Chapter 42

Circulation and Gas Exchange

PowerPoint Lectures for
Biology, Seventh Edition
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Lectures by Chris Romero

- Overview: Trading with the Environment
- Every organism must exchange materials with its environment
  - And this exchange ultimately occurs at the cellular level

- In unicellular organisms
  - These exchanges occur directly with the environment
- For most of the cells making up multicellular organisms
  - Direct exchange with the environment is not possible

- The feathery gills projecting from a salmon
  - Are an example of a specialized exchange system found in animals

Figure 42.1

- Concept 42.1: Circulatory systems reflect phylogeny
- Transport systems
  - Functionally connect the organs of exchange with the body cells

- Most complex animals have internal transport systems
  - That circulate fluid, providing a lifeline between the aqueous environment of living cells and the exchange organs, such as lungs, that exchange chemicals with the outside environment

Invertebrate Circulation

- The wide range of invertebrate body size and form
  - Is paralleled by a great diversity in circulatory systems

Gastrovascular Cavities

- Simple animals, such as cnidarians
  - Have a body wall only two cells thick that encloses a gastrovascular cavity
- The gastrovascular cavity
  - Functions in both digestion and distribution of substances throughout the body

- Some cnidarians, such as jellies
  - Have elaborate gastrovascular cavities

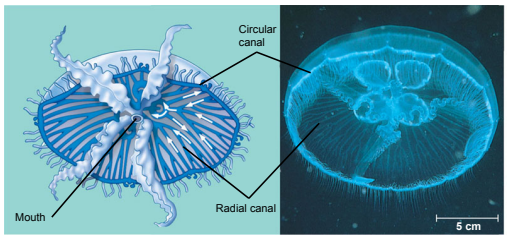


Figure 42.2

Open and Closed Circulatory Systems

- More complex animals
  - Have one of two types of circulatory systems: open or closed
- Both of these types of systems have three basic components
  - A circulatory fluid (blood)
  - A set of tubes (blood vessels)
  - A muscular pump (the heart)

- In insects, other arthropods, and most molluscs
  - Blood bathes the organs directly in an open circulatory system

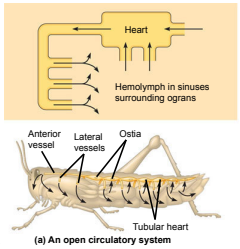


Figure 42.3a (a) An open circulatory system

- In a closed circulatory system
  - Blood is confined to vessels and is distinct from the interstitial fluid

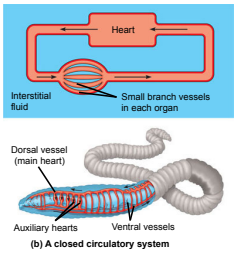


Figure 42.3b (b) A closed circulatory system

- Closed systems
  - Are more efficient at transporting circulatory fluids to tissues and cells

Survey of Vertebrate Circulation

- Humans and other vertebrates have a closed circulatory system
  - Often called the cardiovascular system
- Blood flows in a closed cardiovascular system
  - Consisting of blood vessels and a two- to four-chambered heart

- Arteries carry blood to capillaries
  - The sites of chemical exchange between the blood and interstitial fluid
- Veins
  - Return blood from capillaries to the heart

Fishes

- A fish heart has two main chambers
  - One ventricle and one atrium
- Blood pumped from the ventricle
  - Travels to the gills, where it picks up O_2 and disposes of CO_2

Amphibians

- Frogs and other amphibians
  - Have a three-chambered heart, with two atria and one ventricle
- The ventricle pumps blood into a forked artery
  - That splits the ventricle's output into the pulmocutaneous circuit and the systemic circuit

Reptiles (Except Birds)

- Reptiles have double circulation
  - With a pulmonary circuit (lungs) and a systemic circuit
- Turtles, snakes, and lizards
  - Have a three-chambered heart

Mammals and Birds

- In all mammals and birds
  - The ventricle is completely divided into separate right and left chambers
- The left side of the heart pumps and receives only oxygen-rich blood
  - While the right side receives and pumps only oxygen-poor blood

- A powerful four-chambered heart
  - Was an essential adaptation of the endothermic way of life characteristic of mammals and birds

