parietal serosa slide across one another.

The serosa membranes have specific names depending on their locations. When found surrounding the heart, it is called the pericardium (peri = around + kardia, heart). Therefore, the parietal pericardium lines the pericardial cavity, while the visceral pericardium adheres to the heart. The pleura adheres to the lungs and lines the thoracic cavity, whereas the peritoneum lines the abdominopelvic cavity and adheres to the visceral organs.

Review questions and answers are available online.

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The cell: The common physiological denominator

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Cells: A common denominator

All of the physiological systems, for example, digestive, respiratory, or cardiovascular, depend on the actions and activities of cells. Groups of cells and their products coalesce to create the four basic tissue types (epithelial, neural, muscular, and connective tissues). Attributes of these tissues will be discussed in detail in Chapter 4. Combinations of these tissues produce organs. Functionally related organs are arranged into physiological systems. To illustrate, the digestive system includes the mouth and oral cavity, esophagus, stomach, small intestine and large intestine, and related accessory organs (liver, pancreas, gall bladder). This tube-within-a-tube organization allows for acquisition of food, physical mastication, chemical digestion, and ultimately, absorption of nutrients across the lining of the gastrointestinal (GI) tract into the bloodstream. The mature GI tract has elements of each of the four major tissue types.

The internal lining, the mucosa (an example of epithelial tissue), is composed of a layer of specialized epithelial cells called enterocytes. The enterocytes rest upon a thin layer of extracellular proteins, the basement
membrane. The mucosal layer also includes other specialized connective tissue elements, including the structurally important proteins collagen and elastin, as well as protein-carbohydrate hybrid molecules called proteoglycans. The mucosa also has a population of scattered smooth muscle cells, the muscularis mucosa, and a distinctive connective tissue called the lamina propria. The submucosa appears between the enterocytes and the next major tissue layer, the muscularis. This region provides a passageway for capillaries and lymphatic vessels. Exocrine glands, which produce secretions destined for the lumen of the GI tract, also reside in this location. Closer to the outer circumference of the tract, there are two closely aligned, dense layers of smooth muscle cells called the muscularis externa. The innermost layer of smooth muscle cells are arranged around the circumference of the GI tract, while the outer layer is oriented along the longitudinal axis of the GI tract. The coordinated contraction and relaxation of these two smooth muscle cell layers provide for mixing and movement of gut contents. A thin layer of epithelial cells called the serosa covers the outside of the GI tract that is adjacent to the internal body cavity. The serosa is continuous with the mesentery, which provides a means for entrance of veins, arteries, and nerve fibers into the muscularis externa and submucosa and for general support via attachment to ligaments.

Despite the complexity of tissue and cell types in the GI tract, and requirement of multiple cell and tissue types for maximum efficiency, the essential function of the GI tract depends on the actions of the enterocytes. Consequently, understanding physiological systems and principles ultimately should begin with an appreciation of cellular physiology and function. A common theme that we will emphasize repeatedly is that structure and function go together. This idea will become apparent at multiple levels of organization—molecular, cellular, organ, and system. Our story begins with a discussion of the cell.

Once past the primordial stem cell stage of the embryo, cells acquire varying degrees of structural and functional differentiation. Differentiation of cells equips them for their particular function. For many years, the dogma was that once cells became differentiated, it was impossible to reprogram them cell so that these cells or their daughters could be induced to follow a different path. Under usual circumstances, this likely is true; however, it is also evident that advances in cell and molecular biology have called this dogma into question. For example, development of the cloned sheep Dolly in 1996 was achieved using cultured fibroblasts. Other examples of animals cloned from fully differentiated cells have been recently reported. It is now known that virtually all tissues harbor populations of undifferentiated cells that serve as stem cells capable of being induced to proliferate and thereby create new lineages of cells that can repopulate those tissues. Box 2.1 provides some examples of mammary stem cells.

These examples serve to emphasize an unexpected plasticity of tissues and cells. It may be possible in the future to bioengineer replacements for damaged or diseased organs or tissues as more is learned about the rules governing cell growth and differentiation.

**Box 2.1 Practical anatomy and physiology**

There is a lot in the news lately about stem cells. Much of this involves efforts to produce replacement tissues or organs or combat ravages of cancer and other diseases. What about general physiology? Are there examples? The answer is yes. One of the most elegant demonstrations for the existence of stem cells is for the mammary gland. Using genetically similar mice, researchers first prepared recipient mice which had their rudimentary mammary epithelium surgically removed before puberty. This resulted in animals with an intact mammary fat pad (so-called cleared mammary gland), that is, no remaining mammary parenchymal tissue. Using cell separation and isolation techniques, scientists recreated the entire epithelial (parenchymal) portion of the mammary gland and induced milk synthesis following the injection of a single stem cell into a cleared mammary fat pad (Kordon and Smith, 1998; Bussard and Smith, 2011).

