CHAPTER 53: RESPIRATION

CHAPTER SYNOPSIS

Heterotrophs obtain energy by oxidizing carbon compounds utilizing oxygen and producing carbon dioxide. Oxygen passively diffuses into the layer of water surrounding the epithelial layers and is driven by the difference in oxygen concentration between the interior of the organism and the environment. This relationship is described by Fick's law of diffusion. Many animals increase their diffusion constant by circulating fresh water around their bodies. Other animals increase the diffusion surface via special respiratory organs. External gills are the simplest aquatic gas exchange organs.

Fish circulate water past their gills and out the opercular openings. Most fish possess moveable gill covers that pump water past their gills, ensuring a constant flow of oxygen to maintain a high diffusion constant. The structure of the gill and its blood supply create a countercurrent flow; maximal diffusion occurs the entire length of the gill. Air-oriented respiratory systems are far less efficient. Insects evolved tubular tracheae; other animals evolved lungs. Amphibians breathe with simple sac lungs augmented by cutaneous respiration. Reptile lungs are more complex as their water-tight skin prevents diffusion. Mammal lungs are highly branched with terminal alveoli. They increase their diffusion surface area to meet the demand for more oxygen with greater metabolic activity. Birds evolved a super efficient system with unidirectional air flow by utilizing posterior and anterior air sacs. Gas exchange in birds occurs across parabronchi, minute air vessels rather than the blind-ended alveoli of mammals. Avian respiration requires two cycles of inspiration and exhalation to move a single volume of gas through their respiratory system. Their respiration is nearly as efficient as a fish's due to the 90^o cross-current flow between the air and the blood.

The mammalian respiratory system is contained within the thoracic cavity. A single trachea connects to two bronchi, each divides into bronchioles that branch into alveoli. Human inhalation is a one-cycle pumping system, there is a small residual volume of air that remains within the lungs. Intrapleural fluid supports the lungs within the pleural cavity and enables the lungs to inflate as a result of pressure changes associated with changes in the size of that cavity. Reptiles, birds, and mammals possess negative pressure breathing (air is sucked into the lungs) while amphibians have positive pressure breathing (air is pushed into the lungs). Breathing in humans is dependent on regular contractions of the thoracic muscles and the diaphragm. The amount of air exchanged in passive inspiration and expiration is the tidal volume: vital capacity is the amount of air expired after a forceful, maximum inspiration equal to three to four times the tidal volume.

Breathing is initiated by the respiratory center in the brain. It sends signals to the diaphragm and intercostal muscles to contract. This process is ultimately not under direct conscious control, you cannot asphyxiate yourself by holding your breath. The speed and depth of breathing is dependent on the level of CO_2 in the blood. Chemoreceptors sensitive to blood pH are located in the aorta and carotid artery. The central chemoreceptors in the brain sense changes in pH in the cerebrospinal fluid. Blood pH changes occur as CO_2 forms carbonic acid and further dissociates into hydrogen and bicarbonate ions.

Respiratory gases are transported via the carrier protein hemoglobin. An animal's oxygen-hemoglobin dissociation curve correlates partial pressure of oxygen and its ability to bind to hemoglobin. Oxygen diffuses into the blood plasma within the alveoli and then into the red blood cells. As the oxygen binds with hemoglobin it is removed from the plasma, allowing a greater amount to diffuse. Oxygen is unloaded from capillaries in metabolically active tissues as a result of the Bohr effect. Carbon dioxide is simultaneously absorbed by the blood and is bound to hemoglobin and the red cell cytoplasm. The carbon dioxide is unloaded at the alveoli where hemoglobin preferentially associates with oxygen. Carbon dioxide is carried in the red blood cells through the formation of carbonic acid and bicarbonate. Hemoglobin also transports nitric oxide (NO), a regulatory gas that causes dilation of blood vessels.

CHAPTER OBJECTIVES

ä Describe Fick's law of diffusion and understand how animals alter the variables to evolve more efficient respiratory systems.