- Vertebrate circulatory systems

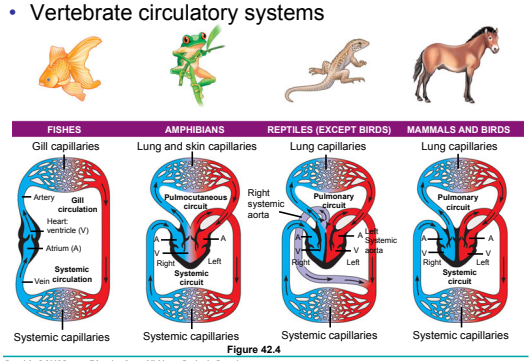


Figure 42.4

- Concept 42.2: Double circulation in mammals depends on the anatomy and pumping cycle of the heart
- The structure and function of the human circulatory system
  - Can serve as a model for exploring mammalian circulation in general

Mammalian Circulation: The Pathway

- Heart valves
  - Dictate a one-way flow of blood through the heart

- Blood begins its flow
  - With the right ventricle pumping blood to the lungs
- In the lungs
  - The blood loads O_2 and unloads CO_2

- Oxygen-rich blood from the lungs
  - Enters the heart at the left atrium and is pumped to the body tissues by the left ventricle
- Blood returns to the heart
  - Through the right atrium

- The mammalian cardiovascular system

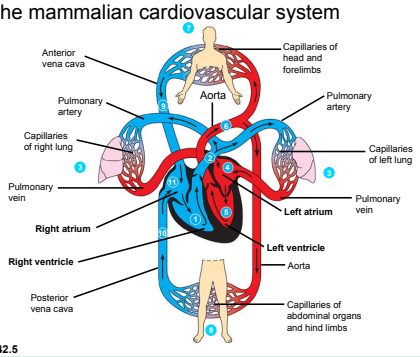


Figure 42.5

The Mammalian Heart: A Closer Look

- A closer look at the mammalian heart
  - Provides a better understanding of how double circulation works

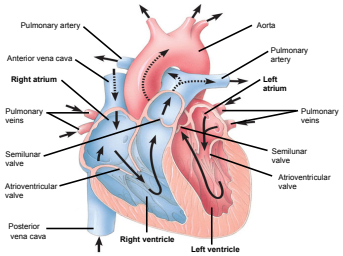


Figure 42.6

- The heart contracts and relaxes
  - In a rhythmic cycle called the cardiac cycle
- The contraction, or pumping, phase of the cycle
  - Is called systole
- The relaxation, or filling, phase of the cycle
  - Is called diastole

- The cardiac cycle

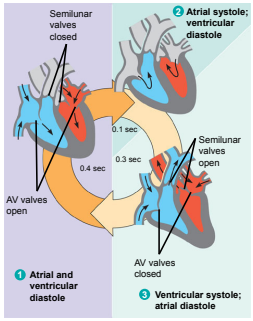


Figure 42.7

- The heart rate, also called the pulse
  - Is the number of beats per minute
- The cardiac output
  - Is the volume of blood pumped into the systemic circulation per minute

Maintaining the Heart's Rhythmic Beat

- Some cardiac muscle cells are self-excitable
  - Meaning they contract without any signal from the nervous system

- A region of the heart called the sinoatrial (SA) node, or pacemaker
  - Sets the rate and timing at which all cardiac muscle cells contract
- Impulses from the SA node
  - Travel to the atrioventricular (AV) node
- At the AV node, the impulses are delayed
  - And then travel to the Purkinje fibers that make the ventricles contract

- The impulses that travel during the cardiac cycle
  - Can be recorded as an electrocardiogram (ECG or EKG)

- The control of heart rhythm

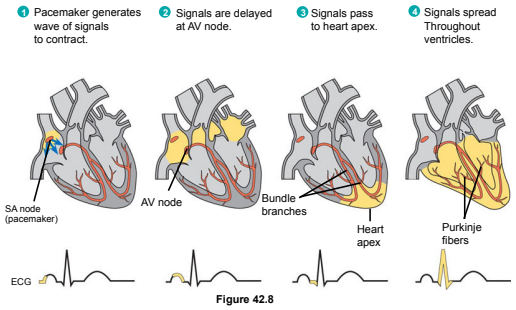


Figure 42.8

- The pacemaker is influenced by
  - Nerves, hormones, body temperature, and exercise

