The Circulatory, Cardiovascular, Lymphatic, and Respiratory Systems

FOCUS 3

ASSIGNMENT 9: THE CIRCULATORY SYSTEM

Read in your textbook, *Clinical Anatomy and Physiology for Veterinary Technicians*, pages 205–210. Then read Assignment 9 in this study guide.

The *circulatory system* has many functions, but most can be summed up as transport operations. The circulatory system provides a means of movement for a variety of substances through the body, including

- White blood cells to provide immunity to the entire body
- Red blood cells to transport oxygen
- Platelets and clotting proteins for forming blood clots
- Buffer chemicals to maintain the proper body pH
- Carbon dioxide waste gas
- Nutrients such as proteins and sugars
- Electrolytes to provide normal electrical charges for cellular function, especially for muscle and nerve cells
- Water
- Waste materials from cellular metabolism

Two types of circulatory systems exist within the body: the *cardiovascular system* and the *lymphatic system*. Blood and its associated cells and products are carried by the cardiovascular system, whereas the lymphatic system carries a fluid called lymph. *Lymph* is composed of water, proteins, and certain white blood cells. Both blood and lymph are important, as they carry out specific functions that will be examined in more detail later in this study guide. You'll also learn more about the individual cells found in blood and

lymph and how they function. In addition to blood and lymph, the body also contains several other fluids in specific compartments of the body that perform unique functions, and you'll study each of these as well.

Cardiovascular System

Think of your cardiovascular system as a vast plumbing system within your body. It consists of a network of blood vessels of three types: arteries, capillaries, and veins. These tubelike vessels carry blood loaded with oxygen, nutrients, water, and electrolytes to your body's cells. They leave the cells carrying blood loaded with carbon dioxide, waste products, and a different mixture of electrolytes and water.

Compare this setup to a plumbing system that carries fresh water to the sinks, shower, and toilets, and then carries away wastewater. Water reaches the plumbing system in your house or apartment because there are pumping stations that provide pressure to force the water through the water mains to your dwelling. Your cardiovascular system has a pump as well—the heart. Together, the heart, arteries, capillaries, and veins constitute a closed fluid system that's crucial to survival.

Anatomy of the Heart

The heart is located in the thoracic cavity within the mediastinum. The *heart* is essentially a large muscle that contracts and relaxes in a rhythmic fashion, creating a pumping action that forces blood to circulate throughout the body. Surrounding the heart is a sac called the *pericardium* that consists of two layers, an outer *fibrous pericardium* and an inner *serous pericardium.*

The fibrous outer layer attaches the heart to the diaphragm. The serous pericardium is made up of an inner visceral layer (the *epicardium*) and an outer parietal layer.

Within the sac, between the two layers of the serous pericardium there's normally a small amount of fluid called *pericardial fluid.* This fluid lubricates the heart and makes

it pump more efficiently. Beneath the epicardium is the muscle layer of the heart, the *myocardium,* which constitutes the heart's largest mass.

Lining the myocardium on the inside of the heart is a layer of elastic epithelial tissue called the *endocardium*. Cardiac muscle cells are called *myocytes.* Myocytes are connected to each other with intercalated disks and *desmosomes.* This allows the cells to work together in conducting electrical impulses and allowing heart muscle cells to contract and relax together. Now, let's look at the gross anatomy of the heart.

Think of the heart as a large muscular sac divided into four chambers (see Figure 8-3 on page 208 of your textbook). The two dorsal chambers closer to the spine are called the *atria* (singular, *atrium*), and the two more ventral chambers closer to the sternum are called the *ventricles.* In humans, the heart sits in such a fashion that there's one atrium and one ventricle each on the right and left sides; thus, there's a right ventricle, left ventricle, right atrium, and left atrium. In most domestic animals, the heart sits slightly skewed so that the right ventricle and right atrium sit slightly cranial to the left ventricle and left atrium. However, the chambers of animals' hearts are given the same names as those in people.

The atria are smaller and less muscular than the ventricles. Dividing the two atria is a wall of muscle called the *interatrial septum.* Between the two ventricles is a similar wall called the *interventricular septum*. Between the atrium and ventricle on either side is a ring of fibrous connective tissue. Attached to these rings are two to three roughly triangular flaps (or valves) of elastic fibrous connective tissue that can cover the opening between the atrium and ventricle.

Chordae tendineae are cords of fibrous tissue that anchor the tips of the flaps to papillary muscles, which are finger-like muscular projections of the myocardium into the lumen (or interior) of the ventricle. This structure of the fibrous ring and its associated flaps is called an *atrioventricular valve.* The right atrioventricular valve usually has three flaps and is therefore known as the *tricuspid valve.* However, in dogs and

cats, there are only two major flaps. The left atrioventricular valve usually has only two flaps and is thus known as the *bicuspid valve* (or *mitral valve*).

There are two semilunar valves that control blood flow out of the heart. The pulmonary artery exits the right ventricle, and the valve controlling blood flow through this opening is the *pulmonary valve.* Exiting the left ventricle is the aorta; thus, the valve controlling blood flow through this opening is called the *aortic valve.* These valves are one-way valves; in other words, blood can flow only in one direction. If blood attempts to flow in the wrong direction, the flaps close over the opening. When certain diseases damage these valves, the valves don't close completely, allowing some blood to flow in the wrong direction. This condition can lead to congestion and increased pressure in certain chambers of the heart as well as some veins, a condition called *heart failure,* which is described as inadequate pumping action of the heart. Ruptured chordae tendineae can lead to both acute valve failure and acute heart failure.

The *base* of the heart is defined as the area where the atria reside along with the entrance and exit of the large blood vessels connected to the heart. The *apex* is the opposite end of the heart, where the ventricles end, which lies near the sternum. The long axis of the heart is a line drawn from the apex to the base.

If you cut the ventricles of the heart in cross section in a plane perpendicular to the heart's long axis, you'll notice a distinct difference in the left and right ventricles. The left ventricle looks very similar to a circle with very thick muscular walls. The right ventricle is crescent-shaped, wraps partially around the left ventricle, and has a much thinner wall. The structural difference of these two chambers is due to the difference in their functions. The left ventricle has to pump against more resistance and needs to generate more pressure than the right ventricle. Moreover, by wrapping around the left ventricle, the right ventricle is aided in its contraction by the pumping of the left ventricle. In other words, as the left ventricle contracts, it pulls the outer wall of the right ventricle against it, helping the

muscles of the right ventricle generate more force. The difference in the right and left atria isn't as marked; both are relatively thin-walled compared with the ventricles.

The heart serves as a pump, pushing blood through the arteries to the rest of the body. Blood takes a specific path through the heart, and the heart contracts in a coordinated fashion to keep the blood flowing. Figure 8-2 on page 208 of your textbook contains a simplified diagram of the pathways that blood takes through the heart.

There are actually two separate circulatory systems to which the heart pumps blood—the systemic circulation and the pulmonary circulation. The *systemic circulation* is the network of blood vessels supplying all cells of the body. The *pulmonary circulation* is the blood supply that goes to the lungs so the blood can be oxygenated and rid itself of carbon dioxide. Therefore, the lungs actually have two supplies of blood: blood rich in oxygen that comes from the heart to supply the pulmonary cells and blood poor in oxygen that goes to the alveoli to be oxygenated. The heart deals with these two supplies somewhat separately. The right side of the heart pumps blood to the pulmonary circulation, whereas the left side pumps blood to the systemic circulation. The exact path the blood takes through the heart can be traced to show how the separate chambers act to pump blood to these two circulatory systems. The right atrium receives blood from the abdomen via a vein called the *caudal vena cava* and from the head via a vein called the *cranial vena cava.* When the right atrium contracts, the blood is forced through the tricuspid valve and into the right ventricle. The right ventricle contracts, forcing the blood through the pulmonary artery to the pulmonary circulation of the lungs, where it's oxygenated.

Blood exiting the pulmonary circulation returns to the heart through the *pulmonary vein,* which empties into the left atrium. Contraction of the left atrium pushes blood through the mitral valve into the left ventricle, which contracts to pump blood through the aortic valve into the aorta and thus into the systemic circulation.

Because the blood must travel in the same direction with each contraction of the heart, as the atria contract, the ventricles must be in a relaxed state to receive the blood. If the

ventricles contracted at the same time as the atria, the pressure generated by the ventricle would work against the pressure being generated by the atrium, and blood wouldn't flow from the atrium to the ventricle. Therefore, the contractions of the atria and ventricles are coordinated.

Generally speaking, the two atria contract at the same time, followed by contraction of both ventricles. Both of these events happen quickly and close together in time; outwardly, the heart almost appears to be beating as a single unit. The cardiac conduction system is responsible for coordinating these events within the heart.

Birds, Reptiles, and Amphibians

The structure of the avian heart is similar to that of mammals, but quite unique in reptile and amphibian species. The location of the heart within the body cavity varies depending on the species. Snakes' hearts aren't completely fixed in place, which serves to facilitate the ingestion of large prey items. Structurally, the hearts of reptiles and amphibians are quite different from those of mammals. Most reptiles and amphibians have three-chambered hearts with two atria and one common ventricle, which is subdivided into three distinct regions.

Before proceeding to the next assignment, take a moment to complete *Self-Check 9.* Remember, you can check your answers by turning to the back of this study guide.

Self-Check 9

1. Identify the four chambers of the heart.

   _____

   _____

   _____

   _____

2. Contraction of the left atrium pushes blood through the _____ valve and into the left ventricle.

3. Contraction of the right atrium pushes blood through the _____ valve and into the right ventricle.

4. The layer of elastic epithelial tissue that lines the myocardium on the inside of the heart is called the _____.

5. Cardiac muscle cells are called _____.

Check your answers with those on page 190.

ASSIGNMENT 10: CARDIOVASCULAR PHYSIOLOGY

Read in your textbook, *Clinical Anatomy and Physiology for Veterinary Technicians,* pages 211–219, 220–238, 440–444, and 460–462. Then read Assignment 10 in this study guide.

Within the heart muscle are modified cardiac muscle cells that form a network called the *cardiac conduction system.* The *Purkinje fibers,* which conduct electrical impulses within cardiac muscle, are part of that system. A collection of cells within the right atrium is called the *sinoatrial (SA) node,* and this is where the normal electrical impulses in the heart originate. At the junction between the atria and ventri-

cles is another collection of cells known as the *atrioventricular (AV) node,* which functions as a gateway through which electrical impulses pass from the atria to the ventricles.

Electrical signals in the heart begin in the right atrium in the sinoatrial (SA) node, also called the *cardiac pacemaker.* These cells have an inherent ability to generate an electrical current, a process called *self-excitation.* The cells of the sinoatrial (SA) node have different "channels" in the cell membrane that transport sodium, calcium, and potassium in or out of the cell. Such movements change the difference in electrical charges across the cell membrane and are somewhat dependent on the levels of sodium, potassium, and calcium in the body.

