The Need for Gas Exchange

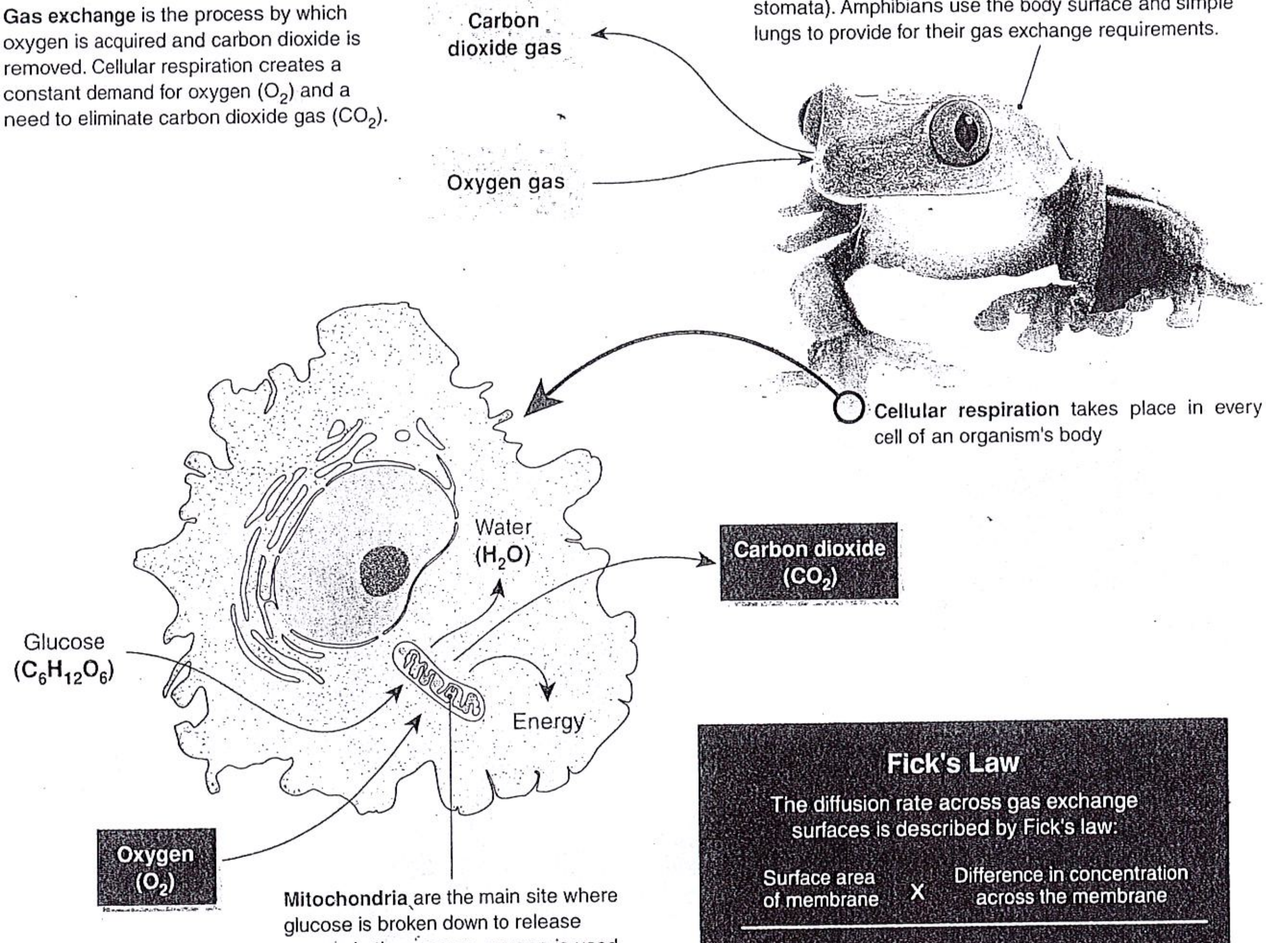
Name: Answer Key

Living cells require energy for the activities of life. Energy is released in cells by the breakdown of sugars and other substances in the metabolic process called **cellular respiration**. As a consequence of this process, gases need to be exchanged (by **diffusion**) between the respiring cells and the environment. In most organisms these gases are carbon dioxide and oxygen. The diagram below illustrates this for an animal. Plant cells also respire, but their gas exchange budget is different because they consume CO_2 and produce O_2 in photosynthesis. Effective gas exchange surfaces are thin so that the barrier they present to diffusion is minimized. Diffusion gradients are maintained by transport of gases away from the gas exchange surface.