ä Understand how primitive invertebrate, advanced vertebrate, and vertebrate respiratory systems each maximize the rate of diffusion.

ä Explain the countercurrent flow exchange in fish gills and indicate which parameters of Fick's equation are optimized.

ä Describe the two major respiratory systems possessed by terrestrial animals and the evolutionary adaptations of each.

ä Compare respiration in amphibians, reptiles, and mammals.

ä Explain the unique respiratory system of birds, their need for a highly efficient system, and the similarities with a fish respiratory system.

ä Describe the anatomy of the human respiratory system and the mechanics of breathing.

ä Understand how breathing and blood gas levels are regulated.

ä Understand the importance of gas carrier molecules in the circulatory system of vertebrates.

ä Describe how oxygen is transported from the alveoli to metabolically active tissue, how carbon dioxide returns, and how the Bohr effect augments this gaseous exchange.

ä Describe carbon dioxide and nitric oxide transport.

KEY TERMS

alveolus (alveoli)
aortic body
bronchiole
bronchus (bronchi)
carotid body
central chemoreceptor
countercurrent flow
cross-current flow
deoxyhemoglobin
emphysema
external gill
Fick's law of diffusion
gill arch
hemoglobin
hyperventilating
hypoventilating
larynx
lung
one atmosphere of pressure
operculum
oxyhemoglobin
parietal pleural membrane
partial pressure (P)
pleural cavity
ram ventilation
tidal volume
trachea
tracheae (insect)
visceral pleural membrane
vital capacity

CHAPTER OUTLINE

53.0 Introduction

I. HETEROTROPHS OBTAIN ENERGY BY CELLULAR RESPIRATION

A. Process Consumes Oxygen and Generates Carbon Dioxide and Water

B. Respiration: Exchange of Oxygen and Carbon Dioxide at Organism Level fig 53.1
1. Includes mechanisms of breathing
2. Includes exchange of gases between cardiovascular system and body

53.1 Respiration involves the diffusion of gases

I. FICK'S LAW OF DIFFUSION

A. In Respiration, Gases Diffuse Across Plasma Membranes
  1. Plasma membranes must be surrounded by water
    a. External environment is aqueous
    b. True even in terrestrial animals
      1) Oxygen dissolves in thin layer of fluid covering respiratory surfaces
      2) Includes surface of alveoli in lungs
  2. Diffusion of oxygen into the epithelial aqueous layer is passive
  3. Driven by the difference in oxygen concentration between two sides of membrane
  4. Mathematical relationship called Fick's law of diffusion
    a. $R = D \times A (\Delta p / d)$
    b. R = rate of diffusion
    c. D = diffusion constant
    d. A = area over which diffusion takes place
    e. Δp = difference in partial pressures on each side
    f. d = distance across which diffusion takes place
  5. Evolutionary changes optimize R by favoring certain parameters fig 53.2
    a. Increase surface area A
    b. Decrease distance d
    c. Increase concentration difference Δp
  6. Evolution has involved changes in all three factors

II. HOW ANIMALS MAXIMIZE THE RATE OF DIFFUSION

A. Coping with Different Conditions
  1. Relying on simple diffusion
    a. Oxygen diffuses too slowly to be efficient over more than 0.5 mm
    b. Severely limits size of organisms
    c. Protists are small enough to utilize simple diffusion fig 53.2a
  2. Creating a water current
    a. Most primitive invertebrate phyla possess no special respiratory organs
    b. Can obtain oxygen via diffusion by increasing Δp in Fick's equation
      1) Increase difference in O_2 concentration by creating a water current
      2) Constantly replace water over diffusion surface
      3) Δp does not decrease as diffusion proceeds
      4) Keep exterior O_2 concentration high
      5) Results in higher rate of diffusion
  3. Increasing the diffusion surface area
    a. More advanced invertebrates and vertebrates possess respiratory organs
      1) Increase surface area over which diffusion occurs
      2) Provides contact between external environment and internal circulating fluids
    b. Increase A and decrease d