The changes in the electrical current, a process called *polarization,* across the SA nodal cell membranes generate an electrical current that's then transmitted through atrial muscle fibers, which is a relatively slow process. The process continues more quickly along fibers within the atrial wall called *internodal pathways* that carry this signal throughout the right and left atria. The atrial muscle fibers contract as the electrical impulse reaches them. The internodal pathways carry the signal to the atrioventricular (AV) node, a collection of conduction fibers located at the junction of the atria and ventricles.

Electrical impulses are slowed as they move through the AV node. This provides the time needed for the atria to empty into the ventricles before the ventricles are signaled to contract. You can see why the timing of the atrial and ventricular contractions is so important. Just ventral to the AV node is the *atrioventricular (AV) bundle,* which conducts the signal into the ventricles. After entering the ventricles, the AV bundle branches out into right and left bundles, which are collections of Purkinje fibers traveling through the right and left ventricles.

The signal is carried rapidly to the apex of the heart before the bundles branch out into the ventricular muscle. Initiating the ventricular contraction at the apex of the heart causes the ventricle to contract in the ventral-to-dorsal direction, squeezing the blood up to the base from the apex. This pushes the blood toward the appropriate artery exiting each ventricle.

The conduction fibers allow for more rapid transmission of the electrical impulse through the heart and also help coordinate the contractions for more effective pumping.

The contraction phase of the heartbeat that occurs as the current travels around the heart is called *systole.* All cells that undergo polarization must undergo repolarization (where the electrolytes' differences across the cell membrane return to normal) before the next depolarization can occur. During repolarization, the cardiac muscle cells relax, and the chambers enlarge and fill with blood, a phase known as *diastole.*

As a survival mechanism, the heart has backup systems when the primary system fails. The AV node and the Purkinje fibers, as well as atrial and ventricular muscle fibers, also have an inherent ability to initiate an electrical current. However, the signal generated is weaker and occurs at a slower rate than those generated by the SA node. Therefore, if the SA node fails, some other cardiac tissue takes over as the pacemaker. It's the tissue that has the most rapid rhythm that takes over next. If several areas fail to generate the current, the heart rate progressively slows to dangerous low levels.

How does your body regulate the beating of its heart? Multiple influences can cause the heart rate to speed up, slow down, become irregular, and cause the strength of cardiac contractions to increase or decrease.

First, electrolytes such as sodium, potassium, chloride, and calcium affect the ability of the cardiac cells—especially the SA and AV nodes—to initiate autonomous electrical activity. For example, if the blood potassium level is excessive, the heart rate slows down, because the electrical charge difference across the cardiac cell membranes is altered so the cells don't fire as rapidly. Drugs called *calcium channel blockers* decrease transmission of the electrical impulse through the AV node by slowing down the repolarization of the AV node cells. This repolarization is dependent on the flow of calcium through the cell membrane via calcium channels.

Second, several nerves can speed up or slow down the heart rate by stimulating the SA node to increase or decrease the pacemaker's rate of firing.

1. Increasing or decreasing the rate of transmission of current through the AV node, these nerves can also increase or decrease the strength of the cardiac contractions.
2. Hormones can also alter the rate and strength of cardiac contractions. In the section on the endocrine system, you'll learn about *adrenaline,* a hormone secreted by the adrenal glands under conditions of stress or exercise that increases the rate and strength of contractions.
3. The amount of blood within the heart helps determine the strength of contractions. As more and more blood fills the heart, the heart senses the stretching of its wall and increases the strength of contractions, up to a point. If the heart wall is stretched too far, the heart muscle begins to fail and the strength of contractions actually drops.

The heart is the force behind the circulatory systems, but the arteries, arterioles, capillaries, venules, and veins carry out the actual transport function of the circulatory system. *Arteries* are defined as blood vessels that carry blood away from the heart toward the cells of the body. *Arterioles* are smaller branches off arteries that connect directly to capillaries. *Capillaries* are microscopic blood vessels that connect arteries to veins and allow the exchange of gases, nutrients, and waste materials between the blood and the body's cells. *Venules* are slightly larger than capillaries; they carry blood from capillaries to veins. *Veins* are blood vessels that carry blood from the body's cells back toward the heart. These definitions hold true for both the systemic and pulmonary circulations. We'll discuss each of these vessels in turn, starting with their anatomy, and then move on to the way this anatomy ties in with their functions.

Blood Vessel Structure

All blood vessels have the same general structure. The outer layer of a blood vessel is the *tunica adventitia,* which is composed of connective tissue. In larger blood vessels, this layer

contains small blood vessels that transport oxygen and nutrients to the cells of the blood vessel walls. This may seem odd because there's blood within the blood vessel, but in larger blood vessels the wall is too thick for the blood within the lumen to supply oxygen and nutrients to all of the cells within the wall.

The middle layer of blood vessels, the *tunica media,* is composed of smooth muscle cells that control the blood vessel's diameter. The tunica media of some blood vessels also contains elastic connective tissue. The muscle cells are arranged in a ring around the diameter of the vessel, so as the muscles contract, the diameter of the vessel decreases, which increases the resistance to blood flow and increases the blood pressure. Contraction of the tunica media muscles is under the control of certain nerves and hormones, especially adrenaline, which causes contraction of the muscles.

The final and innermost layer of the blood vessel is the *tunica intima,* composed of a thin layer of epithelial cells, called the *endothelium,* and underlying connective tissue. As you'll see in the following sections, each type of blood vessel modifies this basic plan to better suit its purpose.

Arteries and Arterioles

Arteries carry blood from the heart to the cells of the body and are also responsible for establishing the blood pressure within the circulatory systems. Two types of arteries exist—elastic arteries and muscular arteries. *Elastic arteries* contain a larger proportion of elastic connective tissue within the tunica media than other arteries. Most of the major arteries close to the heart are elastic arteries, including most of the pulmonary arteries, aorta, and carotid arteries.

During systole, the pressure of the blood being pumped by the heart pushes against the artery's wall, stretching the elastic fibers in the wall. During diastole, the blood pressure against the arterial wall decreases, and the elastic fibers in the tunica media snap back to their original length, causing the diameter of the blood vessel to return to normal. The pressure generated by the recoil of the elastic fibers helps maintain the blood pressure in the circulatory system and keeps blood flowing while the heart is relaxing.

Muscular arteries are branches off the main elastic arteries that carry blood to various regions of the body. Muscular arteries have more muscle than elastic fibers in the tunica media. The larger proportion of muscle allows for finer control of blood vessel diameter, because the fibers in elastic arteries respond reflexively to stretch and aren't under the control of the body. Blood vessel diameter determines the resistance to blood flow and, along with the elastic fibers, the blood pressure. The change from the more elastic tunica media to the more muscular tunica media is gradual.

Arterioles, the smallest form of artery, carry blood from the muscular arteries to the capillaries. They lack significant elastic fibers and have only a few layers of smooth muscle cells in the tunica media; the tunica adventitia and tunica intima are extremely thin. Arterioles gradually decrease in diameter until they reach the capillary beds.

Capillaries

Branching out from each arteriole is a multitude of *capillaries,* tiny vessels that form a network to supply blood to the body's tissues. Capillaries have very thin walls that lack a tunica adventitia or tunica media. Essentially, the capillary wall is composed only of a tunica intima of endothelial cells. Capillaries allow the exchange of gases, fluids, nutrients, and waste products between the blood and the cells of that tissue—hence the need for a thin wall to minimize the distance these substances must cross. Many capillaries have a diameter equal to the width of one red blood cell (or even smaller). Certain areas in the liver, bone marrow, and spleen have larger capillaries called *sinusoids,* because there's a need for sluggish blood flow to allow these organs to perform their functions more effectively.

Eventually, the capillaries fuse together to join the venous side of the capillary bed. More extensive capillary beds are found in tissues such as muscle. Because these muscles have increased metabolic rates, they require more oxygen and nutrients.

Exchange of materials across the walls of the capillaries is very similar to the exchange of gases that occurs in the alveoli of the lungs. Passive diffusion of materials occurs

because the concentration of materials is higher on one side of the capillary wall than on the other side. Cells produce carbon dioxide as a result of cellular metabolism and must get rid of this waste gas.

Cells also need oxygen for cellular energy production. Blood entering the capillary bed is rich in oxygen and poor in carbon dioxide. As blood travels through the capillary bed, carbon dioxide from the cells diffuses across the capillary wall into the blood, whereas oxygen in the blood diffuses across the wall into the cells. Nutrients pass from the blood into the cells, whereas waste materials leave the cells and enter the bloodstream. By the time the blood exits the capillary bed, the blood has more carbon dioxide, less oxygen, more waste products, and less nutrients than when it entered the capillaries.

Veins and Venules

Veins and venules have the same basic structure as arteries and arterioles. However, the tunica media is generally thinner and the lumen of the vessel larger relative to the diameter of the vessel as compared with arteries. This means the wall of a vein is more compliant than that of an artery. Therefore, the venous system can hold more blood volume than the arterial system, although the pressure is lower. Because the muscle layer is much less developed, veins can't generate any pressure on the blood to continue blood flow. Instead, the pumping action of skeletal muscles throughout the body compresses the veins that course through them, which helps pump blood out of the veins. When you breathe in, negative pressure is generated in the right atrium and the major veins in the chest, which tends to draw blood toward the heart. Both of these mechanisms partially explain why exercise increases the flow of blood in the body. Another reason exercise increases blood flow is that the heart's rate and strength of its contractions increase with exercise. The inability to generate internal pressure in the vein means the vein has no way to pump blood in the forward direction as do the arteries. Instead, the veins possess valves, extensions of the venous wall that act as one-way flaps to close off the lumen and prevent blood from flowing in the wrong direction.

Specific Anatomy of the Pulmonary Circulation

The *pulmonary circulation* differs from the systemic circulation because its purpose isn't to carry oxygen and nutrients to cells and carbon dioxide and waste products away from cells. Instead, the purpose of the pulmonary circulation is to carry carbon dioxide to the lungs and to carry oxygen away from the lungs.

Compared with the systemic circulation, the pulmonary circulation's layout is relatively simple. The pulmonary artery carries oxygen-poor blood from the right ventricle to the lungs, where it divides into various branches that travel to each lung. Capillaries line the outer wall of alveoli and are the site where gas exchange between the blood and the alveolar air occurs. These capillaries then join together to form the pulmonary venous system, which eventually forms the pulmonary vein. This vein carries oxygen-rich blood to the heart's left atrium.

Specific Anatomy of the Systemic Circulation

The general purpose of the *systemic circulation* is to take oxygen- and nutrient-rich blood from the heart to the cells of the body, then to carry oxygen- and nutrient-poor blood from the body's cells to the heart. We'll discuss only the major arteries and veins here.