Other animal scientists are working to identify and manipulate stem cells in domestic animals to improve meat and milk production.

**Water: The universal solvent**

Because mammals are composed largely of water (~70%), cellular biochemistry is governed by interactions of physiologically important molecules and water of the cell cytoplasm, the water surrounding the cells (interstitial fluid), or the aqueous environment of various cellular organelles. We all appreciate, at least in a general sense, that water is essential to our survival. But remembering some of the physicochemical attributes of water emphasizes its physiological relevance. Water is an excellent solvent for many but not all physiologically important molecules. Blood plasma, which is about 90% water, transports a myriad of dissolved nutrients (e.g., glucose, amino acids), minerals (e.g., Na, Cl, and K), and gases (e.g., O₂, CO₂). Intracellular water is similarly filled with solutes. The urinary system maintains body water reserves to ensure that blood pressure and volume are adequate and that proper osmolality is maintained.
Water is touted as the biological universal solvent—but why? The answer lies in its abundance and structural properties of the water molecule. The chemical formula for water (H\(_2\)O) is well known, but Figure 2.1 illustrates that water has a distinct dipole moment. This means that there is unequal sharing of electrons between the oxygen and hydrogen atoms of the molecule so that the molecule is polarized. The oxygen atom, because of its greater capacity to attract electrons, has a slight negative charge. The hydrogen atoms therefore have a slight positive charge. This polarity causes the water molecules to arrange themselves so that they form hydrogen bonds (opposite charges attract). Hydrogen bonds, while weak compared with covalent chemical bonds, are very important physiologically because of their abundance. They also are important in attractions between many macromolecules. For example, the two strands of intact DNA are held together by hydrogen bonds between base pairs. Because of its dipole moment, there is a net negative charge associated with the oxygen atoms of the water molecule. This charge separation allows water molecules to organize to form attractant bonds with other water molecules. This property explains many of the attributes of water as the so-called universal solvent and the ability of other polar molecules to readily dissolve in water.

This attribute explains the commonsense example of oils not dissolving in water. Most common oils or lipids are composed of hydrocarbon chains that exhibit equal sharing of electrons between atoms and therefore are of little or no polarity. Such nonpolar molecules cannot associate with water and are described as hydrophobic (water-fearing molecules). Polar molecules, in contrast, readily associate with water and are described as a hydrophilic (water-loving molecules). Interestingly, many cellular and tissue macromolecules have both hydrophobic and hydrophilic regions. For example, the three-dimensional shape of a protein in the cell is determined by physicochemical forces that act to shelter groupings of hydrophobic amino acids away from water while at the same time allowing hydrophilic amino acids’ hydrogen bonding interactions with water. This fundamental property of water means that it can form highly oriented layers or shells around charged areas of large macromolecules, for example, nucleic acids, proteins, or proteoglycans, and thereby impact structure, organization, and function. Biochemists can take advantage of these properties to isolated macromolecules from homogenates of tissues or cells. For example, if the shielding of protein or nucleic acid charges by water is reduced by adding a water-miscible solvent that reduces hydrogen bonding, protein–protein or nucleic acid interactions are enhanced, and precipitation of the macromolecules occurs. This is often achieved by the addition of ethanol or acetone.

