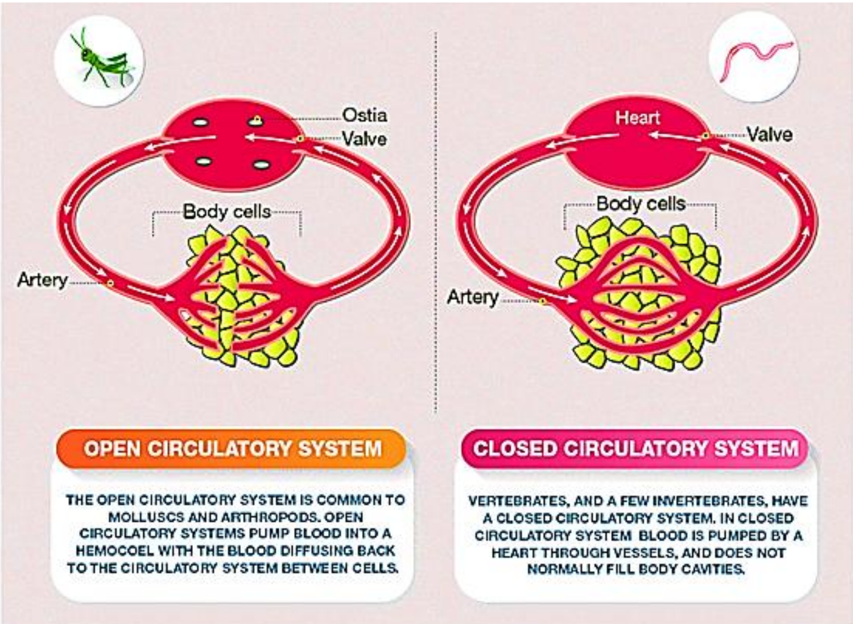
MJC 3 (Comparative Anatomy)
Heart and Aortic arches

Circulation, the process by which nutrients, respiratory gases, and metabolic products are transported throughout a living organism, permitting integration among the various tissues. The process includes the intake of metabolic materials, the conveyance of these materials throughout the organism, and the return of harmful by-products to the environment.
Invertebrate animals have a great variety of liquids, cells, and modes of circulation, though many invertebrates have what is called an open system, in which fluid passes more or less freely throughout the tissues or defined areas of tissue. All vertebrates, however, have a closed system—that is, their circulatory system transmits fluid through an intricate network of vessels. This system contains two fluids, blood and lymph, and functions by means of two interacting modes of circulation, the cardiovascular system and the lymphatic system; both the fluid components and the vessels through which they flow reach their greatest elaboration and specialization in the mammalian systems and, particularly, in the human body.

Types of Circulation:
Protoplasmic streaming also called, cytoplasmic streaming is the movement of the fluid substance (cytoplasm) within a plant or animal cell. Although the mechanism of cytoplasmic streaming is not completely understood, it is thought to be mediated by "motor" proteins—molecules made up of two proteins that use adenosine triphosphate (ATP) to move one protein in relation to the other. If one of the proteins remains fixed on a substrate, such as a microfilament or a microtubule, the motor proteins can move organelles and other molecules through the cytoplasm. Motor proteins often consist of actin filaments, long protein fibres aligned in rows parallel to the streaming just inside the cell membrane. Myosin molecules attached to cellular organelles move along the actin fibres, towing the organelles and sweeping other cytoplasmic contents in the same direction.

Types of Circulatory Systems
1. Open circulatory system
Invertebrates have an open circulatory system. The system is called "open" because blood flows freely within the body cavity and makes direct contact with organs and tissues. In other words, there is no distinction between the blood and the interstitial fluid. In invertebrates, such as insects and crustaceans, the mixture of blood and fluids that surrounds the cells is called hemolymph. In an insect such as the grasshopper, hemolymph is pumped through a single vessel that runs from the head to the abdomen. In the abdomen, the vessel divides into chambers that function as the insect's heart. Tiny