The Need for Gas Exchange

Gas exchange is the process by which oxygen is acquired and carbon dioxide is removed. Cellular respiration creates a constant demand for oxygen (O_2) and a need to eliminate carbon dioxide gas (CO_2).

Gas exchange surfaces provide a means for gases to enter and leave the body. Some organisms use the body surface as the sole gas exchange surface, but many have specialized gas exchange structures (e.g. lungs, gills, or stomata). Amphibians use the body surface and simple lungs to provide for their gas exchange requirements.



Cellular respiration takes place in every cell of an organism's body

Mitochondria are the main site where glucose is broken down to release energy. In the process, oxygen is used to make water and carbon dioxide is released as a waste product.

Fick's Law

The diffusion rate across gas exchange surfaces is described by Fick's law:

$$\frac{\text{Surface area of membrane} \times \text{Difference in concentration across the membrane}}{\text{Thickness of the membrane}}$$

1. Distinguish between cellular respiration and gas exchange: Cellular respiration refers to the production of ATP through the oxidation of glucose. Gas exchange refers to the way in which O_2 and CO_2 are exchanged with the environment.

2. (a) What gases are involved in cellular respiration? Oxygen is required. CO_2 is a waste.

   (b) By which transport process do these gases move? Diffusion.

3. What is the main function of a gas exchange surface? Provides an area that maximizes the exchange of O_2 and CO_2.

4. Describe the three properties that all gas exchange surfaces have in common and state the significance of each:

   (a) Moist surface, so that gases can dissolve and diffuse across.

   (b) Large surface area, so that adequate gas exchange can occur.

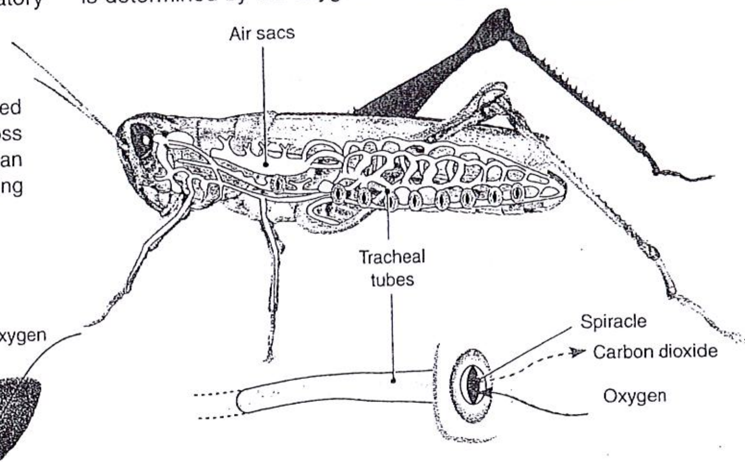
   (c) Thin membrane, so that gases can exchange and diffuse readily.