- Concept 42.3: Physical principles govern blood circulation
- The same physical principles that govern the movement of water in plumbing systems
  - Also influence the functioning of animal circulatory systems

Blood Vessel Structure and Function

- The "infrastructure" of the circulatory system
  - Is its network of blood vessels

- All blood vessels
  - Are built of similar tissues
  - Have three similar layers

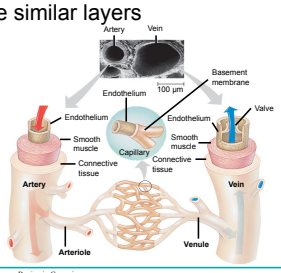


Figure 42.9

- Structural differences in arteries, veins, and capillaries
  - Correlate with their different functions
- Arteries have thicker walls
  - To accommodate the high pressure of blood pumped from the heart

- In the thinner-walled veins
  - Blood flows back to the heart mainly as a result of muscle action

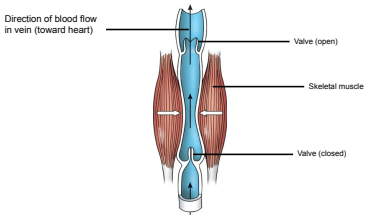


Figure 42.10

Blood Flow Velocity

- Physical laws governing the movement of fluids through pipes
  - Influence blood flow and blood pressure

- The velocity of blood flow varies in the circulatory system
  - And is slowest in the capillary beds as a result of the high resistance and large total cross-sectional area

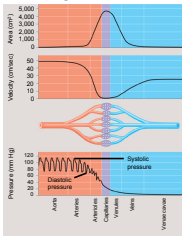


Figure 42.11

Blood Pressure

- Blood pressure
  - Is the hydrostatic pressure that blood exerts against the wall of a vessel

- Systolic pressure
  - Is the pressure in the arteries during ventricular systole
  - Is the highest pressure in the arteries
- Diastolic pressure
  - Is the pressure in the arteries during diastole
  - Is lower than systolic pressure

- Blood pressure
  - Can be easily measured in humans

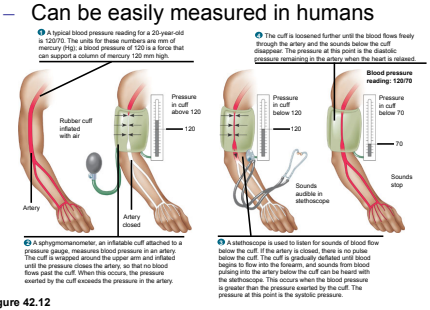


Figure 42.12

- Blood pressure is determined partly by cardiac output
  - And partly by peripheral resistance due to variable constriction of the arterioles

Capillary Function

- Capillaries in major organs are usually filled to capacity
  - But in many other sites, the blood supply varies

- Two mechanisms
  - Regulate the distribution of blood in capillary beds
- In one mechanism
  - Contraction of the smooth muscle layer in the wall of an arteriole constricts the vessel

- In a second mechanism
  - Precapillary sphincters control the flow of blood between arterioles and venules

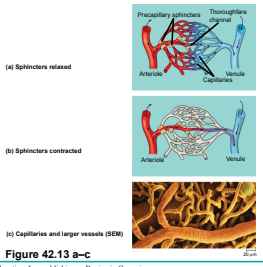


Figure 42.13 a–c

- The critical exchange of substances between the blood and interstitial fluid
  - Takes place across the thin endothelial walls of the capillaries

- The difference between blood pressure and osmotic pressure
  - Drives fluids out of capillaries at the arteriole end and into capillaries at the venule end

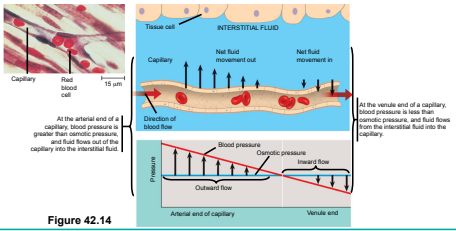


Figure 42.14

Fluid Return by the Lymphatic System

- The lymphatic system
  - Returns fluid to the body from the capillary beds
  - Aids in body defense

- Fluid reenters the circulation
  - Directly at the venous end of the capillary bed and indirectly through the lymphatic system

- Concept 42.4: Blood is a connective tissue with cells suspended in plasma
- Blood in the circulatory systems of vertebrates
  - Is a specialized connective tissue