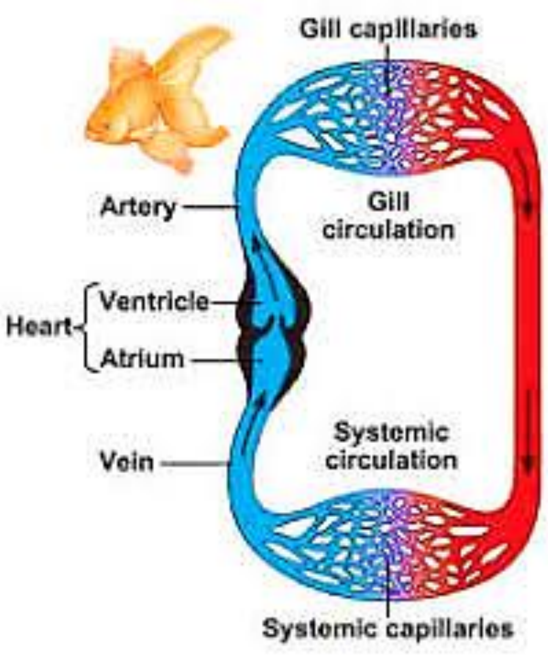


holes in the heart wall, known as ostia, allow hemolymph to enter the heart chambers from the body cavity. The hemolymph is pushed from one chamber to the next by muscle contractions. Nutrients and wastes are exchanged between the hemolymph and cells in the heart chambers before the hemolymph passes back into the transporting vessel to be eliminated from the insect's body.

2. Closed circulatory system

Closed circulatory system, meaning the blood is repeatedly cycled throughout the body inside a system of pipes. The animals, such as all vertebrates, earthworms, squid, and octopus, need a system to circulate the blood, keep it under pressure, and pump it at a speed sufficient to supply the metabolic needs of all parts of the body. This type of system, called a closed circulatory system, keeps the blood physically contained within vessels and separate from other body tissues. The blood follows a continuous fixed path of circulation and is confined to a network of vessels that keeps the blood separate from the interstitial fluid.

3. Single circuit circulation



In the case of single circulatory systems, blood passes through the heart only once on each circuit around the whole of the blood circulation system of the animal. Fish have single circulatory systems in which blood passes through the heart only once each time it completes a full circuit around the fish's body, including through its gills and all other organs and tissues. As applies to all closed circulatory systems, single circulation systems consist of blood, blood vessels and a heart.The fluid (i.e. blood) contained within the network of (blood) vessels must be moved around the system in the correct direction. This is achieved by the heart continuously pumping.In the case of single circulatory systems, e.g. as in fish, the heart receives deoxygenated blood (also described as 'oxygen-poor blood') into the atrium of the heart and pumps it through the ventricle of the heart so that it continues onwards to the gills. The deoxygenated blood is oxygenated as it passes through the gill capillaries which are tiny blood vessels whose walls are so thin that the waste product carbon dioxide can be released from the deoxygenated blood and oxygen accepted into the blood before the blood moves onwards through the blood vessels throughout the rest of the animal's body.

Also in the same way as for all closed circulatory systems, oxygenated blood supplies oxygen to the animal's cells as a result of the blood flowing through the blood vessels from larger arteries, via arterioles, into tiny capillaries where the exchange of materials that fulfil the transport functions of blood occur.

Limitations of Single Circulatory Systems

Blood flow rate and blood pressure falls when blood leaves a fish's gills. The low blood pressure in the single circulatory systems present in fish is fine for fish but would be insufficient for efficient kidney function in mammals. (Mammals have double circulation systems)

4. Double circuit circulation

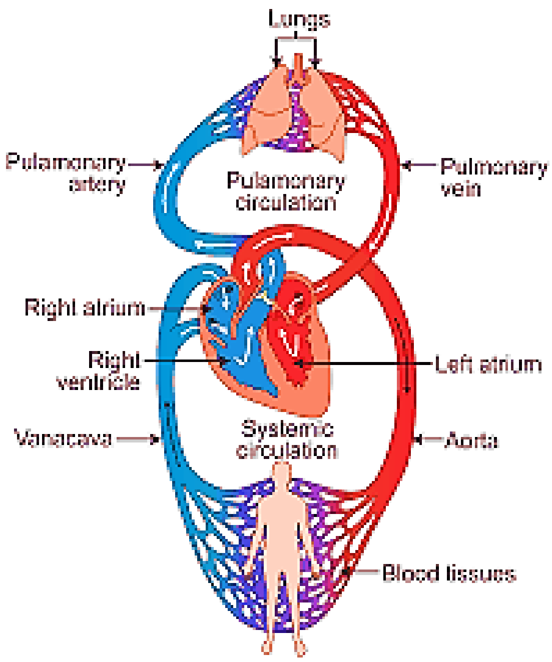
The lung animals (including humans) utilize a double circulatory system which means in which the blood passes through the heart twice before completing a full circuit of the body. In a double circulatory system there are two circuits for blood passing through the heart:

- **Pulmonary Circulation:**

Deoxygenated blood is pumped from the heart to the lungs, oxygenated blood returns to the heart from the lungs.