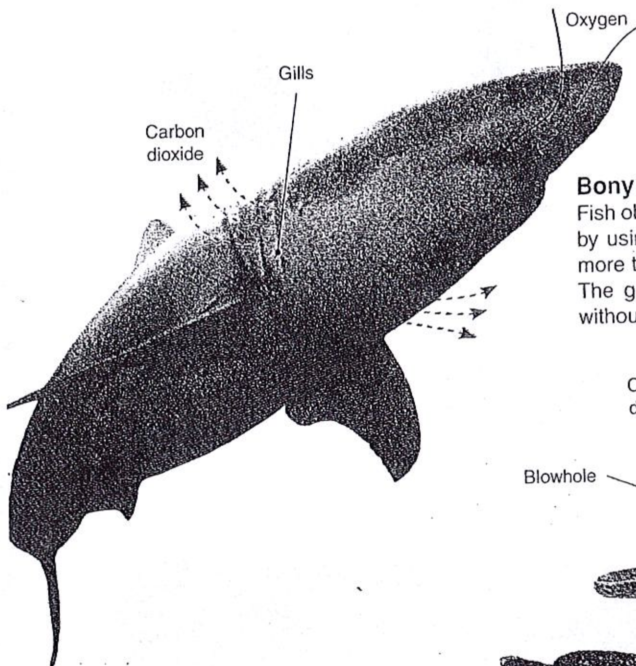
Gas Exchange in Animals

The way an animal exchanges gases with its environment is influenced by the animal's general body form and by the environment in which the animal lives. Small, aquatic organisms, such as sponges and flatworms, require no specialized respiratory structures, but larger animals need more complex exchange systems to support their metabolic activities. The complexity of these is related to the efficiency of gas exchange required. This is determined by the oxygen demands of the organism.

Gas exchange in insects

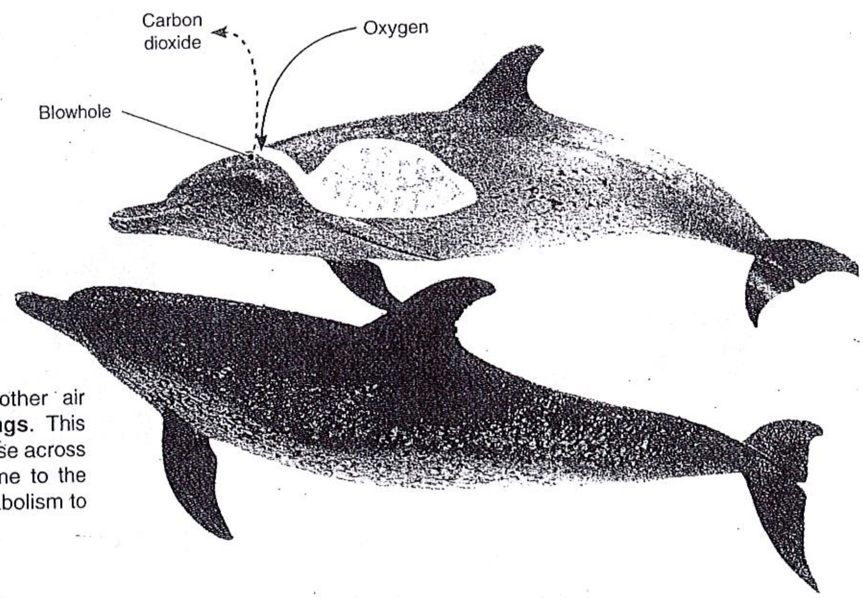
Insects transport gases via a system of branching tubes called **tracheae** (or tracheal tubes). The gases move by diffusion across the moist lining directly to and from the tissues. Larger insects can increase the air moving in and out of these tubes by contracting and expanding the abdomen.





Bony fish, sharks, and rays

Fish obtain oxygen dissolved in water which they extract by using **gills**. Gills can achieve 80% extraction rates; more than three times the rate of human lungs from air. The gills can be exposed directly to the environment without fear of the gas exchange membrane drying out.



Air breathing vertebrates

The gas exchange surface in mammals and other air breathing vertebrates is located in internal **lungs**. This keeps the membrane moist, so that gases can diffuse across it. Marine mammals have lungs and need to come to the surface to breathe. Many have modified their metabolism to allow long duration dives.

1. Describe two reasons for the development of gas exchange structures and systems in animals:

   (a) Provides adequate supply of O_2 for a metabolically active lifestyle.

   (b) Enables animals to attain a larger size and more complex body.

2. Describe two ways in which air breathers manage to keep their gas exchange surfaces moist:

   (a) Produce mucus to help keep surfaces moist.