Blood Composition and Function

- Blood consists of several kinds of cells
  - Suspended in a liquid matrix called plasma
- The cellular elements
  - Occupy about 45% of the volume of blood

Plasma

- Blood plasma is about 90% water
- Among its many solutes are
  - Inorganic salts in the form of dissolved ions, sometimes referred to as electrolytes

- The composition of mammalian plasma

Plasma 55%	
Constituent	**Major functions**
Water	Solvent for carrying other substances
Ions (blood electrolytes) Sodium Potassium Calcium Magnesium Chloride Bicarbonate	Osmotic balance pH buffering, and regulation of membrane permeability
Plasma proteins Albumin Fibringen Immunoglobulins (antibodies)	Osmotic balance, pH buffering Clotting Defense
Substances transported by blood Nutrients (such as glucose, fatty acids, vitamins) Waste products of metabolism Respiratory gases (O_2 and CO_2) Hormones	

Figure 42.15

- Another important class of solutes is the plasma proteins
  - Which influence blood pH, osmotic pressure, and viscosity
- Various types of plasma proteins
  - Function in lipid transport, immunity, and blood clotting

Cellular Elements

- Suspended in blood plasma are two classes of cells
  - Red blood cells, which transport oxygen
  - White blood cells, which function in defense
- A third cellular element, platelets
  - Are fragments of cells that are involved in clotting

- The cellular elements of mammalian blood

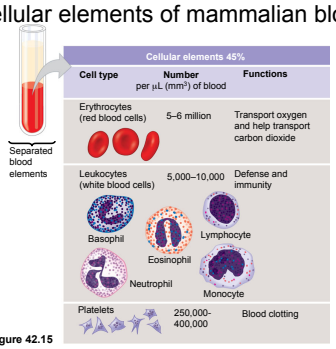


Figure 42.15

Erythrocytes

- Red blood cells, or erythrocytes
  - Are by far the most numerous blood cells
  - Transport oxygen throughout the body

Leukocytes

- The blood contains five major types of white blood cells, or leukocytes
  - Monocytes, neutrophils, basophils, eosinophils, and lymphocytes, which function in defense by phagocytizing bacteria and debris or by producing antibodies

Platelets

- Platelets function in blood clotting

Stem Cells and the Replacement of Cellular Elements

- The cellular elements of blood wear out
  - And are replaced constantly throughout a person's life

- Erythrocytes, leukocytes, and platelets all develop from a common source
  - A single population of cells called pluripotent stem cells in the red marrow of bones

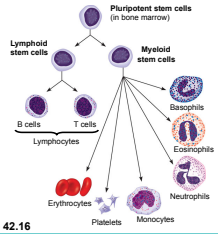


Figure 42.16

Blood Clotting

- When the endothelium of a blood vessel is damaged
  - The clotting mechanism begins

- A cascade of complex reactions
  - Converts fibrinogen to fibrin, forming a clot

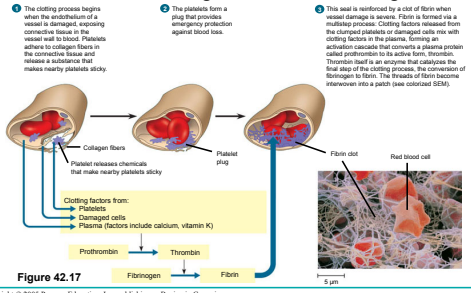


Figure 42.17

Cardiovascular Disease

- Cardiovascular diseases
  - Are disorders of the heart and the blood vessels
  - Account for more than half the deaths in the United States

- One type of cardiovascular disease, atherosclerosis
  - Is caused by the buildup of cholesterol within arteries

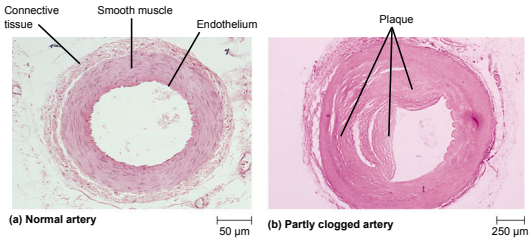


Figure 42.18a, b

- Hypertension, or high blood pressure
  - Promotes atherosclerosis and increases the risk of heart attack and stroke
- A heart attack
  - Is the death of cardiac muscle tissue resulting from blockage of one or more coronary arteries
- A stroke
  - Is the death of nervous tissue in the brain, usually resulting from rupture or blockage of arteries in the head

