UNIT H. RESPIRATORY SYSTEM

Oxygen is critical for our survival. As **aerobic** organisms, we require it for the efficient synthesis of ATP during **cellular respiration**. This complex metabolic pathway is actually the last part of a four-part sequence of processes related to the body's treatment and use of oxygen. The first one is **breathing**, the combination of **inhalation** (inspiration) and **exhalation** (expiration). Inhaling draws air, which is about 21% oxygen, into the **lungs**. Gases are exchanged between the blood and the lungs; oxygen goes into the blood and carbon dioxide comes out. This exchange is called **external respiration**. The circulatory system transports the oxygen from the lungs to tissue capillary beds where **internal respiration** occurs; once more oxygen and carbon dioxide are involved in an exchange process. The oxygen enters the extracellular fluids, diffuses into body cells and is immediately available for mitochondria to use for cellular respiration. Carbon dioxide, a toxic waste product, must be carefully managed and excreted.

In this consideration of the respiratory system, the structures responsible for breathing will be examined. The mechanics of breathing, external respiration, internal respiration, and the safe and efficient transport of gases in blood will also be considered. Cellular respiration is beyond the scope of this unit.

RESPIRATORY STRUCTURES

Breathing is something the body does continuously, without thinking about it. Air flows through a sequence of structures from the nose to the lungs allowing for the exchange of "oxygen-poor" air for "oxygen-rich" air. The **nostrils** are one of the major entryways into the body. They are lined with a **mucosal** cell layer, which secretes mucus. They are also equipped with **nose hairs**. Combined, these specializations trap and filter particulate matter. The debris that is removed from the inhaled air in this manner is discharged through the nose. A rich blood supply in the sinuses allows the presence of large numbers of white blood cells, which offer another layer of protection.

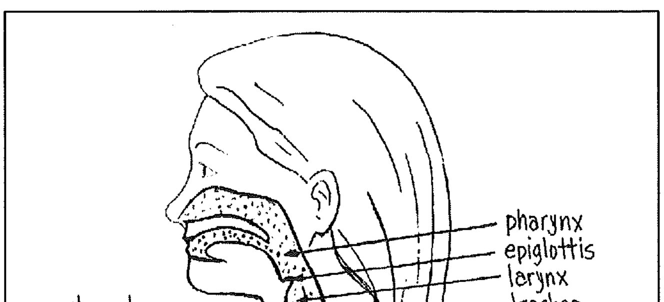


Figure H-1. Respiratory System

The **pharynx** is the common passageway at the back of the mouth for air and food. At the base of the pharynx are to the openings to the **trachea** (glottis) and the **esophagus** (gullet). During swallowing, the **epiglottis** covers the top of the trachea leaving the esophagus available for the entry of food materials. Other times, when the epiglottis is open, air is able to pass into the trachea. The top part of the trachea is specialized into the **larynx**. This "voice box" contains the **vocal cords**, which are two tendons that vibrate to produce sounds as air passes over them in an outward direction. The pitch of the sounds produced is a factor of how taut they are. Vocalization, putting these sounds into words, is a function of the mouth and tongue.

The trachea connects the pharynx to smaller air passageways leading to the lungs. It is held open and protected by the presence of C-shaped rings of **cartilage**. The open part of the "C" is at the back of the trachea, against the esophagus to facilitate swallowing. The trachea branches to form the **bronchi**, which branch repeatedly into ever smaller passageways for air. Like the trachea, the larger air passageways have cartilaginous walls. The smallest branches, called **bronchioles** lack cartilage and depend on elastic fibres to retain their shape.

The continual branching of the the air passageways forms the **bronchiole tree**. The bronchioles end at **alveoli**, which are the sac-like bulges. The mass of a single lung is made up of millions of alveoli and their associated bronchioles. As a unit, they provide a great deal of surface area for the diffusion of gases (external respiration). In addition, alveoli are specialized in a number of ways:

1. The walls of the alveoli are only one cell thick, which aids the diffusion of gases.
2. They have a coating of **lipoproteins** on their inner surface, which helps maintain **surface tension**, preventing their inner walls from sticking together during exhalation.
3. They are equipped with **stretch receptors**, nerve endings that are sensitive to stretch. The alveoli expand during inhalation. The stretch receptors send **impulses** to the **medulla oblongata** of the brain when the alveoli are full enough (stretched). This triggers exhalation.
4. The alveolar surfaces are highly **vascularized** by **pulmonary capillaries** maximizing the exchange of gases.
5. They are kept moist, primarily by water from the circulatory system, which helps maintain their flexibility and allows the gases to diffuse more easily.