B. Atmospheric Pressure and Partial Pressures
  1. Dry air = 78.09% N_2 + 20.95% O_2 + 0.93% (argon + inert gases) + 0.03% CO_2
  2. Amount of air present decreases at high altitudes fig 53.3
  3. At sea level, air pressure measures 760 mm of mercury
    a. Equals the barometric pressure of air
    b. Equivalent to one atmosphere of pressure

4. Each gas within the air exerts a partial pressure(P_x) = 760 x % gas
    a. Nitrogen (P_{N_2}) = 760 x 79.02% = 600.6 mmHg
    b. Oxygen (P_{O_2}) = 760 x 20.95% = 159.2 mmHg
    c. Carbon dioxide (P_{CO_2}) = 760 x 0.03% = 0.2 mmHg
5. Less air, therefore less oxygen present at high altitudes
    a. Barometric pressure above 6000 meters = 380 mmHg
    b. P_{O_2} = 380 x 20.95% = 80 mmHg
    c. Only half the oxygen is available compared to sea level

53.2 Gills are used for respiration by aquatic vertebrates

I. THE GILL AS A RESPIRATORY STRUCTURE

A. Basic Structure of Gills
1. Aquatic organs (gills) project from body into water
    a. Simple gills like papulae of echinoderms fig 53.2c
    b. Convoluted gills of fish fig 53.2e
2. Increase in diffusion surface area enables aquatic organisms to extract more oxygen
3. External gills
    a. Provide greatly increased surface area
    b. Include gills of fish and larval amphibians and neotenic amphibians
4. Disadvantages of external gills
    a. Difficult to constantly circulate water past diffusion surface
    b. Inefficient, highly branched gills offer resistance against movement
    c. Delicate tissues and epithelium are readily damaged
5. Special branchial chambers in other organisms pump water past gills
    a. Internal mantle cavity of mollusks opens to outside, contains gills
    b. Contraction of muscular walls draws water in and expels it
    c. Crustacean cavity lies between body and hard exoskeleton
    d. Movement of limbs draws water through branchial chamber

B. The Gills of Bony Fishes
1. Gills are located between buccal cavity (mouth) and opercular cavity fig 53.4
    a. Buccal cavity opens and closes with movement of mouth
    b. Opercular cavity opened and closed by moving operculum, gill cover
2. Two sets of cavities serve as pumps
    a. Expand alternately to move water into mouth, through gills, out operculum
    b. Lower jaw and floor of mouth to bring water into buccal cavity
    c. Lower pressure in opercular cavity, water moves across gills
    d. One-way flow of water over gills
3. Continuously swimming fish have nearly immovable gill covers
    a. Water constantly forced over gills as fish swim with partially open mouths
    b. Process is a form of ram ventilation
4. Most bony fish have flexible gill covers, permit pumping action

C. Effects of Gill Construction on Parameters of Diffusion
1. Structure of gills fig 53.5
    a. Four gill arches on each side of head
    b. Each gill composed of two rows of gill filaments
    c. Filaments divided into thin lamellae that project into flow of water
    d. Movement of water across lamellae occurs in only one direction
    e. Direction of blood circulation runs opposite that of water flow
    f. Countercurrent flow maximizes Δp between water and blood

2. Advantage of countercurrent exchange fig 53.6a
   a. Least oxygenated blood meets least oxygenated water at back of gill
   b. Most oxygenated blood meets most oxygenated water at front of gill
   c. Diffusion occurs along entire length of gill
3. Concurrent flow if water and blood flowed in the same direction
   a. Oxygen-depleted blood would meet highly oxygenated water
   b. Diffusion would initially be high fig 53.7b
   c. Oxygenated blood would meet less oxygenated water at back of gill
   d. Diffusion would cease, only front part of gill would be functional
4. Fish gills are most efficient respiratory organs