Other physiologically important properties of water include specific heat, thermal conductance, and surface properties. Briefly, water can absorb substantial amounts of heat energy without a drastic change in temperature. Alternatively, a significant amount of heat energy can be lost without a dramatic effect on temperature. This temperature buffering is important since most biochemical processes are temperature sensitive. Evolutionarily, the greater success of warm-blooded mammals compared with cold-blooded animals reflects the appearance of physiological mechanisms to maintain body temperature, and therefore water temperature. Since the water content of animal tissues is so high, the total capacity to store heat energy is correspondingly high. Energy needed to vaporize water is also relatively high. Think of how quickly you feel the cool effect of an alcohol swab on your skin compared with a simple water-moistened swab. This property can be viewed as both an advantage and a disadvantage, depending on the physiological circumstances. In hot environments or with excessive work, thermoregulation depends on sweating or panting in many animals to reduce the thermal load. Too much loss and there is dehydration. New visitors to hot, dry desert environments must be admonished to drink often to make up for unrecognized insensible water losses. Many animals have adapted specialized physiological mechanisms and behaviors to minimize insensible water loss and to maximize efficient use of water. As another example, seal pups reared in polar seas (in many respects a “desert” environment with regard to water availability) depend on water derived from the metabolism of high-fat milk to supply much of their water requirement. Consider the impact of water on accumulation of milk in the mammary gland, blood in the cardiovascular system, or perhaps urine production. There are also numerous moist surfaces on many organs. The surface properties of water also affect fluid movement and the capacity of tissue surfaces to interact. This phenomenon is evident in the meniscus characteristic of a test tube filled with water.
Another commonsense example is the appearance of beads of rainwater on the surface of a waxed car; the wax is very hydrophobic so the molecules of water in the droplet are much more attracted to one another than the nonpolar wax. The spherical shape is a reflection of the physics of attractions between the molecules and the fact that the sphere is the optimal shape to minimize forces. Surface tension describes these forces and is expressed in force per length or newtons (N) per meter. Pure water has a surface tension of 7N/m, but dilute detergent reduces this to about 4N/m. Surface properties of water play a critical role in many physiological processes. Surface-acting amphipathic molecules reduce surface tension. These molecules have distinct polar and nonpolar domains. When placed onto a moist surface environment, the molecules disrupt association between water molecules and at liquid–vapor interfaces limit water-to-water connections and thus the strength of the surface tension. For example, the capacity of the lung alveoli to expand in the newborn requires that the surfaces of the epithelial cells lining the internal surface of the alveolar air sacs be coated with a surfactant. This minimizes the attraction of the surfaces and therefore allows expansion. In fact, the surface tension of lung extracts can be as low as 0.5N/m. Specialized alveolar cells (Type II cells) scattered among the normal epithelial cells secrete surfactant. Production is stimulated by the secretion of glucocorticoids (steroid hormones produced in the adrenal gland), near the time of parturition. Animals that are born prematurely often have respiratory problems because of failed surfactant production.

**Cellular organelles**

Structures found inside cells are called organelles. Examples include the nucleus, mitochondria, and ribosomes. Most organelles are membrane covered. Other organelles, secretory vesicles and lysosomes, for example, are unique because of their membrane-bound contents. Thus, understanding membranes is important to understanding physiology. We begin with lipids and especially phospholipids. Lipids are a very heterogeneous group of molecules, but common attributes include (1) being practically nonsoluble in water but (2) being soluble in nonpolar organic solvents such as ether, ethanol, or chloroform. Lipids include fats, oils, waxes, and related compounds. Figure 2.2 shows the general structure of molecules necessary to produce common fats called triacylglycerols or triglycerides.

Neutral fats are esters composed of two building blocks—glycerol and one of any number of different fatty acids. Glycerol is a 3-carbon alcohol that is most often derived from the catabolism of the common hexose sugar glucose. Fatty acid molecules are linear hydrocarbon chains with a carboxylic acid moiety at one end. This residue or group is the most reactive or functional part of the molecule. Fatty acids vary in length, but the glycerol backbone of the triglyceride is constant. Fatty acids also vary with respect to the number of double bonds between carbon atoms. Those with no double bonds are called saturated fatty acids, those with a single double bond are monosaturated, and those with more than one are polysaturated fatty acids. The degree of saturation and length of the fatty acids affect their properties. For example, the shorter chain members <6 carbons are water soluble and volatile, but longer fatty acids are neither soluble nor volatile. Table 2.1 gives a listing of some of the common fatty acids.
saturated fatty acids, structural formulae, and common features. Common names of many of the fatty acids are widely used, but systemic names make deduction of structure easier. To illustrate, palmitic acid is the common name for the 16-carbon fatty acid hexadecanoic acid. This indicates the carboxylic acid of hexadecane (hexa meaning 6 and deca meaning 10, and ane indicating an alkane). This fatty acid is also written as C\textsubscript{16:0}, which means there are 16 carbons and 0 double bonds. Formally, triglycerides are called tri-acyl esters and are created from the alcohol glycerol and any of a number of particular fatty acids. The reaction involves a dehydration synthesis reaction (water is liberated, e.g., remember the earlier comment about seal pups getting water from milk fat catabolism) between a carbon of the glycerol and the carboxylic acid residue of each of the fatty acid chains to create the ester linkage illustrated generally by this equation:

\[
\text{O} \quad \text{R—C—OH} + \text{HO—R} \quad \text{O} \quad \text{R—C—O—R}
\]