The major artery leaving the heart is the *aorta,* probably the largest blood vessel in the body of domestic animals. The aorta briefly travels cranially from the left ventricle, turns to the left briefly, then turns caudally and travels through the diaphragm and into the abdomen, where it ends at the pelvis by branching into several pairs of arteries called *iliac arteries* that supply the legs and tail. All systemic circulation arteries branch off from the aorta. The first artery to exit the aorta is the *coronary artery,* which supplies blood to the heart muscle and is the artery that becomes clogged in people, leading to heart attacks.

The subclavian arteries branch off the aorta and give rise to the *carotid arteries,* the major arteries supplying blood to the head and neck. There are several major arteries branching off the aorta that supply blood to the abdominal organs, including the *coeliac artery* (also called the *celiac artery*), which supplies the stomach, spleen, and liver; the *cranial mesenteric* and *caudal mesenteric arteries,* which supply the intestines; and the *renal arteries,* which supply the kidneys.

Of practical importance is the *femoral artery,* which branches off the iliac arteries and travels distally along the medial surface of the rear leg. You can feel the pulse by touching the skin over the femoral artery in the groin area and pressing lightly—you'll feel a throbbing sensation with each heartbeat. Sometimes you can feel the pulse by palpating the carotid artery in the neck to each side of the trachea. The lingual artery on the ventral surface of the tongue can be used to monitor the pulse in an anesthetized animal.

Several major veins are of importance as well. The *jugular veins* on each side of the neck carry blood from the head to the cranial vena cava, which empties into the right atrium. The *caudal vena cava* carries blood from the organs in the abdomen to the right atrium. A unique feature of the intestinal blood supply is the *mesenteric vein system,* in which multiple veins from the intestines collectively join together and form the *portal vein.* The portal vein empties into the liver, where the blood is filtered and detoxified. Blood from the liver is drained by the *hepatic vein,* which empties into the caudal vena cava.

Some of the veins in the leg and neck are useful for drawing blood for testing. These include the jugular veins in the neck, the *cephalic vein* on the anterior surface of the front legs, the *lateral saphenous vein* on the lateral surface of the rear legs just proximal to the tarsus, and the *medial saphenous vein* on the medial surface of the femur. Some of these veins are also located where intravenous catheters may be placed to administer medications and fluids. Cattle possess a vein on the ventral surface of the tail near the base that's often used for blood collection.

Fetal Circulation

Unique to the fetus before birth is the *fetal circulation,* which performs the same general functions as the postpartum circulation, but which is structurally different (see Figure 8-7 on page 214 of your textbook). The most important difference between the fetal circulation and mature circulation is that the fetal lungs are shrunken, collapsed, and empty of air; therefore, they don't function. Because the lungs are incapable of gas exchange, the fetus relies on the *placenta,* the membrane attaching the fetus to the mother's uterus, to act as the site of gas, nutrient, and waste product exchange.

Blood is carried from the fetus by the *umbilical arteries* to the placenta, where the fetal blood gets rid of carbon dioxide and wastes and picks up oxygen and nutrients. Blood from the placenta is carried via the *umbilical vein* through the liver and to the right atrium. The vessels to and from the placenta lie within the *umbilical cord.* The fetus doesn't need to pump a lot of blood to the lungs because they aren't functional; therefore, there are two openings within the circulation that shunt blood away from the lungs.

The first opening is the *foramen ovale,* an opening in the interatrial septum that connects the right and left atrium. As the right atrium contracts, part of the blood is pumped into the left atrium, so it doesn't have to travel through the right ventricle and the lungs. The second opening is the *ductus arteriosus,* an opening connecting the pulmonary artery and the aorta, so blood pumped from the right ventricle travels from the pulmonary artery into the aorta, again bypassing the lungs.

Both the foramen ovale and the ductus arteriosus normally close shortly before or after birth, so the normal operation of the pulmonary circulation is quickly established. In some cases, the ductus arteriosus fails to close off after birth, a condition called *patent ductus arteriosus (PDA),* in which blood is partially shunted away from the lung, creating an audible murmur.

Animals with PDA have excessive pressure within the right ventricle because the pressure in the pulmonary circulation is generally lower than the systemic circulation after birth.

This pressure differential causes blood to flow from the aorta into the pulmonary artery, increasing the blood volume and therefore the pressure in the right ventricle, a situation that can lead to heart failure. Surgery in which the PDA is tied off can be performed to correct this condition.

Shunting occurs from the pulmonary artery to the aorta in the fetus because the collapsed lungs provide a large amount of resistance to blood flow, so the pulmonary circulation pressure is greater than the systemic circulation. Various anomalies of the circulatory system occur during fetal development in some animals; some create no problems, but others can be potentially fatal. Some abnormalities of the subclavian arteries or the aorta can wrap around the esophagus, constricting it and preventing food from passing down the esophagus.

Portosystemic shunts are abnormalities of the portal vein in which the portal vein doesn't deliver blood to the liver, but instead carries blood from the intestines to the caudal vena cava. The result is an inability of the liver to detoxify substances absorbed in the intestine, leading to damage to the nervous system that can cause dementia, seizures, and even death. The liver fails to develop normally in patients with a portosystemic shunt because the intestine produces substances that promote normal liver development in the newborn. If a shunt exists, the liver doesn't receive these substances, is smaller than normal, and doesn't function normally. In some cases, surgery can correct the shunt.

Blood

The content of the cardiovascular system is *blood,* a fluid vital to life. Blood contains two major components: a fluid component called plasma and blood cells. *Plasma* is comprised primarily of water (a substance essential to all cells) as well as various proteins, electrolytes, minerals, sugars, fats, acids, and vitamins. Blood acts as the transport medium for nearly all chemicals that need to be delivered from one part

of the body to another. Substances carried by the blood may be dissolved in water, attached to blood proteins or fats, or carried within blood cells. The blood cells are

- *Erythrocytes* (red blood cells)
- *Leukocytes* (white blood cells)
- *Thrombocytes* (platelets)

Each of these cells performs specific functions that we'll examine in more detail later.

In addition to its transport function, blood also provides an environment suitable for the survival of cells. A specific pH level must be maintained for the proper operation of many proteins in the body. If the pH becomes more acidic or more alkaline than normal, many proteins can be damaged and stop functioning properly, a situation that can ultimately be fatal. Blood circulation also helps maintain an even body temperature, because blood is warmed in the central part of the body as a result of body metabolism, and this warm blood is transported to the body's peripheral portions, helping maintain the right temperature for cellular function.

Plasma and Serum

Plasma is the liquid portion of the blood after all the blood cells have been removed. Water is the main ingredient of plasma. Within the water of plasma are

- Dissolved electrolytes
- pH buffers
- Proteins of many types and functions
- Fats
- Sugars
- Vitamins
- Minerals

Plasma is transported to various parts of the body. If you take a blood sample from an animal and let it sit in a tube for several minutes, you'll notice a layer of straw-colored fluid

at the top of the sample and a clot of gel-like red material at the bottom. The portion at the bottom of the tube is a blood clot similar to what forms in the body if you cut yourself. The fluid at the top of the sample is called serum. *Serum* is simply plasma with the clotting proteins removed and is the most common type of blood used to test for various diseases. Serum still contains all the other proteins found in plasma; only the clotting factors are removed. If you want plasma for testing, you must add one of various *anticoagulants* to the blood sample to block the clotting process; anticoagulants used include heparin or sodium citrate.

Probably the most important function of plasma is the transport of *carbon dioxide,* the waste gas produced by the body's cells during normal metabolism. Carbon dioxide dissolves more easily in water than many other gases. However, the majority of carbon dioxide isn't transported directly dissolved in the water. Instead, a carbon dioxide molecule leaves a cell, crosses the capillary wall, and enters a red blood cell (a process that occurs via diffusion). When this occurs, the carbon dioxide molecule reacts with a molecule of water to form carbonic acid. The carbonic acid molecule then breaks down into a molecule of bicarbonate and a hydrogen ion, which can diffuse back into the plasma. *Bicarbonate* is the primary form of transport of carbon dioxide in the blood. A smaller fraction of carbon dioxide binds to hemoglobin for transport and thus stays within the red blood cell. The release of the hydrogen ion would make the blood more acidic if it weren't for the presence of certain pH buffers. These pH buffers are primarily bicarbonate and phosphate, and they neutralize the acid to maintain the proper blood pH. If the blood pH isn't controlled, excessively acidic or alkaline conditions damage proteins in cells, leading to cell death.

Plasma is also involved with water and electrolyte transport to cells. Diffusion of substances in the blood across the vascular wall is a passive process. Fat-soluble substances can diffuse directly through the cell membrane of the endothelium, as can water. Water-soluble substances and some water cross the endothelial barrier via small pores between adjacent endothelial cells.

Various factors affect the movement of substances across the vascular wall, and these factors vary, depending on whether you're examining the arterial end or the venous end of the capillary. At the arterial side of the capillary, fluid tends to flow from the capillary lumen into the extracellular fluid. At the venous end of the capillary, fluid tends to flow back into the capillary, but the net movement of water is out of the capillary.

Hydrostatic pressure, generated by the beating of the heart and the elasticity of the arteries, tends to force water out of the blood vessel and into the extracellular fluid or into body cavities. *Colloidal pressure,* also called *osmotic pressure,* is pressure generated by the presence of proteins, primarily albumin. This pressure tends to retain water where there's a higher concentration of protein. At the arterial end, the colloidal pressure in the extracellular fluid is greater than that in the capillary lumen, so fluid tends to be drawn into the extracellular fluid space.

By the time blood reaches the venous end of the capillary lumen, enough water has been drawn out of the blood to increase the concentration of the albumin in the blood. Because of the increased concentration of albumin, the colloidal pressure in the blood is higher than that in the extracellular fluid. Water tends to flow out of the extracellular space and into the capillary. Hydrostatic pressure at the venous end of the capillary has decreased significantly, so there's less pressure forcing fluid out of the capillary at the venous end. There's a slight net movement of fluid out of the capillary over the length of the capillary. Any excess water in the extracellular space is eventually drained away by the lymphatic system, which we'll examine later.

Why is knowledge of fluid movement important? Any imbalance of these forces can lead to serious consequences. For example, if the albumin level in the blood drops, the colloidal pressure in the blood also decreases, and more fluid flows out of the capillary. This leads to excessive fluid buildup in tissues, a condition known as *edema,* or excessive fluid buildup in body cavities such as the abdomen or pleural cavity, a condition known as *effusion.* These fluid accumulations can be uncomfortable or even fatal.

Blood Cells

As already mentioned, blood cells consist of erythrocytes (red blood cells), leukocytes (white blood cells), and thrombocytes (platelets). *Erythrocytes* are responsible for the transport of oxygen and carbon dioxide in the body; *leukocytes* are part of the body's immune system; and *thrombocytes* are involved in the blood-clotting process. All of these cells are produced in the bone marrow, mostly in the long bones and some of the flat bones. Cells called *stem cells* within the bone marrow divide repeatedly and constantly, giving rise to cells that continue dividing and changing until a mature blood cell of the appropriate type is made. The mature cell is released into the circulation.

