

## The Evolution of Circulatory and Respiratory Systems

1. Exchanging materials with the environment is a characteristic of all living things.
  - a. Cells live in an aqueous environment and the resources they need, like nutrients and oxygen, move across the cell membrane into the cytoplasm and wastes, such as carbon dioxide, move out of the cell.
  - b. In unicellular organisms (like bacteria and most protists) this exchange happens directly with the external environment because the organisms are very small. They have no need for circulatory and respiratory systems.
  - c. In large, multicellular organisms, this is not possible because all cells are not in contact with the external environment. Such organisms are only possible because of the evolution of systems to allow the transport of materials to all cells.
    - i. Some large, multicellular organisms like fungi are relatively simple and have no need for circulatory or respiratory systems.
  - d. Complex systems are required to ensure that all cells get required nutrients and can rid themselves of wastes.
    - i. Diffusion is too slow to be effective over distances greater than a few millimeters.
    - ii. Circulatory systems solve this problem by circulating fluid throughout the body to all cells.
      - (1) For example, in your lungs, oxygen in the air you inhale diffuses into your blood, while carbon dioxide diffuses out of your blood into the air in your lungs.
      - (2) Your heart then pushes blood throughout your circulatory system to all cells in your body.
      - (3) As the blood comes into contact with cells, materials diffuse between the blood and the cells.
2. Circulation and transport in plants.
  - a. The ancestors of plants absorbed water, nutrients and carbon dioxide directly from the water surrounding them. Because they were small, all cells were close enough to water that diffusion was sufficient to transport materials. Even large plant-like protists (*i.e.*, seaweeds) are surrounded by water and nutrients so most cells can just absorb them from the environment.
  - b. **Non-vascular** plants (*e.g.*, mosses) have no system for transporting water or nutrients. This limits the size these plants can attain.
  - c. Many **vascular** plants are terrestrial and so require a system through which they can transport water and nutrients throughout the plant. Roots absorb water and nutrients from the soil while shoots and leaves absorb carbon dioxide from the atmosphere. These systems allowed the plants to be taller and live further from water.
    - i. Water and minerals from the roots can travel to all parts of the plant and food made in the leaves can travel to nonphotosynthetic parts of the plant.

- ii. The **Vascular tissue** conducts materials throughout plant.
  - (1) **Xylem**
    - (a) Dead at maturity, the hard walls provide support for the plant
    - (b) The hollow cells form a continuous channel through the plant from the roots to the leaves and conduct water and minerals upward from the roots.
  - (2) **Phloem**
    - (a) Carry sugar from where it is made to nonphotosynthetic parts of the plant.
    - (b) These cells are softer than xylem and are living at maturity.
- iii. Transpiration is the loss of water from the leaves of plants. Openings in the leaves called **stomata** allow passage of gases for photosynthesis but can be closed when it is too warm.
  - (1) **Cohesion** is the property of water molecules to be attracted to one another. As water molecules move, they pull on neighboring molecules. This creates a continuous chain of water molecules from the tips of the roots to each stomata in the leaves.
  - (2) The majority of water taken up by roots is lost to the air through the stomata in form of water vapor. Water moving into the mesophyll cells pulls water from leaf veins. These water molecules are replaced by those moving from the stem, which are, in turn, replaced by molecules absorbed by the roots. In order to perform photosynthesis, plants must have continual source of water.
  - (3) In plants, this pulling of water molecules on other water molecules by cohesion is called the **transpiration-cohesion-tension** theory of how water moves up a plant.
- iv. Absorption of water by roots
  - (1) Most water enters through root hairs.
  - (2) The solutes in root hairs maintain the movement of water into the roots by osmosis. This is called **root pressure**. Transpiration-cohesion-tension then keeps the water moving upward through the plant.
  - (3) Remember that the solutes in the roots are taken up by active transport.
- v. **Translocation** is the movement of food from one part of the plant to another. It is described by the **pressure-flow** hypothesis.
  - (1) Sugar is loaded into phloem of leaf veins by active transport. Water follows by osmosis, increasing the pressure in the phloem tube.
  - (2) The pressure pushes the sugar solution through the phloem. As more sugar is loaded in and more water enters, the process continues.
  - (3) As the solution moves throughout the plant, cells that need the sugar remove it from the phloem. Water moves out by osmosis. This makes space for more solution to flow to those cells.
    - (a) Loading and unloading the sugar requires energy but the movement of the solution is passive.
    - (b) The result is that the sugar made by photosynthesis moves throughout the plant from where it is made (the **source**) to where it is stored or used (the **sink**).