- Concept 42.5: Gas exchange occurs across specialized respiratory surfaces
- Gas exchange
  - Supplies oxygen for cellular respiration and disposes of carbon dioxide

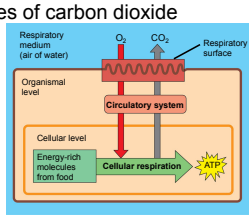


Figure 42.19

- Animals require large, moist respiratory surfaces for the adequate diffusion of respiratory gases
  - Between their cells and the respiratory medium, either air or water

Gills in Aquatic Animals

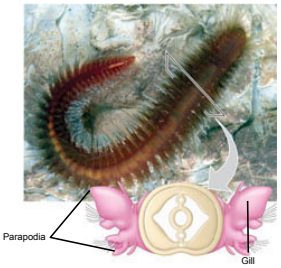
- Gills are outfoldings of the body surface
  - Specialized for gas exchange

- In some invertebrates
  - The gills have a simple shape and are distributed over much of the body

(a) Sea star. The gills of a sea star are simple tubular projections of the skin. The hollow core of each gill is an extension of the coelom (body cavity). Gas exchange occurs by diffusion across the gill surfaces, and fluid in the coelom circulates in and out of the gills, aiding gas transport. The surfaces of a sea star's tube feet also function in gas exchange.

Figure 42.20a

- Many segmented worms have flaplike gills
  - That extend from each segment of their body

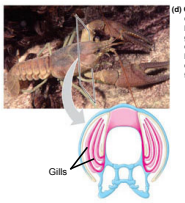


(b) Marine worm. Many polychaetes (marine worms of the phylum Annelida) have a pair of flattened appendages called parapodia on each body segment. The parapodia serve as gills and also function in crawling and swimming.

Figure 42.20b

- The gills of clams, crayfish, and many other animals
  - Are restricted to a local body region

(c) Scallop. The gills of a scallop are long, flattened plates that project from the main body mass inside the hard shell. Cilia on the gills circulate water around the gill surfaces.



(d) Crayfish. Crayfish and other crustaceans have long, feathery gills covered by the exoskeleton. Specialized body appendages drive water over the gill surfaces.

Figure 42.20c, d

- The effectiveness of gas exchange in some gills, including those of fishes
  - Is increased by ventilation and countercurrent flow of blood and water

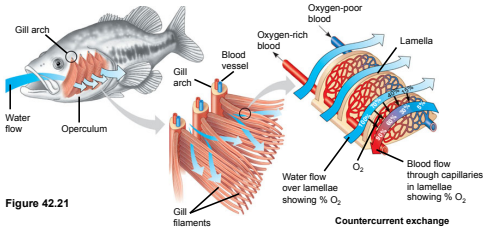
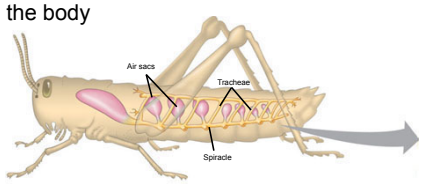


Figure 42.21

Tracheal Systems in Insects

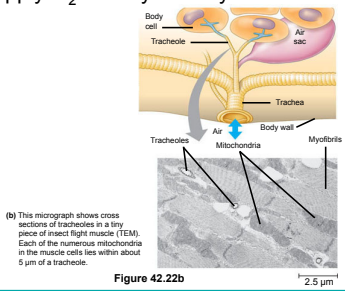
- The tracheal system of insects
  - Consists of tiny branching tubes that penetrate the body



(a) The respiratory system of an insect consists of branched internal tubes that deliver air directly to body cells. Rings of chitin reinforce the largest tubes, called tracheae, keeping them from collapsing. Enlarged portions of tracheae form air sacs near organs that require a large supply of oxygen. Air enters the tracheae through openings called spiracles on the insect's body surface and passes into smaller tubes called tracheoles. The tracheoles are closed and contain fluid (blue-gray). When the animal is active and is using more O_2, most of the fluid is withdrawn into the body. This increases the surface area of air in contact with cells.