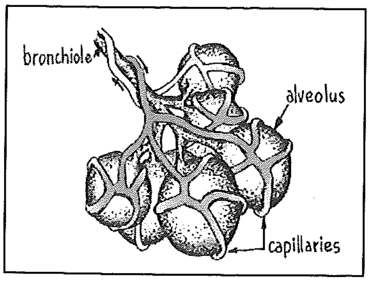


Figure H-2. Alveolar Structure

H-1. CONCEPT CHECK-UP QUESTIONS:

1. Identify and describe each of the four parts of respiration.
2. How are the nasal passageways specialized?
3. a. How are the air passageways protected against collapsing?
   b. Why would it be illogical for the cartilaginous rings of the trachea to be O-shaped?
4. Describe the purposes of the nervous system and circulatory system association with the lungs.

H-1. DISCUSSION QUESTIONS:

1. a. What is the disadvantage of breathing through the mouth?
   b. When is it necessary to breath through one's mouth?
2. Explain how this sentence could help you recall the specializations of alveoli: "Thin wet capillaries stretch over numerous surfaces."

MECHANICS OF BREATHING

The **respiratory centre** is located in the medulla oblongata of the brain stem. It is sensitive to the concentrations of carbon dioxide and hydrogen ions in blood plasma. Both of these are toxins that result from cell metabolism and both need to be excreted. When their concentrations get to a critical level, the medulla oblongata sends nerve impulses to cause the contraction of the **diaphragm** and the **intercostal muscles** (muscles between the ribs). The diaphragm, bowed up when relaxed, moves down when it contracts. When the intercostal muscles contract, they pivot the rib cage upwards and outwards from its attachment to the vertebral column. The combined effect of these motions increases the volume of the **thoracic cavity**. This creates a negative pressure in the cavity (vacuum effect) and air is drawn in through the trachea. This is inhalation, an active process requiring ATP for the contraction of the muscles.

The surfaces of the lungs are covered with a **pleural membrane**. A second (outer) pleural membrane coats the inside of the thoracic cavity. During inhalation, when the rib cage moves (up and out), the outer pleural membrane moves with it. Its moist surface is naturally cohesive to the inner pleural membrane thus the inner membrane also moves with the thoracic cavity walls facilitating the expansion of the lungs. The space between the pleural membranes is called the **interpleural space**. It normally has negligible volume because of the cohesiveness of the membranes. These membranes allow the surface of the lungs to slide smoothly and easily over the inner walls of the thoracic cavity during breathing. In addition, they also seal off the thoracic cavity so the only entry point for air is through the trachea. A puncture to the chest wall, piercing the outer pleural membrane (even without damaging a lung) will result in air being drawn in through the puncture wound during inhalation. This allows the interpleural space to fill with air and puts pressure on the surface of the lung (instead of inside it) causing the lung to collapse. This is called **pneumothorax**.

When the stretch receptors on the surface of the alveoli detect that the alveoli are stretched open, they respond by signaling the medulla to stop the contraction of the diaphragm and intercostal muscles. When the diaphragm relaxes, it bows back upwards. When the rib muscles relax, gravity pulls the rib cage down and in. These actions put pressure on the expanded thoracic cavity, which causes exhalation, the outward movement of air. Exhalation is a passive process.

The **aortic arch** and **carotid arteries** contain nerve receptors called **chemoreceptors** that are sensitive to the oxygen content in blood. If it is critically low, they will help initiate the inhalation response. This is a secondary mechanism. The primary mechanism that triggers inhalation is an elevated concentration of CO_2 and H^{1+} in plasma.

CONDITIONING OF INHALED AIR

As air is drawn through the air passageways into the alveoli it is prepared in three ways. First of all, it is cleaned. The initial cleaning is by the nose hairs and mucus in the **nasal** passageways. The second part of the process occurs further along where debris can no longer get out through the nose. This is a role of the mucosal lining and the **cilia** along the trachea and the bronchi. Pretty well any material other than the gases of the inhaled air will get caught in the mucus. The cilia (microscopic protein filaments) are in constant motion elevating debris-laden mucus up to the pharynx to where it can be swallowed or coughed up and expectorated (spat out).