Carboxylic Acid   Alcohol       Ester

Fluid mosaic model

Glycerol linked with three fatty acids creates a triglyceride, two fatty acids a diglyceride, and a single fatty acid a monoglyceride. Only a few naturally occurring triglycerides have the same fatty acid in all three ester positions. Most are mixed acylglycerols. Phospholipids demonstrated by the general formula shown in Figure 2.3 also contain a phosphoric acid residue. The alcohol moiety in many of the phospholipids is also glycerol, but for others, for example, the sphingophospholipids, the alcohol is sphingosine. Phospholipids are often drawn in the form of a ball to represent the polar head of the molecule and two trailing tails to represent the nonpolar hydrocarbon chains of the fatty acids. Along with associated proteins and some other lipids, the capacity of the phospholipids to spontaneously form bilayers is essential to understanding the formation of all of the cellular membranes. The now-classic organization of the plasma membrane is described as a fluid mosaic model. This consists of a mosaic of globular proteins suspended in a sea of phospholipids. Membranes are organized with the polar heads of two layers of phospholipids oriented either toward the aqueous environment of the interstitial fluid or toward the aqueous environment of the cytoplasm. The hydrophilic hydrocarbon chains of the fatty acids interact so that the membrane has a trilaminar appearance—phospholipid heads on either side with fatty acid tails in the center. This organization is apparent in well-preserved tissues, embedded in plastic resins thinly sectioned (\sim 900\text{nm}) and prepared for examination in an electron microscope. This is sometimes likened to a peanut butter sandwich, with the peanut butter as the tails and the two slices of bread as the phospholipid heads. This fundamental structure is true for all cellular membranes, but there are differences in the specific composition, for example, the Golgi membranes versus the plasma membrane. Proteins associated with the membranes are oriented within either the outer or inner membrane leaflets. Other proteins completely span the membrane. Whatever their specific arrangement, these proteins are called integral membrane proteins. Those that span the membrane are positioned so that fewer polar amino acids occur within the central hydrocarbon tails.
of the fatty acid chains, with polar amino acids located with the polar heads or aqueous surfaces of the membrane. Examples of complex plasma membrane proteins include receptors for hormones or growth factors (GFs) and those required for transport of metabolites and nutrients.

Cellular membranes are fluid, dynamic, and active structures. Membrane components are also interchangeable between many cellular components. For example, in the mammary gland of a lactating mammal, milk components are packaged into secretory vesicles within the Golgi apparatus. These product-containing vesicles progressively make their way to the apical surface of the cell where their contents are released into the storage spaces of the mammary gland by the process of exocytosis. The membrane surrounding the vesicles becomes part of the plasma membrane. Furthermore, lipid droplets synthesized in the cells progressively enlarge and also migrate to the apical surface of the cells for secretion. However, in this case, the droplets literally begin to protrude from the cells and become surrounded by the plasma membrane. This continues until droplets pinch off with the former plasma membrane now encapsulating the droplet. The membrane is now referred to as the milk fat globule membrane, but its origin was the plasma membrane of the cell. Figure 2.4 illustrates the organelles and secretion activity of such a mammary epithelial cell. Similar events occur in many other secretory cells, for example, pancreas, liver, salivary gland, and pituitary gland.

Microscopy techniques

Beginning with invention of the light microscope in the 1600s and progressive improvements in cell preservation, techniques to embed tissue in materials for sectioning, and staining to identify specific cellular components, much has been learned regarding cell structure and function. However, even simple smears of dislodged isolated cells can be very useful in physiological or clinical situations. The Pap smear is routinely used in women’s health to monitor the cells of the cervix. The morphology of the cells is classified to determine if any of the cells appear to have precancerous attributes, for example, altered nuclear morphology or staining characteristics. Another example is the blood smear, that is, a small sample of blood is spread and dried on a microscope slide and then stained. Such smears are cover-slipped, and a differential count is performed. In this procedure, the slide is scanned in a standard pattern and the first 100 white blood cells encountered are identified (lymphocyte, neutrophils, etc.) and tabulated. This information is used to produce a distribution profile of the types of leucocytes in the sample. For example, the horse averages about 55% neutrophils, 35% lymphocytes, 5% monocytes, 3% eosinophils, and 1% or fewer basophils. Changes in these proportions can reflect various diseases. What would be your prediction about a classmate with mononucleosis or a cat with leukemia?

In dairy animals, mastitis (inflammation of the mammary gland) status is routinely evaluated by the presence and number of leukocytes in the milk. The technology used is based on a well-characterized relationship between cell number and the amount of a specific dye that binds to DNA. As the cell number increases in the milk sample, the amount of dye binding...