

BIOPHYSICAL, PHYSIOLOGICAL CLASSIFICATION OF THE CIRCULATORY SYSTEM

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Annotation: Circulatory system, system that transports nutrients, respiratory gases, and metabolic products throughout a living organism, permitting integration among the various tissues. The process of circulation includes the intake of metabolic materials, the conveyance of these materials throughout the organism, and the return of harmful by-products to the environment.

Key words: respiratory gases, metabolic products, lymph, fluid.

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.

A full treatment of human blood and its various components can be found in the article human blood. A discussion of how the systems of circulation, respiration, and metabolism work together within an animal organism is found in the article respiration.

All living organisms take in molecules from their environments, use them to support the metabolism of their own substance, and release by-products back into the environment. The internal environment differs more or less greatly from the external environment, depending on the species. It is normally maintained at constant conditions by the organism so that it is subject to relatively minor fluctuations. In individual cells, either as independent organisms or as parts of the tissues of multicellular animals, molecules are taken in either by their direct diffusion through the cell wall or by the formation by the surface membrane of vacuoles that carry some of the environmental fluid containing dissolved molecules. Within the cell, cyclosis (streaming of the fluid cytoplasm) distributes the metabolic products.

Molecules are normally conveyed between cells and throughout the body of multicellular organisms in a circulatory fluid, called blood, through special channels, called blood vessels, by some form of pump, which, if restricted in position, is usually called a heart. In vertebrates blood and lymph (the circulating fluids) have an essential role in maintaining homeostasis (the constancy of the internal environment) by distributing substances to parts of the body when required and by removing others from areas in which their accumulation would be harmful.

One phylum, Cnidaria (Coelenterata)—which includes sea anemones, jellyfish, and corals—has a diploblastic level of organization (i.e., its members have two layers of cells). The outer layer, called the ectoderm, and the inner layer, called the endoderm, are separated by an amorphous, acellular layer called the mesoglea; for these animals, bathing both cellular surfaces with environmental fluid is sufficient to supply their metabolic needs. All other major eumetazoan phyla (i.e., those with defined tissues and organs) are triploblastic (i.e., their members have three layers of cells), with the third cellular layer, called the mesoderm, developing between the endoderm and ectoderm. At its simplest, the mesoderm provides a network of packing cells around the animal's organs; this is probably best exhibited in the phylum Platyhelminthes (flatworms).

Nematoda, Rotifera, and a number of other smaller eumetazoan classes and phyla have a fluid-filled cavity, called the pseudocoelom, that arises from an embryonic cavity and contains the internal organs free within it. All other eumetazoans have a body cavity, the coelom, which originates as a cavity in the embryonic mesoderm. Mesoderm lines the coelom and forms the peritoneum, which also surrounds and supports the internal organs. While this increase in complexity allows for increase in animal size, it has certain problems. As the distances from metabolizing cells to the source of metabolites (molecules to be metabolized) increases, a means of distribution around the body is necessary for all but the smallest coelomates.

Many invertebrate animals are aquatic and the problem of supplying fluid is not critical. For terrestrial organisms, however, the fluid reaching the tissues comes from water that has been drunk, absorbed in the alimentary canal, and passed to the bloodstream. Fluid may leave the blood, usually with food and other organic molecules in solution, and pass to the tissues, from which it returns in the form of lymph. Especially in the vertebrates, lymph passes through special pathways, called lymphatic channels, to provide the lymphatic circulation.

In many invertebrates, however, the circulating fluid is not confined to distinct vessels, and it more or less freely bathes the organs directly. The functions of both circulating and tissue fluid are thus combined in the fluid, often known as hemolymph. The possession of a blood supply and coelom, however, does not exclude the circulation of environmental water through the body. Members of the phylum Echinodermata (starfishes and sea urchins, for example) have a complex water vascular system used mainly for locomotion.

An internal circulatory system transports essential gases and nutrients around the body of an organism, removes unwanted products of metabolism from the tissues, and carries these products to specialized excretory organs, if present. Although a few invertebrate animals circulate external water through their bodies for respiration, and, in the case of cnidarians, nutrition, most species circulate an internal fluid, called blood.