The more contact air has with moist tissues that are 37°C, the closer the temperature of the inhaled air gets to 37°C. By the time the air arrives at the alveoli there is no appreciable difference between its temperature and that of the surrounding tissues. Finally, inhaled air becomes saturated with water as it passes over the mucous-lined passageways.

H-2. CONCEPT CHECK-UP QUESTIONS:

1. Where is the respiratory centre and what does it do?
2. a. Describe the coordinated contraction of the diaphragm and rib muscles.
   b. How does their combined contraction cause air to be drawn into the lungs?
3. What are the roles of the pleural membranes?
4. When is energy used in breathing and when is it not used?
5. What are the three ways that inhaled air is conditioned before it gets to the alveoli?

H-2. DISCUSSION QUESTIONS:

1. Design a flow chart to illustrate inhalation and exhalation.
2. Describe the inter-relationship between the respiratory system and the:
   a. circulatory system
   b. nervous system
   c. musculoskeletal system
   d. excretory system
3. a. When does oxygen actually enter the body?
   b. When does carbon dioxide actually leave the body?

GAS EXCHANGE

During respiration, molecules of CO_2 and O_2 diffuse between tissues in two places due to differences in their respective concentrations (gas pressure gradients). The first is between the air and blood plasma at the alveoli. This is external respiration. The other, internal respiration, occurs between blood plasma and **extracellular fluid**.

External respiration is the diffusion of oxygen into the pulmonary capillaries and the diffusion of carbon dioxide (and the movement of some water) into the alveoli to be exhaled. The blood at the alveoli is 37°C and has a pH of about 7.38. Under these conditions **hemoglobin** molecules combine with oxygen. (Recall that hemoglobin molecules are transport proteins in the membranes of red blood cells.) Each hemoglobin molecule has four bonding sites. When the blood is leaving the alveoli, normally over 95% of these bonding sites are occupied. The combination of hemoglobin and oxygen is called **oxyhemoglobin** (abbreviated HbO_2). It is in this manner that oxygen is transported to the tissues where internal respiration takes place.

At the tissues, the blood is slightly warmer (about 38°C) and has a slightly lowered pH of about 7.35 due to the effects of cell metabolism. Hemoglobin is very sensitive to these changes and, as it enters systemic capillary beds, it readily releases oxygen [$HbO_2 \rightarrow Hb + O_2$]. The oxygen becomes dissolved in plasma and diffuses into the extracellular fluid along with the water that is forced from plasma (recall capillary-tissue fluid exchange). Once again, hemoglobin is available as a transport molecule.

At the venule side of the capillary bed, when water is drawn back into the blood by osmotic pressure, CO_2 and other **metabolic wastes** from cellular respiration also enter the blood. At these temperature and pH conditions most of the CO_2 reacts with H_2O in the plasma under the influence of the enzyme **carbonic anhydrase**, another protein in the cell membrane of red blood cells. This reaction temporarily forms carbonic acid, which readily dissociates.