Certain diseases (e.g., leukemia) or toxins (e.g., abnormal levels of estrogen) damage the bone marrow and decrease the production of blood cells. This can be documented by the finding of abnormally low numbers of cells in blood samples as well as by the examination of a bone marrow sample. The structure and function of these cells and the diseases associated with them are reviewed in the next few sections.

Red Blood Cells

Structure. In dogs and humans, the erythrocytes are *biconcave disks,* which are disklike cells with deep depressions in the center of each side. Other species have round cells without the central depressions. The erythrocyte cell membrane is quite flexible, allowing the red blood cell to squeeze through even the narrowest capillary. The close proximity of the erythrocyte cell membrane to the capillary endothelium improves the efficiency of gas exchange by decreasing the distance across which the gases must travel.

Erythrocytes are somewhat unusual because mature erythrocytes of most mammals don't possess a nucleus, although immature erythrocytes in the bone marrow have a nucleus. The lack of a nucleus means mature erythrocytes are incapable of manufacturing new proteins or dividing to produce more cells. Therefore, erythrocytes have a limited life span, because no protein can be made for cell repair, which varies with each species. However, erythrocytes aren't chemically inactive.

Function. The primary responsibility of the erythrocyte is the transport of gases throughout the body. Oxygen is carried from the lungs to the cells, and carbon dioxide is carried from the cells to the lungs. Erythrocytes contain a unique molecule called *hemoglobin,* a protein molecule with an iron molecule in the center. Hemoglobin binds both oxygen and carbon dioxide for transport. Without it, there would be much less oxygen and carbon dioxide transport. Hemoglobin is manufactured in the immature erythrocyte (which still possesses a nucleus) in the bone marrow. However, once the erythrocyte matures, no nucleus and no endoplasmic reticulum are present to manufacture more hemoglobin. This fact is crucial because under certain conditions the hemoglobin molecule is irreversibly damaged and becomes of no use for gas transport.

When an erythrocyte passes through the capillaries adjacent to the alveoli, oxygen diffuses from the air in the alveoli through the alveolar wall, through the capillary wall, and then through the erythrocyte membrane. Once inside the erythrocyte, the oxygen molecule binds to a molecule of hemoglobin. The ability of hemoglobin to bind oxygen is somewhat dependent on the following factors:

- Amount of oxygen present
- pH level of the blood
- Level of dissolved carbon dioxide in the blood
- Temperature of the blood

When the erythrocyte reaches a capillary, the oxygen is released by the hemoglobin molecule and diffuses through the erythrocyte cell membrane, through the capillary wall, then into the tissues. The vast majority of oxygen is carried through the body in combination with hemoglobin. Only a very small amount is transported as a directly dissolved substance in the water portion of plasma.

Platelets

Structure. *Platelets* are fragments of cells formed in the bone marrow by budding off the cytoplasm of large cells called *megakaryocytes.* Granules within the platelets contain

chemicals used in the clotting process. The sole purpose of platelets is to contribute to the clotting—*coagulation* or *hemostasis*—process. Platelets are responsible for plugging up small holes caused by small tears or leaks within blood vessels. Platelets adhere to the damaged area of the blood vessel wall, alter their shape so that they have multiple small spiny projections from their surface, and secrete chemicals that attract other platelets. When these platelets stick to the original platelet, a *platelet plug* is formed. This process plugs very small holes.

Large areas of vessel wall damage require the formation of a *fibrin plug,* or *blood clot,* which is a larger, stronger, and more complicated structure than the platelet plug. Fibrin plugs are composed of an interwoven mat of platelets and threads of *fibrin,* a blood protein. Formation of a fibrin plug occurs in two stages: the formation of a platelet plug (or *primary hemostasis*), and formation of active fibrin and its adherence to the platelet plug and blood vessel wall (or *secondary hemostasis*).

Function. Platelets act in the same way as in the formation of a platelet plug in the first stage of hemostasis. The second stage of blood clot formation involves the interaction of various clotting factors (i.e., proteins synthesized in the liver) in the blood to eventually form fibrin.

White Blood Cells

Structure. Several different types of leukocytes exist, and each type has its own unique function. All leukocyte types are involved in the immune system's reaction to infection or some other disease that stimulates the immune response. Leukocytes are generally slightly larger than erythrocytes and all possess a nucleus; thus, unlike erythrocytes, they're capable of normal protein synthesis. Two categories of leukocytes are *granulocytes* and *agranulocytes.*

Three types of granulocytes exist:

1. Neutrophils
2. Eosinophils
3. Basophils

These cells are named based on the way the granules within the cytoplasm take up certain stains used to make the cells more visible under the microscope. The granules are packets of chemicals released by the leukocyte under certain conditions. The content of the granules varies with the type of cell and determines the staining characteristics.

Function. Leukocytes are involved with the body's immune system and with inflammation in some fashion. *Immunity* refers to the body's ability to fight off infection. Inflammation in tissue is clinically defined by four classic hallmarks: redness, heat, swelling, and pain. Inflammation is a consequence of the body's attempt to fight infection or repair damaged tissue. Each leukocyte has particular roles in immunity, although the exact role of some of the cells isn't clear. Leukocytes don't act independently of each other, but instead interact with each other to carry out their part in immunity and inflammation.

The first line of defense in the body is the *neutrophil,* which normally exists in low numbers in the body's tissues and in larger numbers in the circulation. When bacteria invade the body, local neutrophils recognize the bacteria as being foreign and attack the bacteria by engulfment. This process of "swallowing" the bacteria is known as *phagocytosis.* Phagocytosis involves the formation of an indentation in the cell membrane of the neutrophil that eventually surrounds the bacteria completely to form a packet within the cell. This packet (including the bacteria) is known as a *phagosome.*

Lysosomes (i.e., sacks of digestive enzymes) are visible in the cell as some of the microscopic granules in neutrophils. These lysosomes fuse with phagosomes to form a digestive vacuole called a *phagolysosome,* in which the bacteria are digested. In addition, other granules in the neutrophil contain certain other digestive enzymes, and these granules also fuse with the phagolysosome to aid in the destruction of the bacteria. In addition to digesting the bacteria, the neutrophil is also triggered by the act of phagocytosis to release chemicals that initiate the process of inflammation.

These inflammatory chemicals are also released by tissues when they're damaged in any manner. When these chemicals are released into the extracellular space or circulation, they

cause local blood vessels to dilate, bringing more blood and thus more leukocytes into the area. They also make the blood vessel walls "leakier," so leukocytes can leave the blood vessel more readily to enter the tissue and attract more leukocytes into the area.

The visible effect of the inflammatory chemicals is redness, heat due to the increased local blood flow, and swelling due to leaking of fluid from the capillaries into the tissues. Pain, the fourth component of inflammation, is induced by chemical stimulation of pain nerve receptors in the damaged tissue.

Soon after tissue is invaded by bacteria or damaged in any fashion, the area affected is flooded with neutrophils and other inflammatory cells to clean up any bacteria or debris from tissue damage. *Basophils* are present only in very low numbers and aren't phagocytic. The granules in basophils contain high levels of two chemicals: heparin and histamine. *Heparin* blocks the clotting process of blood, preventing small clots from forming in the affected tissue, and thereby increasing blood flow into the tissue. *Histamine* causes constriction of smooth muscles, primarily those in the walls of the venules as well as the walls of the airways in the lungs. The result is decreased outflow of blood from capillaries, which thus engorge with blood, leading to fluid leakage and tissue swelling. This creates a *welt,* which is a red, raised swelling of the skin that often itches. Histamine also causes a decrease in the diameter of the airways, which is a process called *bronchoconstriction. Mast cells* are very similar to basophils but are found in connective tissue rather than in the circulation. Mast cells contain the same granular contents as basophils and are also very involved with allergic reactions. *Eosinophils* are phagocytic like neutrophils but are involved less with defense against bacteria and more with immunity against certain parasites. Eosinophils contain high levels of antihistamine. Thus, eosinophils are believed to be involved with regulation of allergies.

Two types of agranulocytes exist: *lymphocytes* and *monocytes.* No granules exist in the cytoplasm of these cells, but the cytoplasm appears slightly blue under the microscope due to

the presence of cell proteins and endoplasmic reticulum. These cells also contain chemicals for use when needed, but these chemicals aren't visible under the microscope.

Macrophages are monocytes that have migrated out of blood vessels and reside in tissues. Macrophages aren't distinguishable from monocytes, except by their location in tissues as opposed to the circulation. Macrophages are similar to neutrophils and eosinophils in that they're phagocytic, so they can engulf and destroy foreign proteins and bacteria. They also play a role in the activation of the immune system.

Lymphocytes are the most common type of agranulocyte but aren't as common as neutrophils in most mammals. Lymphocytes aren't phagocytic; instead, they regulate the immune system in one of the following ways:

- Destruction of abnormal cells, such as cancer cells or cells infected with a virus, via attack by chemicals released by the lymphocyte
- Production of *antibodies*—proteins that recognize specific foreign proteins
- Recruitment of other cells of the immune system to perform specific functions

Three types of lymphocytes can be identified based on the types of proteins carried on the cell surface: *B cells, T cells,* and *natural killer (NK) cells.* NK cells have the ability to kill some types of tumor cells and cells infected with various viruses. NK cells must come in direct contact with these cells before they can destroy them. B cells are stimulated by certain T cells and/or the presence of an *antigen,* which is a foreign protein, to transform into plasma cells. Plasma cells are responsible for producing antibodies. Antibodies attach to the specific foreign protein that they're designed to recognize (i.e., antibodies for ragweed pollen won't attach to oak pollen proteins). Antibodies signal the other cells of the immune system to attack and destroy that protein or stimulate an allergic reaction to that protein. Nearly all T cells produce *lymphokines,* chemicals that perform one of several functions.

Lymphokine functions include

- Attracting other immune cells, typically macrophages, to the location where they're needed to fight disease
- Suppressing antibody production
- Preventing movement of neutrophils away from the site of inflammation
- Killing cells to which the T cells are attached

Birds, Reptiles, and Amphibians

Avian blood vessels are distinct from mammals' blood vessels in several ways. The pectoral and brachial arteries are relatively large compared with equivalent structures in mammals. Some birds also possess a network of closely associated arteries and veins that serve as a heat exchange system (see Figure 19-33 on page 443 of your textbook).

Unlike those of nearly all mammals, the red blood cells of birds, reptiles, and amphibians are oval and contain a nucleus. The cell that's functionally equivalent to the mammalian neutrophil is called a *heterophil* in birds, reptiles, and amphibians. These cells contain rod-shaped reddish orange cytoplasmic granules. The monocytes of some snakes often contain bluish cytoplasmic granules. Other blood cells and platelets of birds, reptiles, and amphibians are similar to that seen in mammals.

Before proceeding to the next assignment, take a moment to complete *Self-Check 10.* Remember, you can check your answers by turning to the back of this study guide.