53.3 Lungs are used for respiration by terrestrial vertebrates

I. RESPIRATION IN AIR-BREATHING ANIMALS

A. Gills Not Adaptable for Terrestrial Use
   1. Air is less buoyant than water
      a. Lamellae lack structural support, collapse without water buoyancy
      b. More oxygen present in air than in water
         1) Water = 5 to 10 ml O_2 per 1 liter water
         2) Air = 210 ml of O_2 per 1 liter air
      c. Collapse reduces diffusion surface area
      d. Internal air passages remain open due to structural support
   2. Water diffuses into air through evaporation
      a. Terrestrial organisms constantly lose water to atmosphere
      b. Gills provide an enormous surface area for water loss

B. Evolution of Two Kinds of Terrestrial Respiratory Organs
   1. Both systems sacrifice efficiency to reduce water loss
   2. Tracheae of insects fig 53.2d
      a. Extensive series of air-filled passages within body
      b. Oxygen diffuses directly from trachea to cells, no circulatory intervention
      c. Openings close when CO_2 levels are below certain point to limit water loss
   3. Lungs of terrestrial vertebrates fig 53.7
      a. Air saturated with water vapor before reaching area of gas exchange
      b. Air enters and exits through one tube, minimizes evaporation
      c. Vertebrates other than birds use uniform pool of air
      d. Two-way flow of air replaces one-way flow (except in birds)

II. RESPIRATION IN AMPHIBIANS AND REPTILES

A. Amphibians
   1. Structure of the amphibian respiratory system fig 53.8
      a. Lungs are sac-like outpouchings of gut with few folds
      b. Less surface area than other terrestrial vertebrates
      c. Connected to rear of oral cavity (pharynx)
      d. Opening controlled by glottis
   2. Breathing process different from other terrestrial vertebrates
      a. Force air into lungs by creating positive pressure outside lungs
      b. Fill buccal cavity with air, close mouth and nostrils
      c. Elevate floor of oral cavity
      d. Pushes air into lungs
      e. Analogous to mouth-to-mouth resuscitation in humans

3. Breathing process of other vertebrates
   a. Create negative pressure within lungs
   b. Expand thoracic cavity by contractions of muscles
4. Supplemental oxygen obtained by diffusion across moist skin, cutaneous respiration
   a. Skin is wet and well-vascularized
   b. More important in winter when metabolism is low

B. Reptiles
1. Expand rib cages, exhibit negative pressure breathing
2. Lungs have greater surface area
3. Cannot obtain oxygen through watertight skin surface

III. RESPIRATION IN MAMMALS

A. Greater Oxygen Demand in Mammals
1. Metabolic demands greater due to endothermy
2. Lungs more highly branched with alveoli clusters fig 53.9
3. Structure of mammalian lung
   a. Inhaled air brought in through larynx past glottis and vocal chords
   b. Enters cartilage-supported trachea
   c. Splits into right and left bronchi that enter lung
   d. Further subdivide into numerous, small bronchioles
   e. Bronchiole delivers air to blind-ended alveoli
   f. Alveoli surrounded by extensive capillary network
   g. All gas exchange occurs across walls of alveoli
4. Branching and alveoli vastly increase total surface area
   a. Humans have 300 million alveoli in two lungs
   b. Area about 42 times the surface area of body

IV. RESPIRATION IN BIRDS

A. Birds Possess a More Efficient Respiratory System
1. Birds possess parabronchi, tiny vessels through which air flows fig 53.10a
   a. Do not have blind-end alveoli like mammals
   b. Gas exchange occurs in parabronchi
2. Bird air flow is unidirectional like in fish
   a. Other terrestrial vertebrates mix new and old air
   b. Only fresh air enters bird parabronchi, old air exits by different route
3. Birds have two unique groups of air sacs fig 53.10b
   a. Anterior and posterior air sacs expand during inspiration
   b. Sacs compressed during expiration
   c. Air pushed into and through lungs
4. Avian respiration has two-cycles fig 53.10c
   a. Inspiration
      1) Both anterior and posterior air sacs expand
      2) Fresh air passes into only posterior air sacs
      3) Anterior air sacs fill with air from lungs
   b. Expiration
      1) Air from anterior sacs flows out of the body with exhalation
      2) Air in posterior sacs flows into lung
   c. Process repeated in second cycle
   d. Air flows through lungs in only one direction
   e. Air finally exhaled at end of second cycle