- (c) The sugar can be used as energy by cells or can be stored. In the spring, trees begin moving sugar from the roots back up to the shoot system as energy until leaves develop.

3. Circulation and transport in animals.

- a. Invertebrate organisms show a variety of circulatory systems.
  - i. Cnidarians have a simple body plan that does not require a circulatory system. Their digestive system also serves as a circulatory system.
    - (1) A simple body cavity is filled with fluid that is in direct contact with the external environment through an opening in the cavity that serves as both mouth and anus.
    - (2) Thin branches of this cavity extend into the body and tentacles to facilitate the distribution of materials throughout the animal.
    - (3) Nutrients reach all cells by diffusion from these branches.
  - ii. Animals in Phylum Platyhelminthes have a cavity that is highly branched and nutrients and wastes enter and leave cells by diffusion.
- b. More complex animals have many cell layers and are generally larger so diffusion is not sufficient. Basically a circulatory system is circulatory fluid (blood), a group of tubes (blood vessels) and a pump to move the fluid around (a heart). The circulatory fluid carries nutrients and oxygen to cells and carries wastes and carbon dioxide away. Animals display two types of circulatory systems:
  - i. Arthropods and most molluscs have an **open** circulatory system (the cephalopods, like squids and octopuses, are exceptions). In such a system, organs are directly bathed in blood as it circulates freely in the body cavity. The heart circulates blood around the body cavity and through a limited system of tubes.
  - ii. Animals other than arthropods and molluscs (*i.e.*, annelids, some molluscs and all vertebrates) have a **closed** circulatory system. In a closed system blood is contained within blood vessels that branch into smaller and smaller vessels to distribute blood to all cells of the body. Molecules diffuse through the walls of the blood vessels.
- c. Vertebrate hearts contain muscular chambers called **atria** (singular, atrium) and **ventricles**.
  - i. Each atrium receives blood that is returning to the heart. When it contracts, blood is pumped into the ventricle. When a ventricle contracts, blood is pumped away from the heart to the body, lungs, or gills.
  - ii. Vertebrate circulatory systems and hearts display a trend of increasing complexity.
    - (1) Fish have a **two-chambered heart** with one atrium and one ventricle.
      - (a) Blood is pumped from the ventricle first to the gills (**gill circulation**) to absorb oxygen and dispose of carbon dioxide. The blood then travels to all other parts of the body (**systemic circulation**). Blood then returns to the atrium of the heart.
      - (b) The gills contain many capillaries for gas exchange, so the blood pressure is low after going through the gills. Low-pressure blood from the gills then goes directly to the body, which also has a large number of capillaries.
      - (c) This constraint on blood flow limits the amount of oxygen delivered to body tissues and, therefore, the activity level of fish.

- (2) Amphibians have a **three-chambered heart** with two atria and one ventricle.
    - (a) The ventricle pumps blood into a forked vessel that sends some blood to the lungs and skin and some to the body tissues. The blood to the lungs and skin picks up O<sub>2</sub> and releases CO<sub>2</sub> before returning to the left atrium of the heart. The blood in the systemic circuit returns to the right atrium of the heart.
    - (b) Both atria empty into the ventricle where there is mixing of oxygen-rich blood returning from the lungs and skin and oxygen-poor blood returning from the rest of the body.
    - (c) This **double circulation** has the advantage of increasing blood flow to the body tissues because the blood is pumped a second time after it loses pressure in the lungs and skin.
  - (3) Reptiles, like amphibians, have double circulation.
    - (a) Most reptiles have a three chambered-heart but the ventricle is partially divided by a thin wall of tissue which decreases the mixing of oxygen-rich and oxygen-poor blood. (Note that in crocodilians, the ventricle is completely separated into left and right chambers.)
    - (b) Reptiles have two arteries leading from the heart with special valves to allow them to divert most of the blood from the pulmonary circuit to the systemic circuit.
  - (4) In birds and mammals (also crocodilians) the ventricle is completely divided into four separate chambers. This **four-chambered heart** acts as two separate pumps.
    - (a) The left side receives and pumps only oxygen-rich blood while the right side receives and pumps only oxygen-poor blood.
    - (b) After passing through the body, blood is pumped under high pressure to the lungs. Upon returning from the lungs, it is pumped under high pressure to the body.
    - (c) The high rate of oxygen-rich blood flow through the body enables birds and mammals to maintain high activity levels. Also, the mixing of oxygenated and deoxygenated blood is prevented.
    - (d) The increased efficiency of the four-chambered heart permitted birds and mammals to become endotherms. The oxygen demand of providing the energy necessary to maintain a relatively high body temperature could not be met by an open circulatory system or a heart that permits mixing of blood.
4. Gas exchange occurs across specialized respiratory surfaces.
- a. Gas exchange is the uptake of oxygen and the release of carbon dioxide. This exchange is necessary because the process that cells use to produce energy (cellular respiration) requires oxygen and produces carbon dioxide. Do not confuse the process of producing energy (cellular respiration) with the process of gas exchange (respiration, or breathing).
  - b. The source of the oxygen is called the **respiratory medium** is air for terrestrial organisms and water for aquatic organisms. The atmosphere is about 21% oxygen and water contains oxygen dissolved in it.
  - c. The part of an animal's body where gas exchange occurs is called the **respiratory surface**. Gases move across membranes by diffusion. The amount of gas exchange by diffusion is