$$CO_2 + H_2O \rightarrow [H_2CO_3] \rightarrow HCO_3^{1-} + H^{1+}$$

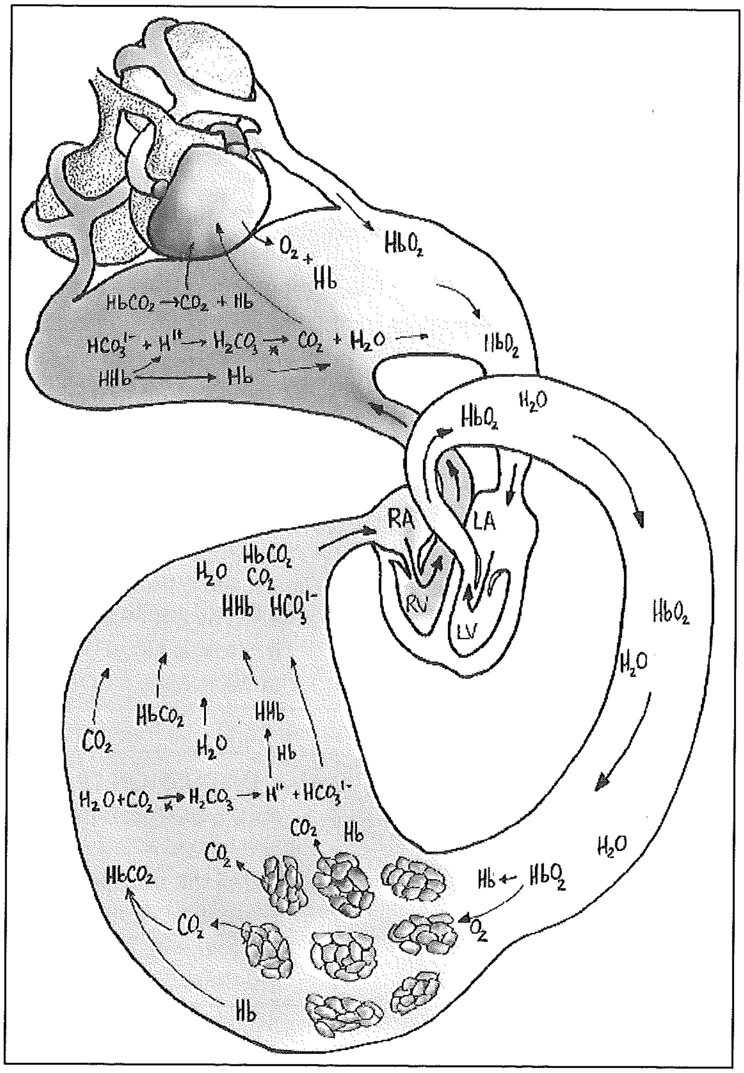


Figure H-3. External and Internal Respiration

The products, **bicarbonate ions** and hydrogen ions, have different fates. Bicarbonate ions are well known buffers in the human body. They are transported freely in blood plasma, buffering it against pH changes. In contrast, hydrogen ions, which would force a decrease in the pH if left alone, are transported safely by bonding onto available hemoglobin and forming **reduced hemoglobin** (HHb) [H^{1+} + Hb → HHb]. As was noted, most of the CO_2 that moves back into blood reacts with carbonic anhydrase. The rest is transported in either of two ways. Some bonds onto Hb and is transported as **carbaminohemoglobin** (abbreviated $HbCO_2$) [CO_2 + Hb → $HbCO_2$]. Finally, a little is transported as a dissolved gas in the plasma. This completes the process known as internal respiration.

From the systemic capillaries, the blood enters the venules, returns to the right side of the heart and is pumped into the pulmonary circuit. The blood arriving in the alveolar capillaries has some specific characteristics. It is transporting bicarbonate ions and a little carbon dioxide gas. The hemoglobin is transporting either CO_2 ($HbCO_2$) or hydrogen (HHb).

At the alveoli the temperature of blood is slightly lower and its pH is slightly higher than in the tissue spaces. These conditions result in the release of the CO_2 and hydrogen from hemoglobin.

$$HbCO_2 \rightarrow Hb + CO_2$$
$$HbH^{1+} \rightarrow Hb + H^{1+}$$

The hydrogen ions are promoted to react with bicarbonate ions by carbonic anhydrase, essentially reversing of the reaction that took place in systemic capillary beds.

$$HCO_3^{1-} + H^{1+} \rightarrow [H_2CO_3] \rightarrow CO_2 + H_2O$$

To conclude this look at external respiration, one must consider the CO_2 concentration in plasma at the arteriole side of the pulmonary capillaries. A small amount has been transported by the plasma, but its concentration is suddenly greatly increased because hemoglobin releases it and it is a product of the carbonic anhydrase reaction. As a result, CO_2 readily diffuses into the alveoli to get exhaled. Some of the water that is produced is exhaled as vapour. The rest remains as a component of plasma. The hemoglobin is once again free to bond to oxygen and the cycle repeats itself.

H-3. CONCEPT CHECK-UP QUESTIONS:

1. Describe the reaction catalyzed by carbonic anhydrase and explain how environmental conditions affect it.
2. List the different substances that hemoglobin transports.
3. a. Why is it important that HHb forms in venous blood?
   b. How is blood buffered against pH fluctuations?
4. In what ways is CO_2 transported in blood. In which form is most transported? Least?