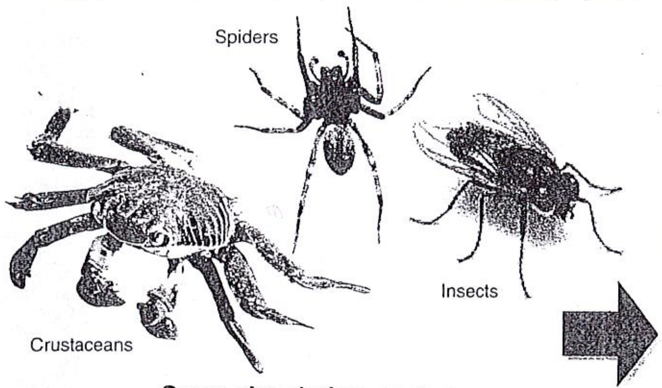
   (b) Water vapor is present in lungs.

3. Explain why gills would not work in a terrestrial environment: The gill filaments would collapse and stick together and they would dry out, no protection or mechanisms to keep them moist.

4. Explain why mammals must ventilate their lungs (breathe in and out): To constantly bring in fresh, oxygenated air.

Open Circulatory Systems

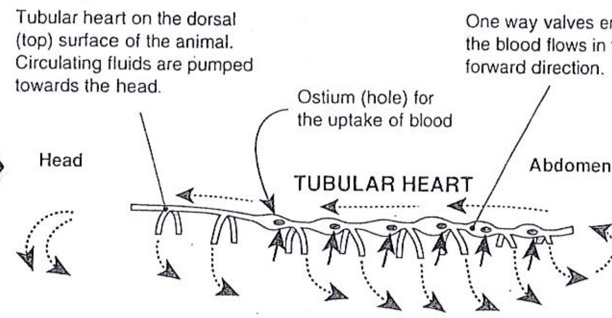
Two basic types of circulatory systems have evolved in animals. Many invertebrates have an **open circulatory system**, while vertebrates have a **closed circulatory system**, consisting of a heart and a network of tube-like vessels. The circulatory systems of arthropods are open but varied in complexity. Insects, unlike most other arthropods, do not use a circulatory system to transport oxygen, which is delivered directly to the tissues via the system of tracheal tubes. In addition to its usual transport functions, the circulatory system may also be important in hydraulic movements of the whole body (as in many mollusks) or its component parts (e.g. newly emerged butterflies expand their wings through hydraulic pressure).



Open circulation systems

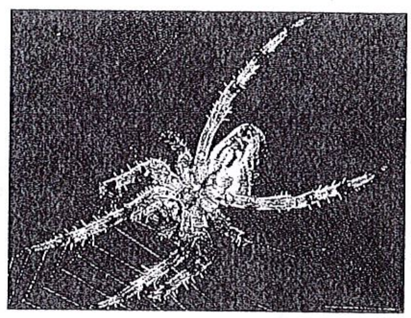
Arthropods and mollusks (except cephalopods) have open circulatory systems in which the blood is pumped by a tubular, or sac-like, heart through short vessels into large spaces in the body cavity. The blood bathes the cells before reentering the heart through holes (**ostia**). Muscle action may assist the circulation of the blood.

Open Circulatory System

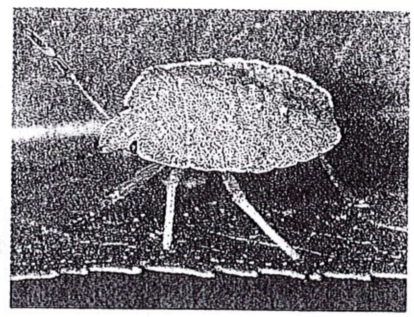


Body fluids flow freely within the body cavity

The circulatory system of crabs is best described as incompletely closed. The thoracic heart has three pairs of ostia a number of arteries, which leave the heart and branch extensively to supply various organs before draining into discrete channel-like sinuses.