5. Direction of air flow is different from the flow of blood
    a. Flow of air and blood are at 90° angles to one another
    b. Called cross-current flow
    c. Less efficient than fish, more efficient than mammals
6. Birds can survive in much higher altitudes than mammals

53.4 Mammalian breathing is a dynamic process

I. STRUCTURES AND MECHANISMS OF BREATHING

A. The Structure of the Mammalian Lung
1. Inspired air travels through trachea, bronchi, and bronchioles
2. Bronchioles deliver air to alveoli where gas exchange occurs
    a. Lines by epithelium only one cell layer thick
    b. Alveoli are outpouchings surrounded by capillaries one cell layer thick
    c. Distance between air and blood is two cell layers, 0.5 to 1.5 μm
3. Partial pressures of gases in the lungs fig 53.11
    a. P_{O_2} of air in lungs normally about 100 mmHg
    b. P_{O_2} of blood is about 105 mmHg
    c. Returned blood has P_{O_2} of 40 mmHg
    d. Blood P_{CO_2} also changes
4. Outside of lungs covered by visceral pleural membrane
5. Inner wall of thoracic cavity lined by parietal pleural membrane
6. Space between membranes called the pleural cavity
    a. Normally small and filled with fluid
    b. Fluid links membranes together like water film holds two sheets of glass together
    c. Lungs held tight to thoracic cavity
    d. Each lung has own pleural cavity, if one punctured, other lung functional

B. Mechanics of Breathing
1. Air drawn into lung by formation of negative pressure
2. Relation to Boyle's Law of gasses
    a. Volume of gas increases, pressure decreases
    b. Volume of thorax increases with inspiration
    c. Lungs expand due to adherence of visceral and parietal pleural membranes
    d. Pressure is lower than atmospheric, air enters lungs
3. During inhalation or inspiration thoracic volume increases
    a. Rib external intercostal muscles contract raising the ribs
    b. Diaphragm contracts, lowers and flattens
    c. Increases volume of thorax
    d. Force deeper inspiration by contracting other thoracic muscles fig 53.12a
4. During exhalation or expiration
    a. Thorax and lungs resist distention, recoil when force subsides
    b. Expansion places structures under elastic tension
    c. Diaphragm and external intercostal muscles relax in unforced expiration
    d. Extra air can be forced out of lungs fig 53.12b
        1) Contraction of abdominal muscles
        2) Diaphragm pushed further up into thoracic cavity

C. Breathing Measurements
1. Tidal volume: Volume inspired and expired in a single breath
    a. About 500 ml of air
    b. Anatomical dead space: 150 ml within air passages
    c. Birds have no "dead volume" of air remaining in lungs as do mammals

2. Vital capacity: Amount of air expired after forceful, maximum inspiration
    a. Men = 4.6 liters, women = 3.1 liters
    b. Emphysema reduces vital capacity
    c. Alveoli destroyed by cigarette smoking
3. Normal breathing rates oxygenate blood, remove carbon dioxide
    a. P_{O_2} and P_{CO_2} kept within normal ranges
    b. Hypoventilation
        1) Breathing insufficient to maintain normal rates
        2) Elevated P_{CO_2} level
    c. Hyperventilation
        1) P_{CO_2} abnormally low
    d. Not equal to increased breathing associated with exercise
        1) Faster breathing matched to faster metabolism
        2) Blood gas measurements remain normal