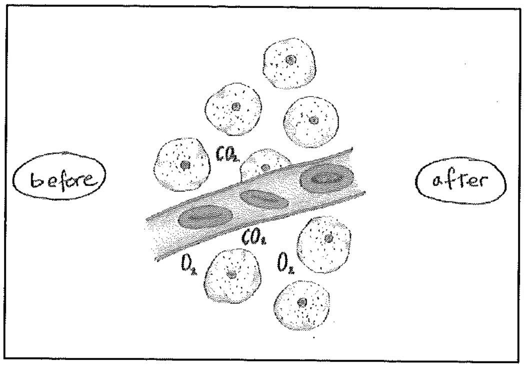
H-3. DISCUSSION QUESTIONS:

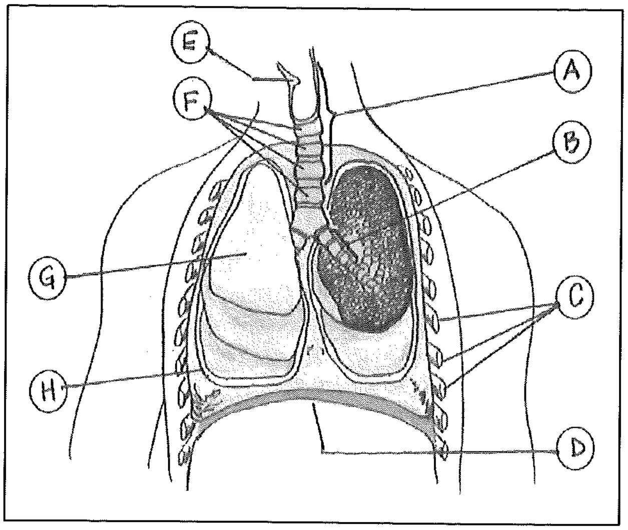
1. Relate the locations of hemoglobin and carbonic anhydrase to the Fluid Mosaic Model.
2. Detail the transport sensitivities of hemoglobin.
3. (Research) People who suffer from COPD often have low oxygen saturation of hemoglobin. What can cause low O_2 saturation and what is the medical solution to aid these people?

UNIT H REVIEW QUESTIONS

CHECK YOUR KNOWLEDGE OF DIAGRAMS:

1. The diagram below depicts a particular stage in the process of internal respiration. Relate the events that happen just before and just after the stage illustrated.





2. Name the structures indicated by letters A to H in the diagram to the right and describe ONE function of each.

CHECK YOUR UNDERSTANDING OF CONCEPTS:

1. The exchange of carbon dioxide and oxygen between the air and the blood is called
   A. breathing.
   B. cellular respiration.
   C. internal respiration.
   D. external respiration.

2. Which is correct about internal respiration?
   A. Decreases CO_2 levels in plasma
   B. Occurs at systemic tissue capillaries
   C. Requires ATP and muscle contraction
   D. Fluctuates due to inhaling and exhaling

3. The region of the respiratory and digestive tracts where both food and air pass is the
   A. larynx.
   B. trachea.
   C. pharynx.
   D. nasal sinus.

4. Which is correct about the trachea?
   A. Conducts peristalsis
   B. Extends from the pharynx to the bronchi
   C. Remains collapsed except when conducting air
   D. Has an epiglottis to prevent airborne particles from entering

5. What does the medulla oblongata detect that results in inhalation?
   A. Deflated alveoli
   B. Inactivity of the air passageways
   C. Vacant bonding sites on hemoglobin
   D. High CO_2 and H^{1+} concentration in plasma

6. The process of inspiration is accomplished by
   A. relaxation of the diaphragm.
   B. relaxation of the intercostal muscles.
   C. reduced air pressure in the thoracic cavity.
   D. increased air pressure in the thoracic cavity.

7. Which occurs at a different time than the others?
   A. Closure of the epiglottis
   B. Contraction of the diaphragm
   C. Contraction of the rib muscles
   D. Increased volume of the thoracic cavity

9. What is one role of the lipoproteins on the interior of alveoli?
   A. Promote gas exchange
   B. Control expansion and contraction of alveoli
   C. Create polar surfaces so tissues remain moist
   D. Prevent alveolar surfaces from sticking together

8. Which two events occur at the same time as the diaphragm pushes on the liver?
   A. Air moves up the trachea and the intercostal muscles lower the rib cage
   B. Air moves down the trachea and the intercostal muscles lower the rib cage
   C. Air moves up the trachea and the intercostal muscles move the rib cage up and out
   D. Air moves down the trachea and the intercostal muscles move the rib cage up and out

10. When blood leaves a pulmonary capillary, it is oxygen-
    A. rich and goes to the left atrium.
    B. poor and goes to the left atrium.
    C. rich and goes to the right atrium.
    D. poor and goes to the right atrium.