- **Systemic Circulation:**

Oxygenated blood is pumped from the heart around the body (including all the organs). That blood returns to the heart deoxygenated (more accurately 'oxygen poor') because much of the oxygen it contained when it left the heart has been supplied to tissues in the body.



The pressure of blood flowing through a double circulation system can be higher than that flowing through a single circulatory system because in the case of double circulation the blood is pressurized twice per cycle around the whole blood system. (However, the blood pressure in a double circulatory system isn't twice that in a single circulatory system - it is not that simple because blood pressure in different parts of the heart varies according to the cardiac cycle and blood pressure around the body also varies e.g. according to the type and location of the blood vessel, and with the general state of health of the person or animal.)

The blood is pumped around the body after it has returned to the heart from the lungs. This is beneficial because blood pressure and flow rate is reduced as it passes through the lungs so if the blood wasn't returned to the heart and pumped onwards it would continue to the tissues of the body at much lower pressure and flow rate than it does in double circulation systems.

The separation of oxygenated (more accurately "oxygen-rich") and deoxygenated (more accurately "oxygen-poor") blood is possible in the cases of double circulation systems that include a 'double pump', i.e. a four chamber, heart. Oxygen-poor blood, which is often called deoxygenated blood - entering the right atrium of the heart via the inferior vena cava and the superior vena cava then leaving the right ventricle of the heart via the pulmonary artery . Oxygen-rich blood, which is often called oxygenated blood or 'reoxygenated blood' - entering the left atrium of the heart via the pulmonary veins then leaving the left ventricle of the heart via the aorta.

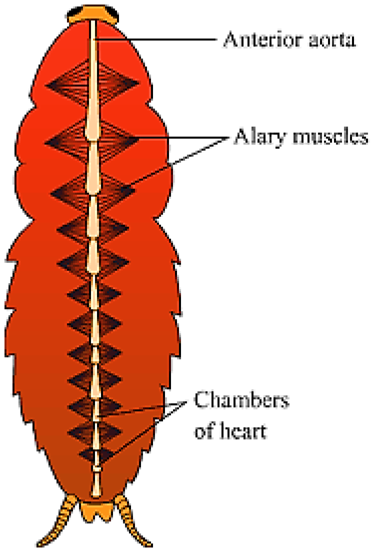
Advantages of double circulation

Double circulation is advantageous for mammals because it increases the pressure and hence the flow rate of blood supplied to the tissues of the body via the systemic circulation. When blood passes through the lungs its pressure is reduced. Therefore if it were not returned to the heart then pumped out again (at higher pressure than the pressure at which it reached the heart from the lungs), it would pass onwards around the body much more slowly. Double circulatory systems are important because they ensure that we are giving our tissues and muscles blood full of oxygen, instead of a mixture of oxygenated and deoxygenated blood. While it may take a bit more energy than a single circulatory system, this system is much more efficient.

Types of Heart:

Heart of Cockroach

The heart of the cockroach is elongated, thick, muscular, tubular and 13-chambered. It lies in the pericardial sinus of the haemocoel. Each chamber of the heart receives oxygenated blood from the dorsal sinus through one pair of slit like openings called ostia. The heart contracts in a postero anterior direction and the blood also flows posteroanteriorly. The alary muscles are responsible for the circulation of blood. The first chamber leads into an aorta, which opens in the head sinuses which are connected to the pericardial sinus through perineural and perivisceral sinuses.



The Fish Heart

The chordates that were ancestral to the vertebrates are thought to have had simple tubular hearts, similar to those now seen in lancelets. The heart was little more than a specialized zone of the ventral artery, more heavily muscled than the rest of the arteries, which contracted in simple peristaltic waves. A pumping action results because the uncontracted portions of the vessel have a larger diameter than the contracted portion, and thus present less resistance to blood flow. The development of gills by fishes required a more efficient pump, and in fishes we see the evolution of a true chamber-pump heart. The fish heart is, in essence, a tube with four chambers arrayed one after the other. The first two chambers—the **sinus venosus** and **atrium**—are collection chambers, while the second two, the **ventricle** and **conus arteriosus,** are pumping chambers.