Self-Check 10

1. The contraction phase of the heartbeat that occurs as the current travels around the heart is called _____.

2. An abnormal blood vessel creating abnormal blood flow around the liver is called a _____.

3. The major arteries supplying blood to the head and neck are the _____ arteries.

4. Normal electrical impulses in the heart originate at the _____.

5. The three types of blood vessels are _____, _____, and _____.

6. In mammals, the *most* common type of agranulocyte in the body is the _____.

7. Leukocytes are also known as _____.

8. Cells involved in the production of antibodies are _____.

9. Name the five types of white blood cells.

_____

_____

_____

_____

_____

Check your answers with those on page 190.

ASSIGNMENT 11: THE LYMPHATIC SYSTEM

Read in your textbook, *Clinical Anatomy and Physiology for Veterinary Technicians,* pages 239–242. Then read Assignment 11 in this study guide.

The *lymphatic system* is somewhat similar to the cardiovascular system because it consists of a network of vessels coursing throughout the body that often parallels that of the blood vessels. However, its structure and function differ significantly from blood vessels. There are two major components to the lymphatic system: the lymphatic vessels and the lymph nodes. Two additional, specialized lymphatic structures can also be found: the thymus gland and the spleen.

The *lymphatic vessels* are thin-walled and look much like veins, but with a thinner wall and more valves. Lymphatic vessels begin as lymphatic capillaries at the tissue level. At this level, protein-rich fluid called *lymph,* which also contains some lymphocytes, is formed. Lymphatic vessels gradually enlarge and fuse together, forming increasingly larger vessels. These vessels eventually empty into the venous blood via a lymphatic vessel called the *thoracic duct.*

Along the path of the larger lymphatic vessels are the lymph nodes, which are aggregates of lymphoid tissue. Scattered throughout the body, especially in the intestines and oral cavity, are congregations of lymph tissue. These congregations of lymph tissue aren't well defined, nor are they associated with lymphatic vessels. The tonsils, which are located in the pharynx, are an example of this type of lymphoid tissue. Lymphoid tissue located within the lining of the intestine is referred to as *gut-associated-lymphoid tissue.*

Lymph Node Anatomy

Lymph nodes are roughly bean-shaped structures that contain large numbers of lymphocytes and lymphatic vessels. Covering the outside of the lymph node is the *capsule,* a layer of dense connective tissue and epithelial cells. Each lymph node is supplied with an artery and vein, one or

more afferent lymphatic vessels that carry lymph to the lymph node, and a single efferent lymphatic vessel that carries lymph away from the lymph node.

Inside the lymph node the afferent lymphatics branch out and form a network of open spaces called *sinuses,* which allow lymph to flow throughout the lymph node. The outer layer of the lymph node is called the *cortex.* The cortex consists of a loose collection of T cells interspersed with roughly round nodules called *lymphoid follicles* that consist of B cells. The middle of the lymph node is called the *medulla.* The medulla consists of sinuses projecting from the afferent lymphatic vessel and medullary cords that are projections of the cortex tissue toward the center of the lymph node.

Thymus Gland Anatomy

The *thymus gland* is a part of the lymphatic system normally found only in young animals. It resides in the thoracic cavity just cranial to the heart. As the animal matures, the thymus gland degenerates until it blends with the surrounding connective tissue. The thymus is organized somewhat like a lymph node, with an outer, denser layer of lymphocytes known as the cortex and an inner, less dense lymphocyte layer called the medulla. Surrounding the thymus gland is a thin layer of dense connective tissue and epithelial cells called the *capsule,* which also contains the blood vessels supplying the thymus. Epithelial cells invade the cortex and medulla to provide a supporting framework upon which the thymic lymphocytes reside. Unlike lymph nodes, the thymus lacks afferent and efferent lymphatic vessels; only blood vessels supply the thymus.

Spleen Anatomy

The spleen is located in the left cranial region of the abdomen, usually situated lateral, ventral, and caudal to the stomach. The *spleen* is a flat, elongated organ shaped somewhat like a tongue. If you cut a spleen in cross section across the long axis, you see a roughly triangular shape in cross section. That is, the spleen is thicker in the middle than on the edges,

rounded in the middle on one side, and pointed in the middle on the other side. If you look closely at this cross section with the naked eye, you'll see two colors of tissue: smaller, rounded, pale areas called the white pulp surrounded by larger amounts of redder tissue called the *red pulp.*

Under the microscope the white pulp consists of clusters of lymphocytes arranged around arterioles. The red pulp consists of phagocytic cells arranged along a connective tissue skeleton interspersed with vascular cavities called *venous sinuses.* The spleen, like the lymph nodes and thymus, is covered with a layer called the *capsule,* which extends deeper into the tissue to form a supporting framework. Supplying the spleen with blood is the *splenic artery;* draining the spleen is the *splenic vein.* Like the thymus gland, the spleen has no lymphatic vessels supplying it.

Lymphatic System Functions

Lymph Nodes and Lymphatic Vessels

The two purposes of the lymph nodes and lymphatic vessels are drainage of excess extracellular fluid and provision of a first line of immunity. There's a net diffusion of fluid into the extracellular space as blood flows from the arterial side of the capillary to the venous side of the capillary. This excess fluid must be drained away; otherwise, the fluid cause the tissue to swell. The lymphatic vessels carry this fluid away. Because there's no pumping organ in the lymphatic system, the movement of lymphatic fluid depends on

- The pumping action of the heart, which circulates the blood and exerts pressure in the extracellular space
- The pumping action of muscles when walking and running, which compresses the lymphatic vessels from outside, forcing the fluid up the lymphatic chain

The valves in the lymphatic vessels prevent the lymphatic fluid from flowing backward. Unlike the cardiovascular system, the lymphatic system carries fluid in only one direction—away from the tissues of the body. There are no lymphatic vessels to carry lymph toward tissues.

The second function of the lymph nodes and lymphatics is the immune function. As lymph is drained from the various areas of the body, it must flow through lymph nodes along the way before it can be emptied into the cardiovascular system. Lymph comes into contact with lymphocytes and macrophages as it flows through the lymph node. If any bacteria, infectious organisms, or cancer cells are present in the lymph, the immune system recognizes them as foreign, and an immune system reaction occurs as described in the section on white blood cells.

The lymph nodes act as filters to remove infectious organisms or cancer cells from the lymph before it can enter the cardiovascular system. When this occurs, a proliferation of lymphocytes occurs within the lymph nodes. The result is an enlargement of the lymph node that can be so severe that it can be palpated from the outside. Veterinarians can sometimes first detect infection or cancer by feeling for enlarged lymph nodes.

Thymus Gland Function

The thymus is important in the early development of the body's immune system. Lymphocytes in the fetus are produced in the bone marrow. After birth, some of these lymphocytes exit the bone marrow and are carried to the thymus via the blood. Once in the thymus, these lymphocytes somehow "learn" which foreign proteins they should attack in the future. Then the lymphocytes develop into mature T lymphocytes (or T cells). Mature T cells then migrate to the lymph nodes, spleen, and other areas of aggregated lymphoid tissue.

Spleen Functions

The spleen carries out several functions. First, the spleen removes foreign particles from the blood via the activity of the phagocytic cells of the red pulp. Unlike other areas of the lymphatic system, the spleen filters blood, not lymphatic fluid. As blood moves through the venous sinuses and over the red pulp, the phagocytic cells ingest foreign material in the blood before entering the splenic vein and returning to the rest of the circulatory system.

Second, the spleen acts like a lymph node to generate an immune response to infection or cancer. As the blood passes through the arterioles, the white pulp is exposed to the blood, stimulating a specific immune response. As in the lymph node, immune stimulation may cause proliferation of white blood cells that may cause the spleen to enlarge grossly.

The third function of the spleen is to remove dying blood cells of all types as they pass through the venous sinuses. The macrophage cells of the red pulp are responsible for carrying out this task.

In some cases, the immune system fails to recognize normal blood cells and destroys them at an excessively high rate. The most common form of this disease is *autoimmune hemolytic anemia,* in which red blood cells are destroyed in the spleen and sometimes also the liver at such a rate that the animal quickly becomes anemic and jaundiced. The spleen can also act as a backup system if the bone marrow is damaged. The spleen, if needed, can produce new blood cells of all types through a process called *extramedullary hematopoiesis.* This splenic hematopoiesis may be all that keeps some anemic animals alive when the bone marrow fails to work properly.

Before proceeding to the next assignment, take a moment to complete *Self-Check 11.* Remember, you can check your answers by turning to the back of this study guide.

Self-Check 11

1. Which of the following *isn't* a function of the spleen in adult mammals?

   a. Production of blood cells
   b. "Education" of T lymphocytes
   c. Filtration of the blood
   d. Generation of an immune response

2. The largest lymphoid organ in the body is the

   a. thymus.
   b. GALT.
   c. tonsils.
   d. spleen.

3. An important lymphatic organ in young animals that atrophies later in life is the

   a. thymus.
   b. GALT.
   c. tonsils.
   d. spleen.

4. Lymph fluid reenters the blood via a vessel called the _____.

5. The part of the spleen that contains blood sinuses is referred to as the _____ pulp.

Check your answers with those on page 190.

ASSIGNMENT 12: THE RESPIRATORY SYSTEM

Read in your textbook, *Clinical Anatomy and Physiology for Veterinary Technicians,* pages 247–257, 445–446, and 463–464. Then read Assignment 12 in this study guide.

The respiratory system has one obvious function—to carry out the act of respiration. *Respiration* is responsible for two processes crucial to survival: external respiration and internal respiration. Respiration provides the body with oxygen and removes certain waste gases from the body. The intake of oxygen and removal of waste gases occurs in the lungs and is called *external respiration.* The transfer of oxygen from the

blood to the body's cells and tissues and the removal of waste gases from these cells into the blood is called *internal respiration.* In this part of your program, we'll examine the respiratory system's parts and how each part functions in the process of respiration.

All domestic animals share similar respiratory system structures. See Box 10-1 on page 248 of your textbook. Following the path of airflow from outside the body to the lungs, the parts of the respiratory system include these structures:

- Nostrils
- Nasal passages
- Pharynx
- Larynx
- Trachea
- Bronchi
- Bronchioles
- Alveolar ducts
- Alveoli

Upper Respiratory Tract Anatomy

All anatomical structures of the respiratory tract that are outside of the lungs are referred to as the *upper respiratory tract.* The upper respiratory tract consists of the nostrils, nasal passages, pharynx, larynx, and trachea. We'll examine each of these in turn to see how they're constructed and how this structure affects function.

The respiratory system is designed for air to enter the body mainly through the nostrils, which allow breathing to continue during such acts as chewing food or drinking water. *Nostrils,* also called *nares,* are a pair of openings at the front of the face just dorsal to the mouth, which are constructed mostly of cartilage and thick stratified squamous epithelium. The nares also feature some muscle and nerve tissue as well as the usual blood vessel supply.