There may also be external circulation that sets up currents in the environmental fluid to carry it over respiratory surfaces and, especially in the case of sedentary animals, to carry particulate food that is strained out and passed to the alimentary canal. Additionally, the circulatory system may assist the organism in movement; for example, protoplasmic streaming in amoeboid protozoans circulates nutrients and provides pseudopodal locomotion. The hydrostatic pressure built up in the circulatory systems of many invertebrates is used for a range of whole-body and individual-organ movement.

Body fluids

The fluid compartments of animals consist of intracellular and extracellular components. The intracellular component includes the body cells and, where present, the blood cells, while the

extracellular component includes the tissue fluid, coelomic fluid, and blood plasma. In all cases the major constituent is water derived from the environment. The composition of the fluid varies markedly depending on its source and is regulated more or less precisely by homeostasis.

Blood and coelomic fluid are often physically separated by the blood-vessel walls; where a hemocoel (a blood-containing body cavity) exists, however, blood rather than coelomic fluid occupies the cavity. The composition of blood may vary from what is little more than the environmental water containing small amounts of dissolved nutrients and gases to the highly complex tissue containing many cells of different types found in mammals.

Lymph essentially consists of blood plasma that has left the blood vessels and has passed through the tissues. It is generally considered to have a separate identity when it is returned to the bloodstream through a series of vessels independent of the blood vessels and the coelomic space. Coelomic fluid itself may circulate in the body cavity. In most cases this circulation has an apparently random nature, mainly because of movements of the body and organs. In some phyla, however, the coelomic fluid has a more important role in internal distribution and is circulated by ciliary tracts.

Fluid compartments

Blood is circulated through vessels of the blood vascular system. Blood is moved through this system by some form of pump. The simplest pump, or heart, may be no more than a vessel along which a wave of contraction passes to propel the blood. This simple, tubular heart is adequate where low blood pressure and relatively slow circulation rates are sufficient to supply the animal's metabolic requirements, but it is inadequate in larger, more active, and more demanding species. In the latter animals, the heart is usually a specialized, chambered, muscular pump that receives blood under low pressure and returns it under higher pressure to the circulation. Where the flow of blood is in one direction, as is normally the case, valves in the form of flaps of tissue prevent backflow.

A characteristic feature of hearts is that they pulsate throughout life and any prolonged cessation of heartbeat is fatal. Contractions of the heart muscle may be initiated in one of two ways. In the first, the heart muscle may have an intrinsic contractile property that is independent of the nervous system. This myogenic contraction is found in all vertebrates and some invertebrates. In the second, the heart is stimulated by nerve impulses from outside the heart muscle. The hearts of other invertebrates exhibit this neurogenic contraction.

Chambered hearts, as found in vertebrates and some larger invertebrates, consist of a series of interconnected muscular compartments separated by valves. The first chamber, the auricle, acts as a reservoir to receive the blood that then passes to the second and main pumping chamber, the ventricle. Expansion of a chamber is known as diastole and contraction as systole. As one chamber undergoes systole the other undergoes diastole, thus forcing the blood forward. The series of events during which blood is passed through the heart is known as the cardiac cycle.

Contraction of the ventricle forces the blood into the vessels under pressure, known as the blood pressure. As contraction continues in the ventricle, the rising pressure is sufficient to open the valves that had been closed because of attempted reverse blood flow during the previous cycle. At this point the ventricular pressure transmits a high-speed wave, the pulse, through the blood of the arterial system. The volume of blood pumped at each contraction of the ventricle is known as the stroke volume, and the output is usually dependent on the animal's activity.

After leaving the heart, the blood passes through a series of branching vessels of steadily decreasing diameter. The smallest branches, only a few micrometres (there are about 25,000 micrometres in one inch) in diameter, are the capillaries, which have thin walls through which the fluid part of the blood may pass to bathe the tissue cells. The capillaries also pick up metabolic end products and carry them into larger collecting vessels that eventually return the blood to the heart. In vertebrates there are structural differences between the muscularly walled arteries, which carry the blood under high pressure from the heart, and the thinner walled veins, which return it at much reduced pressure. Although such structural differences are less apparent in invertebrates, the terms artery and vein are used for vessels that carry blood from and to the heart, respectively.

The closed circulatory system found in vertebrates is not universal; a number of invertebrate phyla have an “open” system. In the latter animals, the blood leaving the heart passes into a series of open spaces, called sinuses, where it bathes internal organs directly. Such a body cavity is called a hemocoel, a term that reflects the amalgamation of the blood system and the coelom.

