CHAPTER 22

Respiration: The Exchange of Gases

Objectives

Introduction Explain how geese can fly at altitudes as high or higher than Mt. Everest. Explain how humans adjust to life at high altitudes.

Mechanisms of Gas Exchange

22.1 Describe the three main phases of gas exchange.
22.2 Describe the properties of respiratory surfaces. Describe four types of respiratory surfaces and the types of animals that use them.
22.3 Explain how the amount of oxygen available in air compares to that available in cold and warm fresh water and salty water.
22.3 Explain how the structure of fish gills maximizes oxygen exchange.
22.4 Explain how a countercurrent exchange mechanism in fish gills maximizes oxygen transfer.
22.5 Explain how breathing air is easier than using water for gas exchange.
22.5 Describe the tracheal system of insects.
22.6 Describe the structures and corresponding functions of a mammalian respiratory system.
22.7 Describe the impact of smoking on human health.
22.8 Compare how humans and birds ventilate their lungs.
22.9 Explain how breathing is controlled in humans.

Transport of Gases in the Body

22.10 Explain how blood transports gases between the lungs and tissues of the body.
22.11 Describe the functions of hemoglobin.
22.12 Explain how a human fetus obtains oxygen prior to and immediately after birth.

Key Terms

gas exchange	tracheole	emphysema
respiration	diaphragm	breathing
respiratory surface	pharynx	negative pressure breathing
gill	larynx	vital capacity
trachea	vocal cord	breathing control center
lung	bronchus	hyperventilating
ventilation	bronchiole	partial pressure
countercurrent exchange	alveolus	hemoglobin

Word Roots

alveol- = a cavity (*alveoli:* one of the dead-end, multilobed air sacs that constitute the gas exchange surface of the lungs)

counter- = opposite (*countercurrent exchange:* the opposite flow of adjacent fluids that maximizes transfer rates)

Lecture Outline

Introduction *Surviving in Thin Air*

A. *Review:* Cellular respiration: Animals need to obtain oxygen and glucose and rid themselves of waste carbon dioxide (Chapter 6; Figures 6.1, 6.2A, and 6.8).

B. Life at high altitude imposes many changes on the organs and tissues that function in respiration.

1. People born in and adapted to high altitudes have relatively large hearts, more red blood cells, and elevated hemoglobin concentrations.
2. A short period of conditioning will help those living in lower altitudes acclimate to higher altitudes. Faster heart rate and larger capillary diameter are replaced over time with deeper and more rapid rates of breathing, more capillaries, and higher numbers of red blood cells and levels of hemoglobin.
3. Many animals are capable of exchanging gases from environments humans would find inhospitable. Some birds can stand the cold and low oxygen concentrations of altitudes of 20,000–30,000 feet. They have more efficient lungs, hemoglobin with a very high affinity for oxygen, a larger number of capillaries, and muscle proteins that hold oxygen.

I. Mechanisms of Gas Exchange

Module 22.1 Overview: Gas exchange involves breathing, the transport of gases, and the servicing of tissue cells.

A. Breathing involves inhaling O_2 and exhaling CO_2 (Figure 22.1).

B. The transport of gases involves diffusion into and transport by hemoglobin in the red blood cells of the circulatory system.

C. Blood supplies every cell with O_2 and picks up waste CO_2.

Module 22.2 Animals exchange O_2 and CO_2 through moist body surfaces.

A. **Respiratory surfaces** vary among animal groups. However, what all respiratory surfaces have in common is that they must be moist, thin, and extensive. Gases must be dissolved in water before they can diffuse in or out. In each part of Figure 22.2A–D, the circle represents a cross section of the animal's body in the region of the respiratory surface, and the green color represents the respiratory surfaces.

B. Earthworms (Module 18.11) and other "skin-breathers" must live in moist environments to keep their skins moist. Small size or flatness provides the high ratio of respiratory surface to body volume required for efficient gas exchange between environment and cells (Figure 22.2A).

C. **Gills** have evolved in most aquatic animals to increase the respiratory surface. They generally project from the body surface (Figure 22.2B).

D. **Tracheae** are specialized breathing tubes found in insects (Module 18.13). These branched tubes bring external gases directly to the inner cells without the aid of the circulatory system (Figure 22.2C).