The shape and size of the nares vary with the species or breed. For example, compare the nostrils of a collie to those of a Pekinese. The presence of cartilage with muscle makes the nose very flexible, allowing the animal to manipulate the nares to control the amount of air entering the lungs. You can see this ability in action during a horse race. Watch how wide open the nares of the horses are as they come down the backstretch. The larger the diameter of the nares, the more air can be moved into the lungs with each breath.

In a similar manner, as a dog sniffs the ground, its nares flare open with each inhaled breath to allow more air in. Brachycephalic breeds, such as Chinese pugs and Persian cats, sometimes have extremely small nares that make breathing difficult. This condition, called *stenotic nares,* sometimes requires surgical correction.

The nostrils open into the nasal passages. The nasal cavity is lined with pseudostratified columnar epithelium. The epithelial cells of the nasal cavity possess small, finger-like projections of the cell membrane called *cilia* (singular, *cilium*) on the surface. Cilia are capable of whiplike motions that, when executed in a coordinated fashion, can move small particles and fluid on the surface of the respiratory passage toward the pharynx. The particles can then be swallowed to be destroyed by the digestive system. This is a protective mechanism to prevent the inhalation of small debris and microbes into the lungs.

Goblet cells, which are interspersed with the ciliated cells, produce *mucus,* a thick high-protein liquid that helps trap microbes and debris in a layer over the cilia. The left and right nasal cavities are separated by a wall called the *nasal septum,* which is constructed of bone and cartilage covered with nasal epithelium. Each nasal cavity is partially divided internally by fine scroll-like whorls of bone called *turbinates,* which arise from the nasal cavity's walls. Each of the chambers within a nasal cavity created by these turbinates is known as a *nasal meatus.*

If the nasal cavity is cut in cross section, on the lateral side you'll see three meatuses called the dorsal, middle, and ventral meatuses, which are separated by two turbinates. On the medial side next to the nasal septum is a large meatus called

the *common meatus.* This meatus communicates with the other three meatuses. All of the meatuses travel the length of the nasal cavity, eventually communicating with the nasopharynx.

The floor of the nasal cavity, known as the *hard palate,* separates the nasal cavity from the oral cavity just ventral to it. The hard palate is composed of the palatine bone, whereas the sides and roof of the nasal cavity are formed primarily by the maxilla bone. *Paranasal sinuses* are cavities within the bones of the skull connected to the nasal cavities via small openings. Most domestic animals have two frontal and two maxillary sinuses, although the exact number and location of the sinuses vary with the species of animal.

When a breath is taken, air enters through the nares, passes through the meatuses, and over the turbinates. The air then enters the pharynx, which lies just rostral to the larynx. Air passing through the upper respiratory system is moistened by the secretions of the goblet cells, filtered by the cilia and mucus on the surface, and warmed by heat radiating from the nasal mucosa. Additionally, nerve endings are present in the mucosa for the detection of smell.

Pharynx

The nasal passages lead into the back of the throat to the pharynx. The *pharynx* is a common passageway for both the respiratory and digestive systems. The soft palate divides the pharynx into the *nasopharynx* (dorsal respiratory passageway) and *oropharynx.* The larynx and pharynx work together to keep food from entering the respiratory system.

Larynx

The *larynx* acts as the gatekeeper to the lower respiratory tract, preventing food and liquid from entering the lower respiratory tract. The larynx is composed of cartilage plates of varying sizes covered with a layer of pseudostratified columnar epithelium. At the forefront of the larynx is the epiglottis, a diamond-shaped laryngeal cartilage. One of the points of the diamond projects rostrally; the *epiglottis* is hinged at its caudal end with the remainder of the larynx.

This allows the epiglottis to move in the dorsal-ventral direction. The epiglottis acts as a flap covering the glottis (opening of the larynx) for swallowing food or liquid.

Caudal to the epiglottis is the *thyroid cartilage,* which is roughly U-shaped, with the open end on the dorsal side. Attached to the caudal side of the thyroid cartilage is the *cricoid cartilage,* which is ring-shaped. Lying inside the U-shaped thyroid cartilage are two *arytenoid cartilages.* A fold of tissue called the *vocal fold* passes between the thyroid and arytenoid cartilage on each side, and these folds are responsible for the animal's "voice." Unlike much of the rest of the respiratory system, the vocal folds are covered with stratified squamous epithelium. When air passes over the vocal folds as the animal exhales, the vibration of the vocal folds creates sound waves of a specific pitch and frequency. Various small muscles attach to these cartilages to control the opening and closing of the larnyx via the epiglottis. These muscles also maintain tension on the vocal folds, which determines the sound made by the animal.

Trachea

Caudal to the larynx and attached to the cricoid cartilage is the *trachea.* Lining the trachea is a layer of mucous covering the tall, pseudostratified columnar epithelium with cilia on the surface. Structurally, the trachea is a series of rings of cartilage called the *tracheal rings* that are connected by soft connective tissue to form a tube. The connective tissue between the rings is elastic, so the rings can move slightly back and forth, which is of some importance during the breathing process. The *tracheal rings* aren't complete but are more C-shaped. They open at the dorsal surface of the trachea (see Figure 10-5 on page 253 of your textbook). A layer of soft connective tissue and a thin muscle called the *trachealis* muscle cover the opening in the tracheal rings. As the tracheal muscle contracts, the ends of the tracheal rings are pulled closer together, decreasing the size of the tracheal lumen.

The trachea begins as a wide tube that passes down the neck and into the chest (or thoracic cavity), ending near the top of the heart. The trachea ends by dividing into two main bronchi at a point called the *tracheal bifurcation.*

Lower Respiratory Tract

The *lower respiratory tract* is comprised of the lungs that contain bronchi, bronchioles, respiratory bronchioles, alveoli, blood vessels, nerves, lymphatics, and the connective tissue that holds them all together (see Figure 10-6 on page 254 of your textbook). The lower respiratory tract contains a series of modified tubes of various sizes that gradually divide and narrow in diameter and finally end in dead-end sacs called *alveoli* (singular, *alveolus*) in the lungs. Most parts of the respiratory system are designed simply to transport air from outside the body to the lungs. During transport through the upper respiratory tract, the body filters the air to remove debris and infectious organisms. Air coming into the body is also moistened so that the alveoli don't dry out. The alveoli are the primary functional units of the respiratory system and are responsible for taking oxygen from the air and transferring it to the bloodstream. Alveoli also help the body eliminate wastes from the blood by transferring the wastes from the bloodstream to the air that's exhaled.

Bronchi and Bronchioles

The final part of the transport portion of the respiratory system is the *bronchial tree,* composed of the bronchi and bronchioles, which carry air from the tracheal bifurcation to the alveoli. As you travel down the bronchial tree, the diameter of the airway decreases, the thickness of the epithelial cell layer and wall decreases, the number of cartilaginous rings decreases, and the amount of smooth muscle in the airway wall increases.

Initially, the trachea separates into a right and left branch. These are the primary or *main-stem bronchi* (singular, bronchus). The primary bronchus then divides into *secondary bronchi* that turn in various directions to supply different lobes

of the lung. Once in the lung lobe, the secondary bronchus divides into *tertiary bronchi* that are directed toward different parts of the lung lobe. When the tertiary bronchi end, the *bronchioles* begin. Bronchioles divide many times into increasingly smaller bronchioles. Almost no cartilage exists in the bronchioles; the epithelium in bronchioles is ciliated, with simple columnar cells and a few goblet cells. The smallest bronchioles are *terminal bronchioles;* they're the last part of the air conduction portion of the respiratory system. Beyond this point the respiratory structures begin to perform the function of gas exchange.

Respiratory Bronchioles, Alveolar Ducts, Alveolar Sacs, and Alveoli

Respiratory bronchioles are thin tubules composed of cuboidal ciliated epithelial cells. Respiratory bronchioles carry out some gas exchange because there are scattered alveoli along the walls of the bronchiole. Smooth muscle cells are found in the wall of the respiratory bronchiole and around the opening to each alveolus and alveolar duct. The constriction and relaxation of these smooth muscle cells helps regulate the amount of air entering the alveoli.

Each respiratory bronchiole terminates in alveolar sacs (see Figure 10-7 on page 254 of your textbook). *Alveolar ducts* connect the alveolar sacs to little outpouchings known as *alveoli*. Alveoli open at one end and have three basic components in their walls: epithelial cells, connective tissue, and capillaries, which are tiny blood vessels. A thin layer of fluid is present on each alveolus. This fluid contains a substance called surfactant. *Surfactant* contains a *lipid* (i.e., fatty substance) that helps decrease the surface tension—the tendency of water molecules to attract and pull on each other—of the fluid lining alveoli and respiratory bronchioles. Reducing this fluid's surface tension allows the lungs to expand with less effort.

Lungs

In humans and all domestic animals, there are two lungs—left and right. Each lung is further subdivided into lobes, which are connected to each other near the tracheal bifurcation but which then separate into physically distinct, roughly wedge-shaped organs with separate airways and blood supplies. The number of lobes and their position in relation to each other vary with the species of animal. The left lung in domestic species is divided into two parts: a cranial lobe and a caudal lobe. In some species, the cranial lobe of the left lung is further divided into cranial and caudal parts.

In all common domestic species except the horse, the right lung is divided into four lobes: the cranial lobe, the middle lobe, the caudal lobe, and the accessory lobe, which sits on the median plane just caudal to the heart. Horses lack a middle lobe. Ruminants have a further subdivision of the right cranial lung lobe into cranial and caudal parts.

The surface of the lungs is covered with a thin layer of elastic connective tissue and a single layer of flattened epithelial cells called *mesothelial cells;* this lining, called the *pleura,* is continuous with a similar lining on the inside of the thoracic cavity's wall. Between the lungs and the thoracic wall is the *pleural space,* a cavity that normally contains only a very small amount of watery fluid that lubricates the lungs so they can slide over the thoracic wall. Normally, the lungs fill most of the thoracic cavity surrounding the heart (which sits medially) and lie against the inside of the ribs, which are lateral to the lung. The *mediastinum* is the area that contains the heart, trachea, esophagus, blood vessels, nerves, and lymphatic structures. A small notch between lung lobes is present on both sides of the chest, which allows the heart to contact the thoracic wall directly. Caudally, the lungs abut the *diaphragm,* the wall of muscle that separates the thoracic cavity from the abdomen. The diaphragm is very important in the process of respiration, as we'll see later.

Cranially, the thorax is open—forming a passageway known as the *thoracic inlet*—to allow the trachea, esophagus, blood vessels, and nerves to travel to and from the thorax and neck. The thoracic inlet is very small compared with the

diaphragm, so with all the structures passing through it, the thoracic inlet nearly seals off the thoracic cavity from the neck.