In spiders, arteries from the dorsal heart empty the hemolymph into tissue spaces and then into a large ventral sinus that bathes the book lungs where gas exchange takes place. Venous channels conduct the hemolymph back to the heart.



The hemolymph occupies up to 40% of the body mass of an insect and is usually under low pressure due its lack of confinement in vessels. The circulation of the hemolymph is aided by body movements such as the ventilating movements of the abdomen.

1. Explain how an open circulatory system moves fluid (hemolymph) about the body: The blood is pumped by a tubular heart through short vessels into large spaces in the body cavity. The blood bathes the cells before reentering the heart.

2. Explain why arthropods do not bleed in a similar way to vertebrates: Blood is not contained in blood vessels like vertebrates, fluid will leak from any damage to the body.

3. Compare insects and decapod crustaceans (e.g. crabs) in the degree to which the circulatory system is closed: The crab system is more closed. The crab system is "incompletely closed". It has a number of vessels that branch extensively to supply organs.

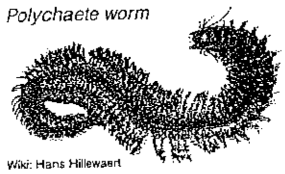
4. (a) Explain why the crab's circulatory system is usually described as an open system: The blood is pumped and bathes organs before draining into openings called sinuses.

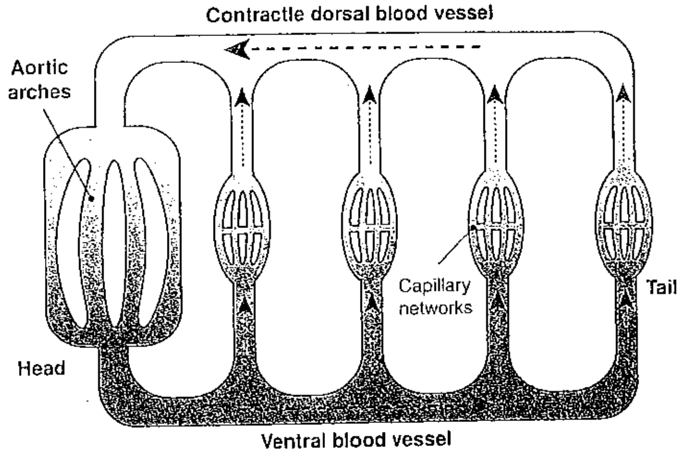
   (b) ~~Explain in what~~ way this description is not entirely accurate: The heart does push blood into blood vessels that deliver the blood to various organs.

Closed Circulatory Systems

Closed circulatory systems are used by vertebrates, annelids (earthworms) and cephalopods (octopus and squid). The blood is pumped by a heart through a series of arteries and veins. Oxygen is transported around the body by the blood and diffuses through capillary walls into the body cells. Closed circulatory systems are useful for large, active animals where oxygen can not easily be transported to the interior of the body. They also allow the animal more control over the distribution of blood flow by contracting or dilating blood vessels. Closed systems are the most developed in vertebrates where a chambered heart pumps the blood into blood vessels at high pressure. The system can also be divided into two separate regions, the pulmonary region taking up oxygen and the systematic region pumping oxygenated blood to the rest of the body.