Figure 42.22a

- The tracheal tubes
  - Supply O_2 directly to body cells



(b) This micrograph shows cross sections of tracheoles in a tiny piece of insect flight muscle (TEM). Each of the numerous mitochondria in the muscle cells lies within about 5 µm of a tracheole.

Figure 42.22b

Lungs

- Spiders, land snails, and most terrestrial vertebrates
  - Have internal lungs

Mammalian Respiratory Systems: A Closer Look

- A system of branching ducts
  - Conveys air to the lungs

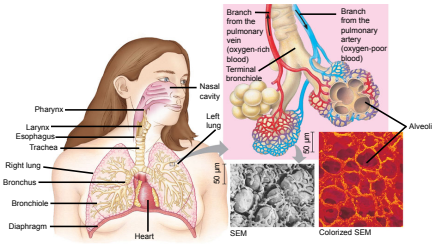


Figure 42.23

- In mammals, air inhaled through the nostrils
  - Passes through the pharynx into the trachea, bronchi, bronchioles, and dead-end alveoli, where gas exchange occurs

- Concept 42.6: Breathing ventilates the lungs
- The process that ventilates the lungs is breathing
  - The alternate inhalation and exhalation of air

How an Amphibian Breathes

- An amphibian such as a frog
  - Ventilates its lungs by positive pressure breathing, which forces air down the trachea

How a Mammal Breathes

- Mammals ventilate their lungs
  - By negative pressure breathing, which pulls air into the lungs

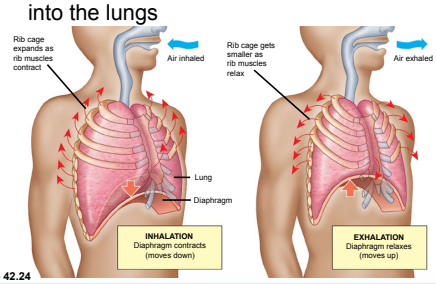


Figure 42.24

- Lung volume increases
  - As the rib muscles and diaphragm contract

How a Bird Breathes

- Besides lungs, bird have eight or nine air sacs
  - That function as bellows that keep air flowing through the lungs

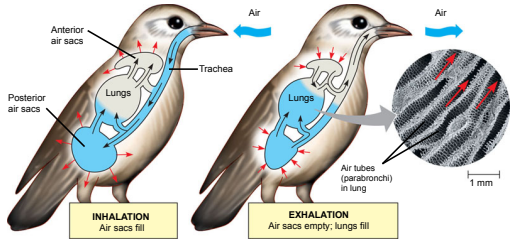


Figure 42.25

- Air passes through the lungs
  - In one direction only
- Every exhalation
  - Completely renews the air in the lungs

Control of Breathing in Humans

- The main breathing control centers
  - Are located in two regions of the brain, the medulla oblongata and the pons

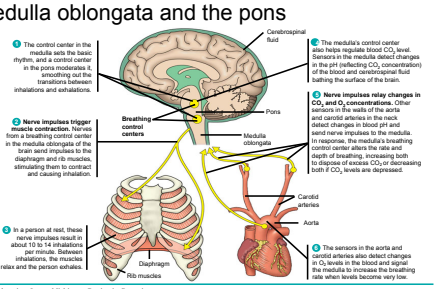


Figure 42.26

- The centers in the medulla
  - Regulate the rate and depth of breathing in response to pH changes in the cerebrospinal fluid
- The medulla adjusts breathing rate and depth
  - To match metabolic demands

- Sensors in the aorta and carotid arteries
  - Monitor O_2 and CO_2 concentrations in the blood
  - Exert secondary control over breathing

- Concept 42.7: Respiratory pigments bind and transport gases
- The metabolic demands of many organisms
  - Require that the blood transport large quantities of O_2 and CO_2

The Role of Partial Pressure Gradients

- Gases diffuse down pressure gradients
  - In the lungs and other organs
- Diffusion of a gas
  - Depends on differences in a quantity called partial pressure

- A gas always diffuses from a region of higher partial pressure
  - To a region of lower partial pressure

- In the lungs and in the tissues
  - O_2 and CO_2 diffuse from where their partial pressures are higher to where they are lower