E. **Lungs** are found in the majority of terrestrial vertebrates (Figure 22.2D). They are composed of branched tubes ending in tiny internal sacs lined with a moist epithelium. Gases are carried between the lungs and body cells by the circulatory system.

Module 22.3 Gills are adapted for gas exchange in aquatic environments.

A. The chief advantage of exchanging gases with water is that energy does not have to be expended to keep the transfer surface wet.

B. However, the concentration of O_2 is only 3–5% of its concentration in air, and the warmer and saltier the water, the less O_2 it can carry. Consequently, gills must be very efficient to extract O_2 from water.

C. Energy is expended as a fish covers its gill surfaces with water by "inhaling" water with its opercula closed and mouth opened, and "exhaling" the water across the gills with its mouth closed and opercula opened. The process of increasing contact of the surface area with oxygen is called **ventilation** regardless if it's a fish, bird, or any other animal.

D. Oxygen-poor blood enters each gill filament and crosses the lamellae (red blood cells travel single file here), picking up O_2 and leaving CO_2 (Figure 22.3).

Module 22.4 Countercurrent flow in the gills enhances O_2 transfer.

A. **Countercurrent exchange** is a general principle of transfer found in many animal systems. *NOTE:* For example, a countercurrent system is used in thermoregulation (Module 25.2) and to enhance water reabsorption in the kidneys (Module 25.11).

B. Countercurrent exchange is the transfer of a substance from a fluid flowing in one direction to another fluid moving in the opposite direction.

C. Opposite flows maintain a diffusion gradient that enhances the transfer of the substance, O_2 in the case shown (Figure 22.4).
NOTE: To impress students with the efficiency that results from this arrangement, diagram a transfer system in which both fluids flow in the same direction.

D. This mechanism is so efficient in fish that their gills remove more than 80% of the oxygen dissolved in the water flowing through them.

Module 22.5 The tracheal system of insects provides direct exchange between the air and body cells.

A. Air contains much more O_2 than an equal volume of water, and air is easier to move than water. Thus, terrestrial animals expend less energy in ventilating their respiratory surfaces.

B. Tracheae in an insect branch throughout the body, conveying air directly to body cells (Figure 22.5A, B, and C).

C. Included in the system are tracheal air sacs that work like bellows when muscles around them alternately contract and relax, moving air out and in.

D. Water is conserved, and respiratory surfaces remain moist because only the ultimate narrowest tubes, the **tracheoles,** contain fluid. It is across the tracheoles that gas exchange occurs.

Module 22.6 Terrestrial vertebrates have lungs.

A. Since lungs are restricted to one part of the body, unlike tracheae, the circulatory system must be involved in transporting the gases to and from body cells.

B. Amphibians supplement their lungs with skin breathing, but all other terrestrial vertebrates (and aquatic reptiles and mammals) have efficient lungs only.

C. The human respiratory system includes: the nasal cavity (filters, warms, humidifies, and samples odors of incoming air), the **pharynx** (controls the passage of air through the mouth region and into the **larynx** [Module 21.6]), and a branched system of tubes (**trachea** and **bronchi**) that lead into the lungs. (Figure 22.6A).

D. Exhaling through the **vocal cords** of the larynx produces sounds.
NOTE: This branched system is another example of the hierarchical organization of life (Module 1.1).

E. Lungs include the ultimate branches of the **bronchioles** and the grapelike clusters of **alveoli.** Gas exchange occurs across the alveolar surfaces (Figure 22.6B).

F. All surfaces of the respiratory system are lined by moist epithelium. In all but the alveoli and smallest bronchioles, cilia and a thin film of mucus that helps eliminate dust, pollen, etc., cover this tissue.

G. A muscular **diaphragm** helps move air in and out of the lungs.

H. O_2 in inhaled air dissolves in a film of moisture lining the alveoli, then diffuses across the epithelial cells and into a web of capillaries that surrounds the alveolus. CO_2 diffuses the other way (Figure 22.6C).

Module 22.7 Connection: Smoking is one of the deadliest assaults on our respiratory system.

A. Mucus covering the epithelium of the respiratory system traps particles and microorganisms that are then swept out of the respiratory system by the action of cilia.
Review: Cilia (Module 4.18).