Birds, Reptiles, and Amphibians

Avian species contain many specialized structures to accommodate the higher energy level and rapid metabolism. The mouth and nasal chambers are linked by a structure called the choanae. The *choanae* are internal nares that open from the nasal chambers into the roof of the mouth. Unlike in mammals, the larynx isn't involved in production of sound in birds. The diaphragm is absent in birds. The trachea is structurally similar to mammals but is elongated in some species. An enlargement of the trachea above the sternum, the *syrinx,* serves as the sound-producing organ in birds. The two main-stem bronchi divide into structures called *mesobronchi,* which contain no cartilaginous rings. The mesobronchi divide into four to six secondary *ventrobronchi.* The ventrobronchi divide to become the *parabronchi* that connected to air capillaries, where gas exchange occurs. *Air sacs* comprise the majority of the volume of the avian respiratory system. These are small membranous sacs that act as a storage site for air, aid in thermoregulation and help provide buoyancy to water birds.

The structure and physiology of the respiratory systems of reptile and amphibian species is highly diverse. Reptiles are capable of surviving long periods of time without breathing. The glottis of most amphibians and reptiles is located behind the tongue. It's highly mobile in snakes to allow for breathing during ingestion of prey. Three distinct lung morphologies are found in reptiles (see Figure 20-13 on page 464 of your textbook), while the amphibians have simple saclike structures. Some species of salamander have no lungs and rely entirely on cutaneous respiration. Reptiles lack a diaphragm, although some species possess membranous structures that are analogous to the diaphragm of mammals.

Self-Check 12

Questions 1–6: Match the following terms with their definitions by placing the letter of the best definition in the blank space next to each term.

_____ 1. Turbinates	a. Smallest dead-end sacs in the lung; used for exchange of gases
_____ 2. Alveoli	b. Cavity dorsal to the soft palate
_____ 3. Nasopharynx	c. Fluid lining of the alveolus
_____ 4. Glottis	d. Opening of the larynx
_____ 5. Larynx	e. Composed of thyroid, cricoid, and arytenoid cartilages
_____ 6. Surfactant	f. Scroll-like sheets of tissue dividing each nasal cavity into several divisions

7. The diamond-shaped cartilaginous flap that covers the opening of the larynx when you swallow food or liquid is called the _____.

8. The _____ is located between the lungs and thorax.

Check your answers with those on page 191.

ASSIGNMENT 13: RESPIRATORY FUNCTION

Read in your textbook, *Clinical Anatomy and Physiology for Veterinary Technicians,* pages 258–263 and 447–448. Then read Assignment 13 in this study guide.

When you breathe, a series of mechanical events occur that forces air in and out of the lungs. Some of this process is active and requires expenditure of energy, whereas other parts are passive and require little or no energy. You learned

previously that much of the upper and lower respiratory tract is designed to transport air to the alveoli for gas exchange. So how is air forced in and out through these conducting tubes?

The respiratory system itself actually does little to actively draw air into the lungs, because the muscles within these structures are used mainly to increase or decrease the overall diameter of the pathways for air movement. This action increases or decreases the resistance to airflow but doesn't actually pump the air in or out. The structures responsible for air movement are actually outside the lungs and airways and consist of the ribs, the *intercostal muscles* (those between the ribs), the breastbone (the sternum), the pleural cavity, and the diaphragm.

Picture a hand bellows, which is used to blow air over a fire to fan the flames. The paddles on either side of the bellows are rigid. When pulled apart, air is drawn into the sac between them, and when the paddles are pushed together, air is forced out of the bellows. The faster the paddles are drawn apart or pushed together, the faster the air moves in or out, and the greater the force generated. The farther apart you pull the paddles, the more air enters the bellows. Principles of physics involving pressure and the behavior of gases dictate why air moves when the bellows open and close.

The thoracic cavity can be compared to a bellows. The ribs and sternum form the rigid part of the thoracic cavity, and the diaphragm and tissues of the thoracic inlet form the soft walls of the thorax. When an animal breathes in, the diaphragm contracts and moves caudally, increasing the length of the thoracic cavity; this is the largest component of breathing in air. External muscles along with some intercostal muscles help by pulling the ribs cranially and laterally, which moves the sternum farther from the spine, increasing the depth of the thoracic cavity in the dorsal-ventral direction.

The change in dimensions of the thoracic cavity increases the volume of the thorax. This increase generates *negative pressure.* In other words, the pressure in the thoracic cavity is less than the atmospheric air pressure. Negative pressure is transmitted from the thoracic wall to the lungs via the pleural space, which normally contains only a very small amount of fluid. Once negative pressure is generated in the

lungs, the pressure in the alveoli is less than that of the outside air. Gases tend to move from an area of higher pressure to one of lower pressure, so air enters the lungs via the conducting portions of the respiratory system until the pressure in the alveoli equals that of the outside air. This process of breathing in air is called *inspiration,* which is an active process.

Expiration is the opposite of inspiration; in other words, it's breathing air out of the lungs. Expiration is mostly a passive process. The muscles pulling on the ribs and diaphragm both relax, and the elastic nature of the intercostal muscles and diaphragm causes them to return to the resting position, which decreases the volume of the thoracic cavity. The elastic tissue within the alveolar walls, walls of the bronchi and bronchioles, and pleura surrounding the lung cause the lungs to snap back into the resting position. The collapse of the lungs and the decrease in the volume of the thoracic cavity both create positive pressure within the alveoli and airways (i.e., the pressure in the alveoli is greater than that of the atmosphere). Therefore, air moves out of the lungs and into the atmosphere.

The diameter of the bronchi, bronchioles, respiratory bronchioles, and alveolar ducts plays a significant role in inspiration and expiration. All of these structures have more flexibility in diameter because of the smooth-muscle tissue within their walls. Generally speaking, when the muscles in one area contract, the muscles in other areas do likewise, so the bronchial tree tends to act as a single unit when dilating or constricting the airways. Thus, the diameter of the smaller airways is more important than that of the larger airways in determining resistance within the respiratory system. The greater the resistance to airflow, the more energy must be expended to overcome that resistance so air can enter the alveoli.

Several factors influence the contraction and relaxation of these smooth muscles. Signals from the nervous system, inflammatory chemicals released into the blood during an allergic reaction, and certain hormones can all make the

airways dilate or constrict. In patients with asthma, an allergic disease with thickening of the walls of the airway and accumulation of secretions within the lumen of the airways, the diameter of the airways is markedly decreased, and the patient can't move air in or out very well. A class of drugs called *bronchodilators* is used to open the airways in patients with asthma or other diseases involving the respiratory system.

Any breakdown in these various processes can lead to *dyspnea* (i.e., breathing difficulty). Injuries or deformities of the ribs, spine, or sternum can alter the shape and volume of the thoracic cavity and make it difficult to fully expand the chest during inspiration. Diseases that increase the resistance to expansion can also cause dyspnea. Examples include *pleuritis,* inflammation of the pleura that can lead to scarring and stiffness of the pleura; respiratory distress syndrome; and *fibrosis,* scarring of the lung tissue.

Obstructions of the conducting portion of the respiratory system also cause respiratory problems. Tracheal collapse, laryngeal paralysis, cancer, and foreign bodies all can cause obstructions of the airways. Excessive fluid accumulation in the alveoli, which can occur with pneumonia or heart failure, causes obstruction of the alveoli, leading to dyspnea. Fluid or air can also accumulate in the pleural cavity, exerting pressure on the lungs from the outside so that the lungs can't expand fully. Weakness of the respiratory muscles can prevent the muscle contractions needed for chest expansion, which is a potentially fatal disorder. A diaphragmatic hernia can also cause lung collapse.

Chemical Process of Respiration

Now that we've reviewed the physical events that compose mechanical respiration, we'll examine the chemical events that lead to gas exchange in the alveoli. The purpose of *gas exchange* is to take oxygen into the body and eliminate carbon dioxide from the body. At its most basic level, gas exchange is the diffusion of a gas from an area of higher concentration to an area of lower concentration. Diffusion actually occurs in both directions, but the net movement is

from high concentration to low concentration. Diffusion of gases occurs whether the gases are dissolved in liquid, traveling through cellular materials, or actually in the gaseous state.

Under normal circumstances, oxygen moves from the air, dissolves in the alveolar wall, travels across the wall, and then crosses the wall of the capillary, where it dissolves into the blood and is taken into red blood cells for distribution to the body. Carbon dioxide travels in the opposite direction. When this occurs, each gas acts independently of the other gases in the mixture; in other words, oxygen diffuses from an area of high oxygen concentration to an area of lower oxygen concentration, regardless of the carbon dioxide concentration in either area. This means that both functions of gas exchange can occur at the same time in the same alveolus, so the body doesn't need separate organs for oxygen intake and carbon dioxide output.

Another important concept to grasp is that gas exchange is a passive process of diffusion, requiring no energy expenditure by the body. The only energy expended by the body is used in the physical process of respiration previously described. Several factors govern gas exchange, including the physical characteristics of the gases, rate and depth of respiration, and structure of the alveoli. We'll examine each of these factors in some detail, and we'll review how they relate to respiratory illness.

The amount of a gas in air or liquid is determined by the physical characteristics of that gas. The normal atmosphere at sea level contains approximately 79 percent nitrogen and approximately 20 percent oxygen, with very small amounts of carbon dioxide and water vapor. The air that you breathe in is humidified by the respiratory tract's secretions. The effect of increasing water vapor in the air is to dilute the concentration of the gases in that air proportionately. The amount of gas dissolved in a liquid depends on how easily the particular gas dissolves in the particular liquid. Carbon dioxide, for example, dissolves much more readily in water than does oxygen.

In tissues, the major determinant of gas concentration is how well that gas dissolves in the water within a particular tissue, so the factors mentioned for liquids hold true in tissues as well. The gases we're concerned about, oxygen and carbon dioxide, readily pass through cell membranes. Thus, cell membranes aren't a major impediment to gas exchange. The difference in the amounts of gas on each side of a membrane is called the *pressure difference*. The greater the differences between the amounts of gas on each side of a membrane, the larger the pressure difference. The larger the pressure difference, the more rapidly gas exchange occurs. The amount of oxygen in the air versus the amount of oxygen in the blood, for example, in part determines how quickly oxygen is taken into the body.

When you breathe in, you increase the amount of oxygen in the alveoli, and this increases the pressure difference because it increases the oxygen in the alveolar air relative to the amount of oxygen in the blood. Inspiration increases the concentration of oxygen in the alveoli, but not all of the oxygen brought into the alveolus diffuses across the alveolar wall. As the oxygen diffuses into the alveolar wall, the concentration of oxygen in the alveolar air decreases until it approaches the level of the dissolved alveolar oxygen. If the oxygen levels on both sides of a membrane are equal, there's no net diffusion. However, the next breath brings in more oxygen, increasing the concentration of oxygen in the alveolar air again.

The opposite is true for carbon dioxide—each breath decreases the carbon dioxide concentration in the alveolus. It actually takes several breaths in and out to replace all of the air in a given alveolus. Part of the reason for this is the fact that when you breathe out, you can't completely empty the lungs of all air (and you wouldn't want to do so!). Gas exchange occurs even at the point of maximum expiration, but to a lesser extent than at maximum inspiration. This constant minimum level of gas exchange prevents severe and sudden changes in the amount of oxygen or carbon dioxide in the blood, which could be fatal.