II. MECHANISMS THAT REGULATE BREATHING

A. Breathing Initiated by Respiratory Control Center in Brain
1. Located in medulla oblongata
2. Sends nerve signals to diaphragm and intercostal muscles
    a. Stimulate muscles to contract
    b. Contraction and expansion of chest causes inspiration
    c. Expiration proceeds when neurons stop producing impulses
3. Breathing muscles are skeletal, but are under involuntary control
4. Can be voluntarily over-ridden in hypo- or hyperventilation

B. Reflex Pathway Prevents Life-Threatening Alterations in Breathing
1. Holding breath causes increase in blood P_{CO_2}
    a. Causes increase in carbonic acid, lowers blood pH
    b. Peripheral chemoreceptors in aortic and carotid bodies are sensitive to pH
    c. Send impulses to respiratory control center to reinitiate breathing
2. Central chemoreceptors detect changes in pH of cerebrospinal fluid (CSF) fig 53.13
3. Peripheral chemoreceptors are responsible for immediate changes
4. Central chemoreceptors are responsible for sustained changes
5. Increased respiratory rate eliminates excess CO_2, pH returns to normal fig 53.14
6. Indefinite hyperventilation also prevented by chemoreceptors
    a. Decrease in P_{CO_2} and increase in pH stop reflex drive to breathe
    b. Constrict cerebral blood vessels, cause dizziness
    c. Can hold breath longer by hyperventilating first
7. P_{O_2} is a stimulus for breathing only under special conditions
    a. At high altitudes where P_{O_2} is low
    b. In patients with emphysema

53.5 Blood transports oxygen and carbon dioxide

I. HEMOGLOBIN AND OXYGEN TRANSPORT

A. Association of Respiratory and Circulatory Systems
1. Oxygen dissolved in blood dependent on P_{O_2} of air
    a. Blood plasma can contain only 3 ml O_2/liter
    b. Whole blood contains nearly 200 ml O_2/liter
    c. Most oxygen bound to hemoglobin inside red blood cells

2. Hemoglobin: Oxygen carrier protein within the blood of most animals
    a. Four polypeptide subunit protein
    b. Each subunit combines with iron containing heme group fig 53.15
    c. Hemoglobin picks up oxygen in lungs
        1) Bright red color when bound with oxygen
        2) Called oxyhemoglobin
    d. Hemoglobin releases oxygen at tissues
        1) Called deoxyhemoglobin
        2) Dark red color, looks blue under skin
    e. Hemoglobin widely distributed oxygen carrier protein throughout animal kingdom
3. Hemocyanin: Second carrier protein found in many invertebrates
    a. Uses copper instead of iron
    b. Does not occur within blood cells, exists free in hemolymph

B. Oxygen Transport
1. At sea level, P_{O_2} is 105 mmHg
    a. Less than that of atmosphere due to mixing of old air in anatomical dead space
    b. Blood leaving alveoli slightly less due to inefficiency in lung function
2. At P_{O_2} of 100 mmHg, 97% bound to hemoglobin in red blood cells
3. Percent saturation in arterial blood is 97% at sea level
4. Extracellular fluid surrounding tissues has lower P_{O_2}
    a. Oxygen diffuses from capillaries into tissues
    b. P_{O_2} of venous blood is 40 mmHg, percent saturation is 75%
5. Graphical representation is an oxyhemoglobin dissociation curve fig 53.16
    a. At rest, 22% (97-75) of the oxyhemoglobin releases oxygen to tissues
    b. One fifth of oxygen unloaded in tissues, four-fifths in blood as reserve
        1) Blood can additionally supply oxygen needs at exercise
            a) If venous blood P_{O_2} is 20 mmHg, saturation is 35%
            b) Amount unloaded now 62% (97-35)
        2) Blood contains reserves for 4-5 minutes without breathing
6. Presence of CO_2 at metabolizing tissues
    a. Combines with water to form bicarbonate and H^+, lowers pH of blood
    b. Occurs in red blood cells, hemoglobin has less affinity for oxygen
    c. Hemoglobin releases oxygen more readily
    d. Dissociation curve shifted to right, called Bohr effect fig 53.17a
    e. Increasing temperature has similar effect on hemoglobin oxygen affinity
        1) Skeletal muscles produce CO_2 more rapidly during exercise
        2) Active muscles also produce heat
        3) Blood unloads greater amount of oxygen during exercise