B. Microorganisms and particles are also phagocytized by macrophages inhabiting the lining of the respiratory system.

C. A breath of air in a polluted city may contain thousands of chemicals, many potentially harmful. Air pollutants such as sulfur dioxide, carbon monoxide, and ozone are associated with serious respiratory diseases, and asbestos fibers and radioactive radon gas have been linked with lung cancer.

D. Tobacco smoke is one of the worst sources of toxic air pollutants. Components are known to irritate epithelial cells and inhibit or destroy cilia and macrophages. This allows more of the toxins to reach the lungs' alveoli; the frequent coughing of smokers is the respiratory system's attempt at cleaning itself.

E. **Emphysema** is a disease of cigarette smokers characterized by the alveoli becoming brittle and eventually rupturing.

F. Lung cancer, caused by exposure to tobacco smoke, is nearly always fatal (Figure 22.7A, B).
NOTE: The leading cause of death among smokers is cardiovascular disease. The list of the adverse effects of smoking is a long one; some of the more important ones to emphasize are the effects of both active and passive smoking on prenatal development, infants, and children. These effects include (but are not limited to) an increased probability of cleft lip and cleft palate, decreased transfer of vitamin C to the fetus, increased risk of low birth weight babies, increased risk of allergies, delayed lung development, and increased risk of pneumonia. Smoking has been linked to SIDS (sudden infant

death syndrome). Smokers are more likely to experience an ectopic pregnancy than non-smokers are, and smokers taking birth control pills are more likely to experience adverse side effects (Module 27.8).

Module 22.8 Breathing ventilates the lungs.

A. During inhalation, the rib cage expands, the rib muscles and diaphragm contract, and the chest expands. The lungs also increase in size. These changes reduce the air pressure within the alveoli, and air moves in as a result of the higher pressure outside (Figure 22.8A). This is called **negative pressure breathing.**

B. During exhalation, the rib muscles and diaphragm both relax, decreasing the volume of the rib cage and forcing air out.
NOTE: The elastic cartilage holding the rib cage together helps increase and decrease the rib cage's volume.

C. The normal volume of each breath is about 500 mL. The maximum volume that one can inhale and exhale, the **vital capacity,** is about 3500 mL and 4800 mL for college-age females and males, respectively. The air that remains in the lungs after complete exhalation is the residual volume. This is proportionally greater (relative to vital capacity) in older and more diseased people.

D. Gas-exchange systems of birds are more efficient than most mammals' gas-exchange systems are. Birds maintain a one-way flow of air between two air sacs in addition to lungs. The sacs act like bellows and are not involved with gas exchange. The air tubes within the lungs have no residual volume of air because all the air travels through the lungs in one direction while the blood travels in the opposite direction, another example of a countercurrent exchange system (Figure 22.8B).

Module 22.9 Breathing is automatically controlled.

A. Although breathing can be consciously controlled, most of the time automatic control centers in our brain regulate our breathing movements (Figure 22.9).

B. **Breathing control centers** are located in the lower parts of the brainstem, the pons and the medulla oblongata (Module 28.15). About 10–14 times a minute, nerves from those areas signal the diaphragm and rib muscles to contract.

C. Increased cellular respiration causes increased concentrations of CO_2 in the blood. CO_2 reacts with water to form carbonic acid, lowering the pH. The medulla senses the pH drop and increases the rate and depth of breathing, thus eliminating more CO_2 from the blood in the lungs. **Hyperventilation** also causes an increase in the pH of the blood.
NOTE: This is one of the mechanisms that results in panting during and after strenuous exercise. Lactic acid buildup also contributes to the acidity of the blood during strenuous exercise (Module 6.15).

D. During severe depression of O_2 levels in the blood, sensors on arteries near the heart signal the breathing control center. This response may occur at high altitudes, where required levels of O_2 cannot be obtained by normal breathing.

II. Transport of Gases in the Body

Module 22.10 Blood transports the respiratory gases, with hemoglobin carrying the oxygen.

A. The human circulatory system functions in gas transport. One side of the heart pumps O_2-poor, CO_2-rich blood from the body to the lungs, and the other side of the heart pumps O_2-rich, CO_2-poor blood from the lungs to the rest of the body (Figure 22.10A).

B. Every gas in a mixture accounts for a portion (that gas's **partial pressure**) of the mixture's total pressure. At each location (lungs and tissues), gases are exchanged as they diffuse along their own partial pressure gradient.