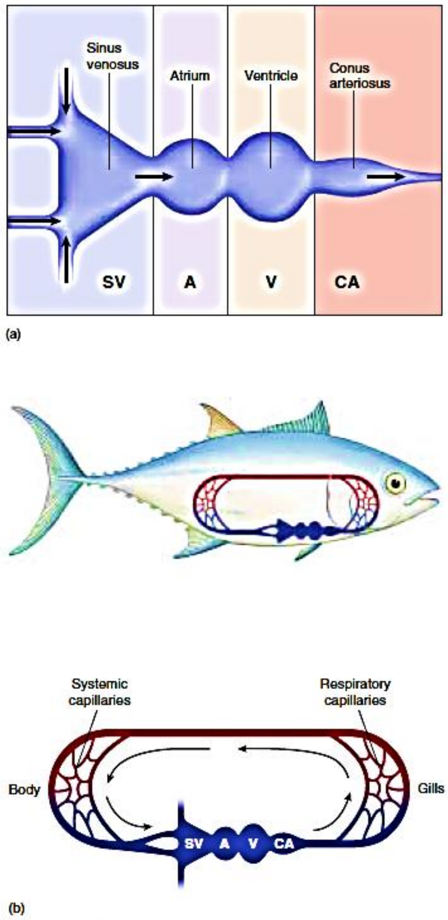


FIGURE 52.12
The heart and circulation of a fish. (*a*) Diagram of a fish heart, showing the chambers in series with each other. (*b*) Diagram of fish circulation, showing that blood is pumped by the ventricle through the gills and then to the body. Blood rich in oxygen (oxygenated) is shown in red; blood low in oxygen (deoxygenated) is shown in blue.

As might be expected, the sequence of the heartbeat in fishes is a peristaltic sequence, starting at the rear and moving to the front, similar to the early chordate heart. The first of the four chambers to contract is the sinus venosus, followed by the atrium, the ventricle, and finally the conus arteriosus. Despite shifts in the relative positions of the chambers in the vertebrates that evolved later, this heartbeat sequence is maintained in all vertebrates. In fish, the electrical impulse that produces the contraction is initiated in the sinus venosus; in other vertebrates, the electrical impulse is initiated by their equivalent of the sinus venosus.

The fish heart is remarkably well suited to the gill respiratory apparatus and represents one of the major evolutionary innovations in the vertebrates. Perhaps its greatest advantage is that the blood that moves through the gills is fully oxygenated when it moves into the tissues. After blood leaves the conus arteriosus, it moves through the gills, where it becomes oxygenated; from the gills, it flows through a network of arteries to the rest of the body; then it returns to the heart through the veins. This arrangement has one great limitation, however. In passing through the capillaries in the gills, the blood loses much of the pressure developed by the contraction of the heart, so the circulation from the gills through the rest of the body is sluggish. This feature limits the rate of oxygen delivery to the rest of the body.

Amphibian and Reptile Circulation

The advent of lungs involved a major change in the pattern of circulation. After blood is pumped by the heart through the *pulmonary arteries* to the lungs, it does not go directly to the tissues of the body but is instead returned via the *pulmonary veins* to the heart. This results in two circulations: one between heart and lungs, called the **pulmonary circulation,** and one between the heart and the rest of the body, called the **systemic circulation.**

If no changes had occurred in the structure of the heart, the oxygenated blood from the lungs would be mixed in the heart with the deoxygenated blood returning from the rest of the body. Consequently, the heart would pump a mixture of oxygenated and deoxygenated blood rather than fully oxygenated blood. The amphibian heart has two structural features that help reduce this mixing. First, the atrium is divided into two chambers: the right atrium receives deoxygenated blood from the systemic circulation, and the left atrium receives oxygenated blood from the lungs. These two stores of blood therefore do not mix in the atria, and little mixing occurs when the contents of each atrium enter the single, common ventricle, due to internal channels created by recesses in the ventricular wall. The conus arteriosus is partially separated by a dividing wall which directs deoxygenated blood into the pulmonary arteries to the lungs and oxygenated blood into the *aorta*, the major artery of the systemic circulation to the body. Because there is only one ventricle in an amphibian heart, the separation of the pulmonary and systemic circulations is incomplete. Amphibians in water, however, can obtain additional oxygen by diffusion through their skin. This process, called **cutaneous respiration,** helps to supplement the oxygenation of the blood in these vertebrates.