II. CARBON DIOXIDE AND NITRIC OXIDE TRANSPORT

A. Carbon Dioxide Transport
1. As red blood cells unload oxygen, blood absorbs CO_2 from tissues fig 53.18
    a. 8% dissolved in plasma, 20% binds to hemoglobin
    b. 72% enters red blood cells
        1) Carbonic anhydrase catalyzes formation of carbonic acid (H_2CO_3)
        2) Carbonic acid dissociates to form bicarbonate (HCO_3^-) and hydrogen ions (H^+)
        3) H^+ binds to deoxyhemoglobin, bicarbonate moves into plasma
        4) Chloride ion exchanged for bicarbonate ion (chloride shift)
        5) CO_2 removed from plasma, allows loading of greater amounts
        6) Bicarbonate serves as major buffer in blood plasma

2. Blood carries CO_2 back to lungs
3. Lower P_{CO_2} of air in alveoli
    a. Carbonic anhydrase reaction proceeds in reverse
    b. Gaseous CO_2 released, diffuses into alveoli
    c. Leaves body with next exhalation fig 53.19

B. Nitric Oxide Transport
  1. Hemoglobin also holds and releases nitric oxide gas (NO)
  2. Important regulatory gas acts on many cells to change shapes and functions
      a. Presence of NO in blood vessels causes them to expand
      b. Relaxes surrounding muscle cells
      c. Blood flow and pressure regulated by NO in bloodstream
  3. Hemoglobin carries NO as super nitric oxide, has extra electron
      a. Binds to cysteine amino acid
      b. Blood picks up super nitric oxide in lungs along with oxygen
  4. At body capillaries, O_2/CO_2 gas exchange occurs
      a. Hemoglobin release of NO can increase blood flow, blood vessels expand
      b. Hemoglobin traps excess NO on empty iron atoms, causes vessels to constrict
  5. Blood returns to lungs to release CO_2 and regular NO bound to iron atoms in hemoglobin
  6. Picks up O_2 and super NO to continue cycle

INSTRUCTIONAL STRATEGY

PRESENTATION ASSISTANCE:

Compare the countercurrent analogy with a heat pump. If very cold air meets very warm air a lot of exchange will occur, but only over a short distance.

Discuss the mammal diving reflex and its effects on children accidentally submerged in cold water.

Very active fish (*i.e.* trout) require large amounts of oxygen and live in cold moving water. Other fish have adapted to water low in oxygen by reducing metabolism (catfish) or by evolving special labyrinth organs (*Bettas*).

Many aquatic turtles significantly increase the time that they can remain submerged by utilizing cloacal respiration. Oxygen in the water diffuses across the cloacal membrane, similar to cutaneous respiration in amphibians and sea snakes.

Discuss why birds need the most efficient respiratory systems, especially with regard to their body metabolism and flight altitude.

VISUAL RESOURCES:

Make a super inexpensive model lung using a balloon and an empty 1 or 2 liter plastic bottle. Depress the bottle slightly, place the balloon inside the stem of the bottle (but don't drop it!). It takes a little dexterity to get the lip of the balloon on the stem of the bottle, but it is possible. When the bottle is released the lung balloon will inflate, when the bottle is depressed it will deflate. This model best exemplifies a garter snake system. They have only a single functional lung in their elongate bodies, the other lung is a mere bubble at the end of the bronchus.

Compare the volume of walnuts versus smaller hazelnuts in a jar. Similarly an animal with smaller, more numerous alveoli has a greater lung volume than one with few, large alveoli.

Several biological supply companies sell a respiratory model that uses a specially prepared actual cow lung. It is elastic enough that it can be expanded and deflated by breathing into and out of it.