C. O_2 is not very soluble in water. **Hemoglobin** in red blood cells has a much higher affinity for O_2 than water. Hemoglobin consists of four polypeptide chains, each chain attached to a heme chemical group with an iron atom in its center. Each iron atom can carry one O_2 molecule (Figure 22.10B).

Module 22.11 Hemoglobin helps transport CO_2 and buffer the blood.

A. Chemical moderation of pH level is known as buffering. By helping transport CO_2, hemoglobin helps buffer the blood.

B. Within red blood cells, CO_2 reacts with water to form H_2CO_3. This breaks into acidic H^+ and basic HCO_3^- ions more quickly in red blood cells under the control of an enzyme there (carbonic anhydrase). Hemoglobin picks up most H^+ ions and allows most HCO_3^- ions to diffuse back into the plasma. This provides a buffer in the blood that will react with any H^+ ions that are picked up elsewhere (Figure 22.11A).

C. When blood flows through the lungs, the process is reversed. H^+ ions are given up by the hemoglobin, reacting with the HCO_3^- ions to form H_2CO_3. This is then converted back into CO_2, and the CO_2 diffuses from the blood to the air (Figure 22.11B).

Module 22.12 Connection: The human fetus exchanges gases with the mother's bloodstream.

A. The fetus lies within a watery bath of amniotic fluid. Its lungs are filled with this fluid.

B. Capillaries from the fetal blood supply (through the umbilical cord) mix with capillaries of the uterus in the placenta (Figure 22.12).

C. A countercurrent arrangement of these capillaries facilitates the transfer of gases between fetus and mother. A fetus also has a different type of hemoglobin from the mother. This fetal hemoglobin has a higher affinity for oxygen than normal adult hemoglobin, thus enhancing the transfer of O_2 from mother to fetus.

D. When the baby is born, when placental transfer stops, CO_2 concentration in the blood increases, lowering the pH and stimulating the breathing center, causing the baby to take its first breath.
Preview: Refer to this module when discussing fetal changes that take place during the third trimester of pregnancy (Module 27.17).

Class Activities

1. A bell-jar model of lungs with a diaphragm can be built or purchased from biological supply companies. To build a model, take a Y-shaped tube and place balloons on the two ends (these will be the lungs), secure the stem of the Y-shaped tube in a stopper, and place this in the neck of the bell jar. Secure a piece of rubber across the wide, open end of the bell jar (this will be the diaphragm); the bell jar itself plays the role of the thoracic cavity. When the rubber diaphragm is pulled on, the volume of the bell jar increases and air will enter the balloons. When the rubber diaphragm is allowed to return to its original position, the volume of the bell jar will decrease and air will be forced out of the balloons. This is an elegantly simple way of demonstrating the forces that fill and empty mammalian lungs.

2. Find the average pulse rate and blood pressures of the nonsmokers versus the smokers in the class. Let the smokers go outside to smoke and when they come back, see how their average pulse rate and blood pressure have changed.

Transparency Acetates

Figure 22.1	Three phases of gas exchange
Figure 22.2A	The entire outer skin
Figure 22.2B	Gills
Figure 22.2C	Tracheae
Figure 22.2D	Lungs
Figure 22.3	The structure of fish gills
Figure 22.4	Countercurrent flow in a fish gill
Figure 22.5A	The tracheal system of an insect
Figure 22.5C	Tracheal connections to body cells
Figure 22.6A	The human respiratory system
Figure 22.6B	The structure of alveoli
Figure 22.8A	How a human breathes
Figure 22.8B	How a bird breathes
Figure 22.9	Control centers that regulate breathing (Layer 1)
Figure 22.9	Control centers that regulate breathing (Layer 2)
Figure 22.10A	Gas exchange in the body
Figure 22.10B	Hemoglobin loading and unloading of O_2
Figure 22.11A	CO_2 transport from the body tissues into the blood
Figure 22.11B	CO_2 transport from the blood into the lungs
Figure 22.12	A human fetus and placenta in the uterus

Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Activities and Thinking as a Scientist	Module Number
Web/CD Activity 22A: *The Human Respiratory System*	22.6
Web/CD Activity 22B: *Transport of Respiratory Gases*	22.11
Biology Labs On-Line: *HemoglobinLab*	22.11