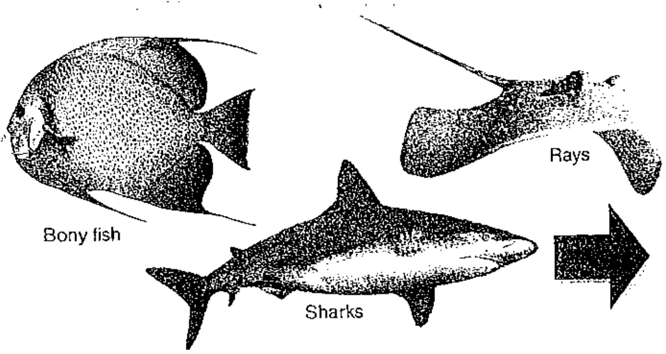
INVERTEBRATE CLOSED SYSTEMS

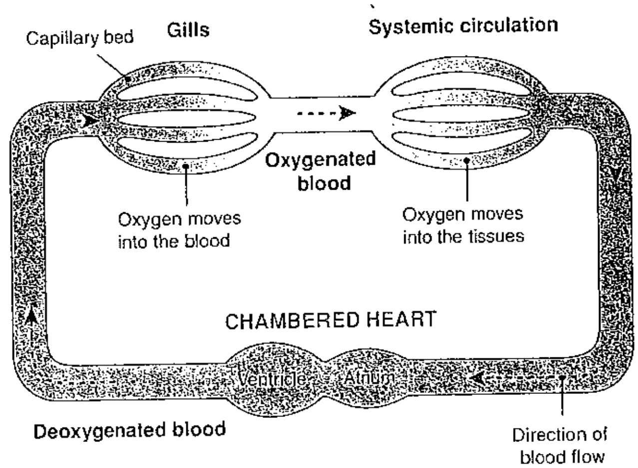




The closed systems of many annelids (e.g. earthworms) circulate blood through a series of vessels before returning it to the heart. In annelids, the dorsal and ventral blood vessels are connected by lateral vessels in every segment (right). The dorsal vessel receives blood from the lateral vessels and carries it towards the head. The ventral vessel carries blood posteriorly and distributes it to the segmental vessels. The dorsal vessel is contractile and is the main method of propelling the blood, but there are also several contractile aortic arches ('hearts') which act as accessory organs for blood propulsion.