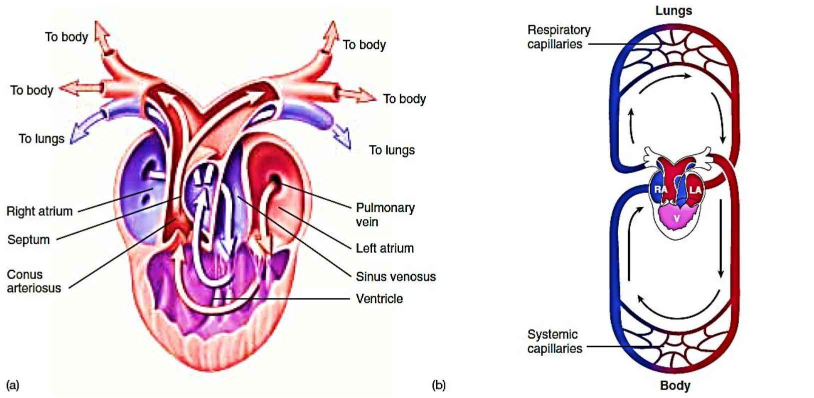


FIGURE 52.13
The heart and circulation of an amphibian. (*a*) The frog heart has two atria but only one ventricle, which pumps blood both to the lungs and to the body. (*b*) Despite the potential for mixing, the oxygenated and deoxygenated bloods (red and blue, respectively) mix very little as they are pumped to the body and lungs. The slight mixing is shown in purple. RA = right atrium; LA = left atrium; V = ventricle.

Among reptiles, additional modifications have reduced the mixing of blood in the heart still further. In addition to having two separate atria, reptiles have a septum that partially subdivides the ventricle. This results in an even greater separation of oxygenated and deoxygenated blood within the heart. The separation is complete in one order of reptiles, the crocodiles, which have two separate ventricles divided by a complete septum. Crocodiles therefore have a completely divided pulmonary and systemic circulation. Another change in the circulation of reptiles is that the conus arteriosus has become incorporated into the trunks of the large arteries leaving the heart.

Mammalian and Bird Hearts

Mammals, birds, and crocodiles have a four-chambered heart with two separate atria and two separate ventricles. The right atrium receives deoxygenated blood from the body and delivers it to the right ventricle, which pumps the blood to the lungs. The left atrium receives oxygenated blood from the lungs and delivers it to the left ventricle, which pumps the oxygenated blood to the rest of the body. This completely double circulation is powered by a two-cycle pump. Both atria fill with blood and simultaneously contract, emptying their blood into the ventricles. Both ventricles contract at the same time, pushing blood simultaneously into the pulmonary and systemic circulations. The increased efficiency of the double circulatory system in mammals and birds is thought to have been important in the evolution of endothermy (warm-bloodedness), because a more efficient circulation is necessary to support the high metabolic rate required.

Because the overall circulatory system is closed, the same volume of blood must move through the pulmonary circulation as through the much larger systemic circulation with each heartbeat. Therefore, the right and left ventricles must pump the same amount of blood each time they contract.

If the output of one ventricle did not match that of the other, fluid would accumulate and pressure would increase in one of the circuits. The result would be increased filtration out of the capillaries and edema (as occurs in congestive heart failure, for example). Although the volume of blood pumped by the two ventricles is the same, the pressure they generate is not. The left ventricle, which pumps blood through the higher-resistance systemic pathway, is more muscular and generates more pressure than does the right ventricle.

Throughout the evolutionary history of the vertebrate heart, the sinus venosus has served as a pacemaker, the site where the impulses that initiate the heartbeat originate. Although it constitutes a major chamber in the fish heart, it is reduced in size in amphibians and further reduced in reptiles. In mammals and birds, the sinus venosus is no longer evident as a separate chamber, but its disappearance is not really complete. Some of its tissue remains in the wall of the right atrium, near the point where the systemic veins empty into the atrium. This tissue, which is called the *sinoatrial (SA) node,* is still the site where each heartbeat originates.