proportional to the surface area of the respiratory surface but inversely proportional to the distance the gases must travel. Because of this, respiratory surfaces are thin and have very large surface areas. Remember that all cells live in water so the respiratory surface, which is made of cells, must also be kept moist at all times.

- d. Diffusion is driven by the difference in oxygen concentration between the interior of the organism and the external environment so a concentration gradient must be maintained.
  - e. Gases are distributed throughout the organism by the circulatory system.
5. A trend of increasing complexity can be seen in the respiratory systems of organisms.
- a. We've learned that diffusion is too slow to be efficient over more than about 0.5 mm, which limits the size of cells and of organisms.
  - b. Bacteria and protists are very simple and small enough to utilize simple diffusion but as size increases, surface area to volume ratio decreases. For organisms to be larger, a better method of getting oxygen is necessary.
  - c. Most primitive phyla possess no special respiratory organs but get oxygen by creating a water current to constantly replace water over the respiratory surface.
  - d. More advanced invertebrates and vertebrates possess respiratory organs with an increased surface area over which diffusion occurs. This system provides contact between the external environment and internal circulating fluids (like blood). A larger surface area enables organisms to get more oxygen from the environment.
    - i. Some animals (like earthworms) use their entire outer surface as a respiratory surface. They keep their skin moist to facilitate gas exchange. This is sufficient for a long, slender animal like an earthworm but would not provide enough exchange for larger animals.
    - ii. Gills provide a respiratory surface for aquatic animals.
      - (1) Gills are folded body tissue that provide a large surface area.
      - (2) Because water doesn't contain very much dissolved oxygen, it is necessary to keep water circulating over the gills.
        - (a) The disadvantage of external gills is that it is difficult to constantly circulate water past the diffusion surface because the highly branched gills resist water movement.
        - (b) Internal gills are more efficient because water can flow over the gills.
      - (3) Water passes through the mouth into two cavities containing the gills.
      - (4) Water then passes out of the body after passing over the gills and through the cavity. This is a one way flow of water over the gills.
    - iii. Insects use a tracheal system made up of tubes that branch throughout the body.
      - (1) The tubes are open to the outside. The tubes branch smaller and smaller to reach nearly every cell in the body. The smallest tubes are close enough to cells for diffusion to be adequate for gas exchange.
    - iv. Lungs provide a respiratory surface for terrestrial animals.
      - (1) Gills are not useful for terrestrial animals because they consist of fine filaments which would clump together if not surrounded by water. This would drastically decrease the surface area.
      - (2) Terrestrial organisms constantly lose water to the atmosphere, making gills a huge surface area for water loss.
      - (3) Instead, the respiratory surface is kept inside the body and is exposed to the external environment only through narrow tubes.
      - (4) For animals that have lungs, the tubes inside lungs do not reach all cells of

the body so a circulatory system is necessary to distribute the gases. Lungs have tiny tubes inside them to provide the large surface area required for an efficient respiratory surface.

- (5) Gills are not possible for the part of the amphibian life cycle spent out of water. They have simple lungs instead (some of no lungs at all).
  - (a) These simple lungs do not provide a very large surface area. The poor efficiency is offset by the high concentration of oxygen in the air compared to that in water.
  - (b) The amphibian skin is moist and serves as an additional respiratory surface.
  - (c) This limitation on gas exchange limits amphibians to being small, relatively inactive and ectothermic.
- (6) The fully terrestrial lifestyle of most reptiles makes keeping the skin moist impossible so an alternative to diffusion through the skin is required.
  - (a) Reptiles are generally somewhat more active than amphibians so they have a greater need for oxygen.
  - (b) Reptilian lungs are more developed to provide a larger surface area for gas exchange.
- (7) Birds and mammals have a high activity level and they are endothermic so require a large amount of oxygen.