A corollary of this effect is that your rate of respiration affects the degree of diffusion, because the faster you breathe, the more quickly the air in the alveoli is replaced and the more rapidly oxygen intake and carbon dioxide output occur. This is why respiratory rate increases when you exercise or are under stress; your body needs more oxygen, so it replaces the dead air in the lungs more quickly by breathing faster. You also breathe more deeply when exercising, so that more air enters the alveoli, increasing oxygen intake and carbon dioxide output. Yawning is the body's way of increasing oxygen intake by increasing the depth of respiration.

Other than the characteristics of the gases and the effect of the depth and rate of breathing, the main factors affecting gas exchange are the alveoli's physical characteristics. The respiratory unit consists of a respiratory bronchiole and its associated alveolar ducts, alveolar sacs, and alveoli. All of the gas exchange within the lung occurs within the respiratory unit's alveoli. A sheet of interconnecting capillaries that lies immediately next to the alveolar wall surrounds each respiratory unit in the lungs and facilitates gas exchange.

The respiratory membrane is the total of all the layers through which gases must pass during gas exchange. Starting with the inner surface of the alveolus, the layers of the respiratory membrane include the following: a layer of alveolar fluid, which contains surfactant, lining the alveolus; the alveolar epithelium; the alveolar epithelial basement membrane; a very thin layer of interstitial tissue composed of connective tissue proteins and water; a capillary basement membrane; and the capillary endothelium. In some areas, the interstitial tissue is missing and the alveolar and capillary basement membranes fuse, decreasing the number of layers that must be crossed. Although several layers exist, the combined thickness of these layers is quite small, so the distance traveled by the gases is short.

Once across the capillary endothelium, the gas dissolves in the water in the blood, then crosses the cell membrane of the red blood cells. The alveolar capillaries are so narrow in diameter that the red blood cells often touch the capillary

endothelium as they pass through, which eliminates the distance a gas must cross from the capillary endothelium to enter the red blood cell.

Two characteristics of the respiratory membrane influence the amount and rate of gas exchange. First, there's the large surface area over which gas exchange can occur. There are literally millions of small alveoli packed into each lung, and each alveolus has its own wall for gas exchange. The second characteristic that influences the amount and rate of gas exchange is that the respiratory membrane is very thin, decreasing the distance across which gases must diffuse.

When fluid accumulates in the alveoli, as can occur with pneumonia or heart failure, the thickness of the fluid layer increases and the rate of gas exchange decreases; thus, patients with these conditions experience dyspnea. Sometimes damage to the lung causes scar tissue to be laid down in the interstitial tissue, again increasing the thickness of the respiratory membrane and causing dyspnea.

As you can see, the process of gas exchange requires both *ventilation*—the process of moving air in and out of the alveoli—and *perfusion*—the process of carrying blood to tissue. The *ventilation-to-perfusion ratio* describes the amount of ventilation relative to the perfusion of a given area of lung. Any derangement of either ventilation or perfusion, or both, leads to improper intake of oxygen or output of carbon dioxide, resulting in an abnormal ventilation-to-perfusion ratio. This situation is called *ventilation-perfusion mismatch.*

Ventilation can be decreased when the airway is occluded with fluid, as in pneumonia or heart failure, or with a mass, such as a tumor or an inhaled foreign object. No oxygen intake or carbon dioxide output occurs because ventilation is decreased; even though perfusion may be normal, the oxygen content of the blood traveling through that area is low and the carbon dioxide concentration is high relative to blood in other areas of the lung. The body can actually adjust the blood flow to areas where ventilation is lower so that more blood reaches areas with better ventilation, helping maintain a more normal ventilation-to-perfusion ratio.

Perfusion may decrease due to a blood clot in the vessels leading to that area of lung. Ventilation is unaffected, but the oxygen in the alveoli can't reach the blood. To a lesser extent, this occurs normally in your lungs when you're standing. The blood flow to the upper areas of lung is less than that in the lower lung, so an increased ventilation-to-perfusion ratio exists in the upper lung. When you exercise, the blood flow to the upper lung increases to help normalize the ventilation-to-perfusion ratio. The airways may constrict slightly to decrease ventilation to areas where the perfusion is poor, but this control mechanism isn't as powerful as the ability to alter blood flow.

The volume of air that passes through the respiratory system during inspiration and expiration varies, depending on the size of the animal and its physical condition and activity level. The tidal volume, minute volume, and residual volume are the standard measures of air quantity involved in respiration. *Tidal volume* refers to the total amount of air that passes through the respiratory system during one complete breath (inspiration and expiration). *Minute volume* is the total amount of air that passes through the respiratory system during one minute. *Residual volume* refers to the remaining air within the alveolus after expiration.

Control of Respiration

So how does the body control the process of respiration to match its needs to take in oxygen and get rid of carbon dioxide? Of course, humans have voluntary control over respiration—you can hold your breath for some period of time, you can breathe quickly or slowly, or you can take shallow or deep breaths. However, voluntary control of respiration requires some degree of thought, and you can't spend your entire life thinking about breathing. Therefore, the body has automatic, or involuntary, controls over respiration, and these are primarily located in the brain. Numerous factors influence these involuntary controls. Let's take a look.

The *respiratory center* is an area of nerve cells located in the brain's medulla oblongata and pons. (These areas are discussed in more detail in the part of your program covering

the nervous system.) Various parts of the respiratory center control inspiration, expiration, and the rate and depth of breathing. These nerve cells must coordinate the muscles that expand the chest, open the larynx, and end the inspiration to allow passive expiration to occur. Damage to this area of the brain can be fatal, as respiration might cease altogether, or cause abnormalities in the duration, depth, or rate of breathing.

Certain drugs, especially narcotics such as barbiturates and morphine, depress the activity of the respiratory center, which is why overdoses of these drugs can be fatal. The ideal anesthetic drug depresses the conscious centers of the brain without excessively depressing the respiratory center; however, nearly all anesthetics depress respiration to some extent. When you voluntarily control respirations, the conscious centers of your brain override the respiratory center signals.

Most of the respiratory center's regulation is chemical in origin. In particular, the level of carbon dioxide in the blood is crucial to control of respiration. Your body needs to get rid of carbon dioxide, which is a waste gas produced as a by-product of cellular respiration and metabolism. As the level of carbon dioxide in the blood increases, breathing becomes more frequent and deep, thus eliminating more carbon dioxide. Why does this occur? The respiratory center has sensors that detect the level of carbon dioxide in the blood vessels passing through it. This area of the respiratory center is called the *chemosensitive area.* Oxygen is needed for cellular respiration and energy production, but oddly enough, it has less of a direct effect on respiratory control.

Special sensors called *chemoreceptors* are present in the carotid arteries and aorta; both of these major blood vessels carry blood from the heart to the head or to the rest of the body. These chemoreceptors are known as the *carotid bodies* and *aortic bodies,* respectively. The chemoreceptors sense the level of oxygen in the arterial blood passing by these areas. If the oxygen falls below certain levels, the chemoreceptors send signals via nerves to the respiratory center to stimulate

breathing. This occurs only if the blood oxygen level is severely reduced, so normally these chemoreceptors play a minor role in controlling respiration.

The reason oxygen is less important in controlling respiration is that the normal level of oxygen in the blood is maintained at a level much higher than absolutely necessary for normal function, so a small drop in the oxygen level isn't critical. On the other hand, changes in the carbon dioxide level can be lethal if excessive, in part because excessive carbon dioxide causes an increase in the blood's acid level.

Panting is unique to animals that are unable to lower heat by sweating. Dogs and cats lack the sweat glands possessed by people and some other animals and have no other mechanism to lose heat. An area of the brain called the *hypothalamus* senses increased blood temperature and then signals an area of the respiratory center called the *panting center.* The effect is to increase the rate of respiration, which increases the replacement of alveolar air with new, cooler air. Panting also increases the rate of evaporation from the oral cavity and nose, which helps the cooling process as well. Animals may also pant when nervous, possibly due to increased body temperature caused by the stressed condition. Panting differs somewhat from respirations with respiratory illness. Most animals with dyspnea have increased respiratory effort; panting animals, on the other hand, take rapid breaths with a minimum of effort.

Intake of oxygen to carry out cellular respiration for energy production is crucial to an animal's survival, as is the elimination of waste products—primarily carbon dioxide—of cellular respiration. If the body is deprived of oxygen, energy production to carry out cell functions declines, and the cells begin to die. Accumulation of waste products can be fatal because such a situation leads to alterations in the internal environment. The respiratory system is designed to carry out both processes with a minimum of energy expenditure by the animal. We've also seen how the physical and chemical processes of respiration occur and how these functions can be altered by certain disease conditions.

The vital importance of the respiratory system is demonstrated by the fact that the first step in cardiopulmonary resuscitation is to be sure the airway is open and functional. Emergency medical technicians usually immediately place an endotracheal tube to provide oxygen to an unconscious patient. Without the intake of oxygen and the elimination of carbon dioxide, the body dies, even if the heart is still pumping (although the heart muscles can't function for long without oxygen, so respiratory problems often lead to cardiac arrest as well).

Birds, Reptiles, and Amphibians

Avian respiration requires two inhalations and two expirations to transport one pocket of air through the entire respiratory system. The first inspiration is initiated by expansion of the thoracoabdominal space. This creates a pressure gradient that draws air into the posterior air sacs. The air is warmed and humidified within the air sacs and is then pushed into the lungs during the first expiration. The second inspiration moves the air from the lungs to the anterior air sacs, and the second expiration results in the air leaving the body through the trachea. The respiratory rate of birds varies with species, activity level, age, sex, time of day, and outdoor temperature.

Reptiles generally rely on the movements of muscle groups to inflate the lungs, while amphibians use pumping actions of the buccal cavity and pharynx to perform this task.

Now, review the material you've learned in this study guide as well as the assigned pages in your textbook for Assignments 9–13. Once you feel you understand the material, complete *Self-Check 13*. Then check your answers with those provided at the end of this study guide. If you've missed any answers, or you feel unsure of the material, review the assigned pages in your textbook and this study guide. When you're sure that you completely understand the information presented in Assignments 9–13, complete your examination for Lesson 3.

Self-Check 13

Questions 1–5: Match the following terms with their definitions by placing the letter of the best definition in the blank space next to each term.

_____ 1. Ventilation

_____ 2. Bronchodilator

_____ 3. Chemoreceptor

_____ 4. Perfusion

_____ 5. Tidal volume

a. Total amount of air passing through the respiratory system

b. Process of moving air in and out of the alveoli during one complete breath

c. Sensor that detects changes in the oxygen level of arterial blood

d. Drug that opens the airways to permit easier respirations

e. Process of carrying blood to tissue

6. The respiratory center is located in the brain's pons and _____.

7. The area of the brain that senses increased blood temperature is the _____.

Check your answers with those on page 191.