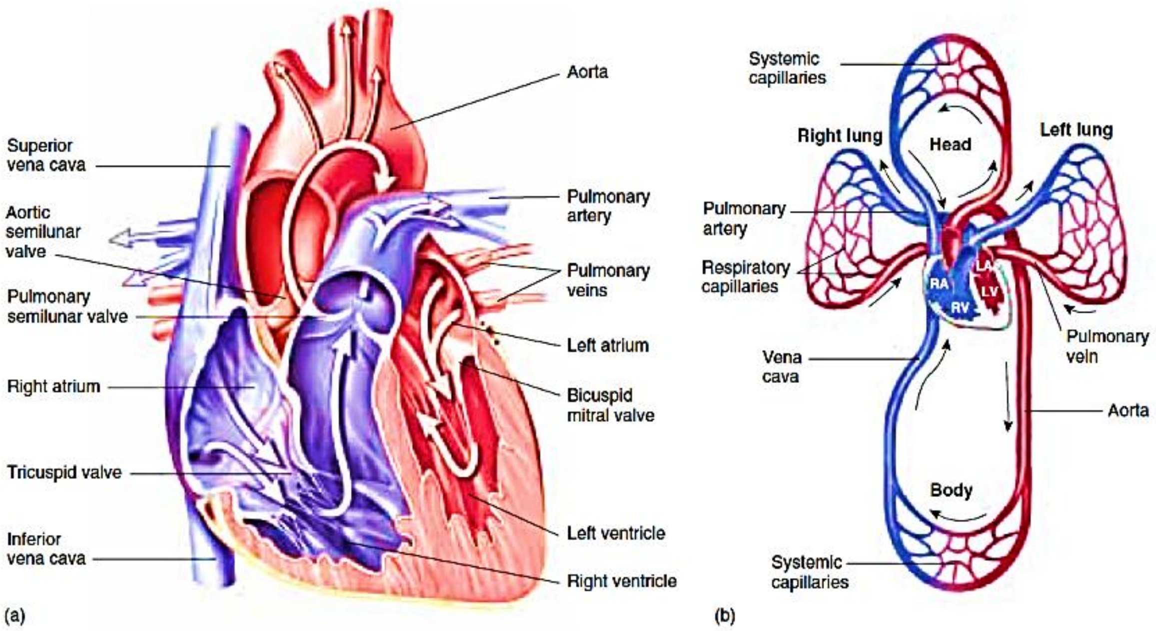


FIGURE 52.14
The heart and circulation of mammals and birds. (*a*) The path of blood through the four-chambered heart. (*b*) The right side of the heart receives deoxygenated blood and pumps it to the lungs; the left side of the heart receives oxygenated blood and pumps it to the body. In this way, the pulmonary and systemic circulations are kept completely separate. RA = right atrium; LA = left atrium; RV = right ventricle; LV = left ventricle.

Functioning

Blood flows through the heart in one direction, from the atria to the ventricles, and out of the great arteries, or the aorta for example. Blood is prevented from flowing backwards by the tricuspid,bicuspid, aortic, and pulmonary valve.The heart acts as a double pump. The function of the right side of the heart (see right heart) is to collect de-oxygenated blood, in the right atrium, from the body (via superior and inferior vena cavae) and pump it, via the right ventricle, into the lungs (pulmonary circulation) so that carbon dioxide can be dropped off and oxygen picked up (gas exchange). This happens through the passive process of diffusion. The left side (see left heart) collects oxygenated blood from the lungs into the left atrium. From the left atrium the blood moves to the left ventricle which pumps it out to the body (via the aorta). On both sides, the lower ventricles are thicker and stronger than the upper atria. The muscle wall surrounding the left ventricle is thicker than the wall surrounding the right ventricle due to the higher force needed to pump the blood through the systemic circulation. Starting in the right atrium, the blood flows through the tricuspid valve to the right ventricle. Here, it is pumped out of the pulmonary semilunar valve and travels through the pulmonary artery to the lungs. From there, blood flows back through the pulmonary vein to the left atrium. It then travels through the mitral valve to the left ventricle, from where it is pumped through the aortic semilunar valve to the aorta and to the rest of the body. The (relatively) deoxygenated blood finally returns to the heart through the inferior vena cava.