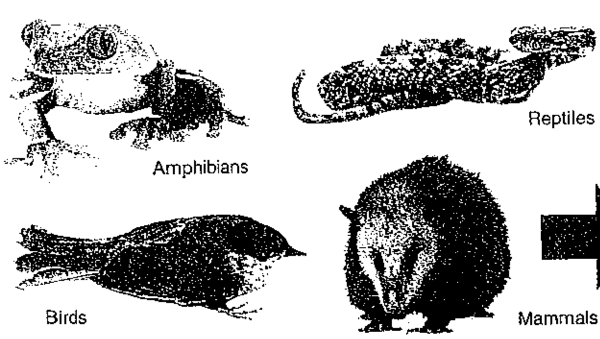
VERTEBRATE CLOSED SYSTEMS

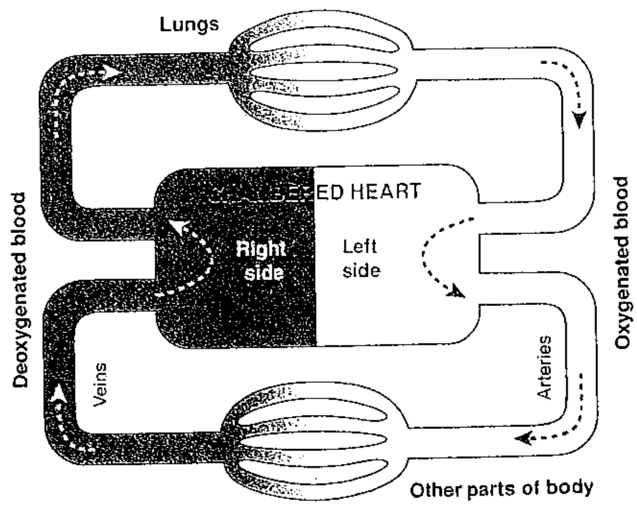




Closed, single circuit systems

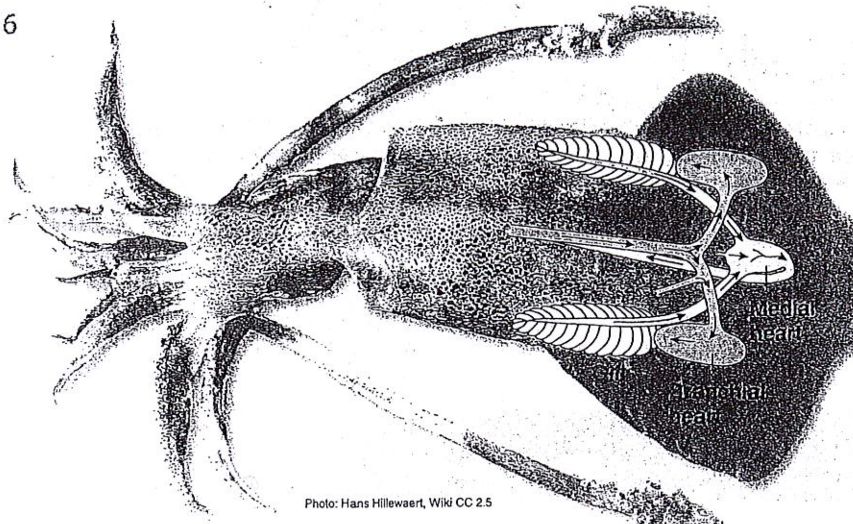
In closed circulation systems, the blood is contained within vessels and is returned to the heart after every circulation of the body. Exchanges between the blood and the fluids bathing the cells occurs by diffusion across capillaries. In single circuit systems, typical of fish, the blood goes directly from the gills to the body. The blood loses pressure at the gills and flows at low pressure around the body.





Closed, double circuit systems

Double circulation systems occur in all vertebrates other than fish. The blood is pumped through a pulmonary circuit to the lungs, where it is oxygenated. The blood returns to the heart, which pumps the oxygenated blood, through a systemic circuit, to the body. In amphibians and most reptiles, the heart is not completely divided and there is some mixing of oxygenated and deoxygenated blood. In birds and mammals, the heart is fully divided and there is no mixing.



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Cephalopod Mollusks: High Performing Invertebrates

The circulatory system is largely closed in all cephalopod mollusks (nautilus, cuttlefish, squid, and octopus). It has an extensive system of vessels making it the most complex and efficient system of all the mollusks, and enables cephalopods to be active, intelligent predators.

The circulatory system consists of one systemic heart, two branchial hearts, and blood vessels. The branchial hearts, which sit at the gill base, collect deoxygenated blood from all the body parts and direct it through the gills. The blood returns to the medial systemic heart and is pumped to the body via an anterior and posterior aorta, through smaller vessels and into tissue capillaries.

1. Describe the main difference between closed and open systems of circulation: In a closed system, the blood circulates through a system of complete and closed/connected blood vessels.

2. Describe where the blood flows to immediately after it has passed through the gills in a fish: After passing through the gills ~~body~~ blood immediately goes to the body.

3. Describe where the blood flows immediately after it has passed through the lungs in a mammal: The blood returns to the heart and is then pumped to the body.

4. Explain the higher functional efficiency of a double circuit system, relative to a single circuit system: In a double circuit system, the blood can be pumped to the body at higher pressure and velocity.

5. Hearts range from being simple contractile structures to complex chambered organs. Describe basic heart structure in:

   (a) Fish: One atrium to receive blood, one ventricle to pump blood.

   (b) Mammals: 4 total chambers. Right atrium receives blood from body, right ventricle pumps to lungs; left atrium receives from lungs, left ventricle pumps to body.

6. Explain how a closed circulatory system gives an animal finer control over the distribution of blood to tissues and organs: It can direct and adjust the flow and amount of blood going to particular locations/organs.

7. Compare and contrast a vertebrate closed circulatory system with the circulatory system of an annelid: Vertebrate systems use a single heart with chambers to pump blood, the annelid system uses a contractile dorsal vessels and aortic arches to pump blood.

8. "*Comparisons of the circulatory systems of insects, decapods (e.g. crabs), annelids, and cephalopod mollusks indicates that there is a gradient between fully open and fully closed circulatory systems*". Discuss this statement:

   In insects the system is very open, in crabs the system has become mostly closed and directed to organs, in annelids the system is completely closed with contractile vessels to move blood, and finally in cephalopods which have hearts to pump blood to the gills and a heart to pump blood to the body.