Invertebrate circulatory systems

Basic physicochemical considerations

To maintain optimum metabolism, all living cells require a suitable environment, which must be maintained within relatively narrow limits. An appropriate gas phase (*i.e.*, suitable levels of oxygen and other gases), an adequate and suitable nutrient supply, and a means of disposal of unwanted products are all essential.

Direct diffusion through the body surface supplies the necessary gases and nutrients for small organisms, but even some single-celled protozoa have a rudimentary circulatory system. Cyclosis in many ciliates carries food vacuoles—which form at the forward end of the gullet (cytopharynx)—on a more or less fixed route around the cell, while digestion occurs to a fixed point of discharge.

For most animal cells, the supply of oxygen is largely independent of the animal and therefore is a limiting factor in its metabolism and ultimately in its structure and distribution. The nutrient supply to the tissues, however, is controlled by the animal itself, and, because both major catabolic end products of metabolism—ammonia (NH_3) and carbon dioxide (CO_2)—are more soluble than oxygen (O_2) in water and the aqueous phase of the body fluids, they tend not to limit metabolic rates. The diffusion rate of CO_2 is less than that of O_2 , but its solubility is 30 times that of oxygen. This means that the amount of CO_2 diffusing is 26 times as high as for oxygen at the same temperature and pressure.

The oxygen available to a cell depends on the concentration of oxygen in the external environment and the efficiency with which it is transported to the tissues. Dry air at atmospheric pressure contains about 21 percent oxygen, the percentage of which decreases with increasing altitude. Well-aerated water has the same percentage of oxygen as the surrounding air; however, the amount of dissolved oxygen is governed by temperature and the presence of other solutes. For example, seawater contains 20 percent less oxygen than fresh water under the same conditions.

The rate of diffusion depends on the shape and size of the diffusing molecule, the medium through which it diffuses, the concentration gradient, and the temperature. These physicochemical constraints imposed by gaseous diffusion have a relationship with animal respiration. Investigations have suggested that a spherical organism larger than 0.5 millimetre (0.02 inch) radius would not obtain enough oxygen for the given metabolic rate, and so a supplementary transport mechanism would be required. Many invertebrates are small, with direct diffusion distances

of less than 0.5 millimetre. Considerably larger species, however, still survive without an internal circulatory system.

Animals without independent vascular systems

A sphere represents the smallest possible ratio of surface area to volume; modifications in architecture, reduction of metabolic rate, or both may be exploited to allow size increase. Sponges overcome the problem of oxygen supply and increase the chance of food capture by passing water through their many pores using ciliary action. The level of organization of sponges is that of a coordinated aggregation of largely independent cells with poorly defined tissues and no organ systems. The whole animal has a relatively massive surface area for gaseous exchange, and all cells are in direct contact with the passing water current.

Among the eumetazoan (multicellular) animals the cnidarians (sea anemones, corals, and jellyfish) are diploblastic, the inner endoderm and outer ectoderm being separated by an acellular mesoglea. Sea anemones and corals may also grow to considerable size and exhibit complex external structure that, again, has the effect of increasing surface area. Their fundamentally simple structure—with a gastrovascular cavity continuous with the external environmental water—allows both the endodermal and ectodermal cells of the body wall access to aerated water, permitting direct diffusion.

This arrangement is found in a number of other invertebrates, such as Ctenophora (comb jellies), and is exploited further by jellyfish, which also show a rudimentary internal circulatory system. The thick, largely acellular, gelatinous bell of a large jellyfish may attain a diameter of 40 centimetres (16 inches) or more. The gastrovascular cavity is modified to form a series of water-filled canals that ramify through the bell and extend from the central gastric pouches to a circular canal that follows the periphery of the umbrella. Ciliary activity within the canals slowly passes food particles and water, taken in through the mouth, from the gastric pouches (where digestion is initiated) to other parts of the body. Ciliary activity is a relatively inefficient means of translocating fluids, and it may take up to half an hour to complete a circulatory cycle through even a small species. To compensate for the inefficiency of the circulation, the metabolic rate of the jellyfish is low, and organic matter makes up only a small proportion of the total body constituents. The central mass of the umbrella may be a considerable distance from either the exumbrella surface or the canal system, and, while it contains some wandering amoeboid cells, its largely acellular nature means that its metabolic requirements are small.

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