11. Stimulation of the nerve endings on alveolar surfaces results in
    A. shallow breathing.
    B. adjustments to the gas content in blood.
    C. contraction of the diaphragm and rib muscles.
    D. a reduction of the volume of the thoracic cavity.

12. Oxygen enters blood at the alveoli by
    A. osmosis.
    B. diffusion.
    C. active transport.
    D. facilitated transport.

13. The pleural membranes are an advantage because they
    A. are ciliated to promote fluid movement.
    B. are selectively permeable to filter out debris.
    C. prevent gas exchange outside of the thoracic cavity.
    D. provide smooth surfaces for tissues to slide over each other.

14. Which structure does NOT contain nerve receptors sensitive to gas concentrations in plasma?
    A. Alveoli
    B. Aortic arch
    C. Carotid artery
    D. Medulla oblongata

15. What happens to air as it moves towards the alveoli?
    A. The concentration of O_2 in it is monitored
    B. Particulate matter in it is removed by mucus
    C. The relative proportion of CO_2 in it is decreased
    D. Moisture is removed from it and added to the blood

16. Which BEST describes the roles of cilia and mucus in the air passageways?
    A. Mucus filters debris and cilia move it anteriorly
    B. Mucus adds moisture to the air and cilia filter debris from it
    C. Mucus traps debris and adds moisture and cilia move mucus anteriorly
    D. Cilia filter debris and mucus contributes to the flexibility of the membranes

17. Which is true of blood when oxygen binds with hemoglobin compared to when oxygen is released?
    A. It is cooler and less acidic
    B. It is warmer and less acidic
    C. It is cooler and more acidic
    D. It is warmer and more acidic

18. What changes occur to blood to cause HHb to release H^{1+}?
    A. pH increases, temperature increases
    B. pH decreases, temperature increases
    C. pH increases, temperature decreases
    D. pH decreases, temperature decreases

19. Where does HHb get converted to HbO_2?
    A. Liver cells
    B. Lung capillaries
    C. Heart ventricles
    D. Tissue capillaries

20. The pH of blood remains relatively constant during internal respiration because the released H^{1+}
    A. bonds to hemoglobin.
    B. joins with OH^{1-} to form water.
    C. reacts with carbonic anhydrase.
    D. are absorbed by white blood cells.

21. HbO_2 releases O_2 in the same region as
    A. HCO_3^{1-} is produced.
    B. NH_3 is converted to urea.
    C. CO_2 is removed from plasma.
    D. Blood pressure drops below 10mmHg.

22. What happens to oxygen that is released from hemoglobin?
    A. Forced out of blood
    B. Metabolized with sugar in blood to produce ATP
    C. Bonds to red blood cells for transport to a capillary bed
    D. Reacts with carbonic anhydrase to form bicarbonate ions

23. Which is TRUE of hemoglobin?
    A. Loses oxygen in both the systemic and pulmonary capillary beds
    B. Gains oxygen in both the pulmonary and systemic capillary beds
    C. Gains oxygen in the systemic capillaries and loses it in the pulmonary capillary beds
    D. Loses oxygen in the systemic capillaries and gains it in the pulmonary capillary beds

24. Which transports blood with the highest concentration of HHb?
    A. Pulmonary veins
    B. Coronary arteries
    C. Hepatic portal vein
    D. Pulmonary arteries

25. Which is produced in a different region than the others?
    A. HHb
    B. HbO_2
    C. HCO_3^{1-}
    D. $HbCO_2$

26. Carbonic anhydrase is different from hemoglobin because it is
    A. active with CO_2 and H_2O
    B. active in deoxygenated blood.
    C. affected by temperature and pH changes.
    D. located in the membranes of red blood cells.

27. After blood leaves regions where CO_2 diffuses into it, it becomes
    A. cooler and more acidic.
    B. warmer and more acidic.
    C. cooler and more alkaline.
    D. warmer and more alkaline.

BUILD YOUR UNDERSTANDING:

1. Describe the functions of mucus in the respiratory system:
2. Compare and contrast external and internal respiration.
3. How are alveoli specialized for their function?
4. a. Identify TWO differences in conditions between the blood in systemic capillaries and pulmonary capillaries.
   b. How do these differences affect the function of hemoglobin?
   c. How do these differences affect the function of carbonic anhydrase?
5. Contrast the triggers for inhalation vs. exhalation.
6. In your own words, describe the mechanics of the breathing process. Include the functions of at least five structures.