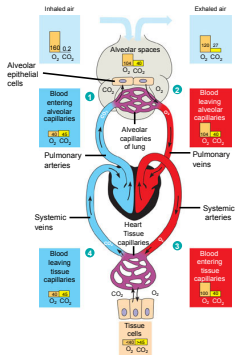


Figure 42.27

Respiratory Pigments

- Respiratory pigments
  - Are proteins that transport oxygen
  - Greatly increase the amount of oxygen that blood can carry

Oxygen Transport

- The respiratory pigment of almost all vertebrates
  - Is the protein hemoglobin, contained in the erythrocytes

- Like all respiratory pigments
  - Hemoglobin must reversibly bind O_2, loading O_2 in the lungs and unloading it in other parts of the body

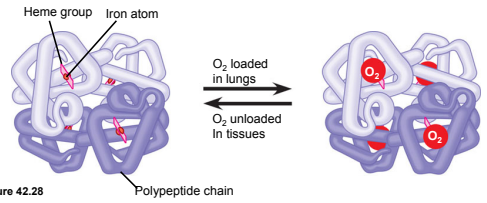


Figure 42.28

- Loading and unloading of O_2
  - Depend on cooperation between the subunits of the hemoglobin molecule
- The binding of O_2 to one subunit induces the other subunits to bind O_2 with more affinity

- Cooperative O_2 binding and release
  - Is evident in the dissociation curve for hemoglobin
- A drop in pH
  - Lowers the affinity of hemoglobin for O_2

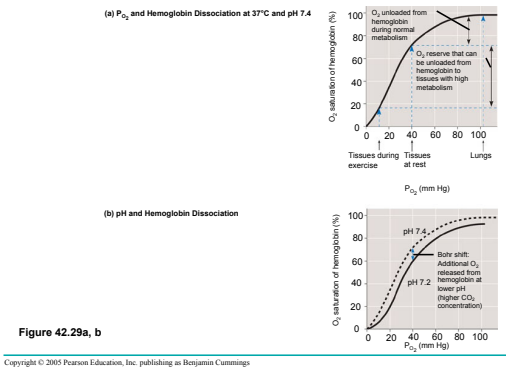


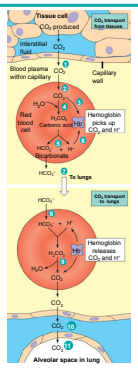
Figure 42.29a, b

Carbon Dioxide Transport

- Hemoglobin also helps transport CO_2
  - And assists in buffering

- Carbon from respiring cells
  - Diffuses into the blood plasma and then into erythrocytes and is ultimately released in the lungs

1. Carbon dioxide produced by body tissues diffuses into the interstitial fluid and the plasma.
2. Over 90% of the CO_2 diffuses into red blood cells, leaving only 7% in the plasma as dissolved CO_2.
3. Some CO_2 is picked up and transported by hemoglobin.
4. However, most CO_2 reacts with water in red blood cells, forming carbonic acid (H_2CO_3), a reaction catalyzed by carbonic anhydrase contained. Within red blood cells.
5. Carbonic acid dissociates into a biocarbonate ion (HCO_3^-) and a hydrogen ion (H^+).
6. Hemoglobin binds most of the H^+ from H_2CO_3 preventing the H^+ from acidifying the blood and thus preventing the Bohr shift.



7. Most of the HCO_3^- diffuse into the plasma where it is carried in the bloodstream to the lungs.
8. In the HCO_3^- diffuse from the plasma red blood cells, combining with H^+ released from hemoglobin and forming H_2CO_3.
9. Carbonic acid is converted back into CO_2 and water.
10. CO_2 formed from H_2CO_3 is unloaded from hemoglobin and diffuses into the interstitial fluid.
11. CO_2 diffuses into the alveolar space, from which it is expelled during exhalation. The reduction of CO_2 concentration in the plasma drives the breakdown of H_2CO_3 Into CO_2 and water in the red blood cells (see step 9), a reversal of the reaction that occurs in the tissues (see step 4).

Figure 42.30

Elite Animal Athletes

- Migratory and diving mammals
  - Have evolutionary adaptations that allow them to perform extraordinary feats

The Ultimate Endurance Runner

- The extreme O_2 consumption of the antelope-like pronghorn
  - Underlies its ability to run at high speed over long distances

Figure 42.31

Diving Mammals

- Deep-diving air breathers
  - Stockpile O_2 and deplete it slowly