

BLOOD CIRCULATION: ITS DYNAMICS AND PHYSIOLOGICAL CONTROL

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Summary

The circulation (or circulatory system) is a complete circuit of vessels distributing the blood via the arterial system (see *Arterial Blood Supply and Tissue Needs*) to the microcirculation of different tissues where the exchange of materials between the blood and the interstitial space takes place (see *Microcirculation*), and collecting the blood from the capillary region via the venous system (see *Venous System*). It is divided into two major parts: the pulmonary circulation which supplies the lungs serving primarily the exchange of oxygen and carbon dioxide between the internal environment and the atmospheric air, and the systemic circulation which supplies the tissues of all the other organs in the organism with metabolic materials (“fuels”) and chemical information. The blood is propelled by the cyclic (pulsatile) pumping activity of the left and the right

heart which are able to maintain an appropriate pressure head in both the systemic and the pulmonary circulation, respectively (see *Heart*). Dynamically active skeletal muscles help in pumping of venous blood.

Blood circulation performs several important physiological functions in the body, contributing substantially to maintaining homeostatic conditions of the fluids in the extracellular space for optimal internal conditions for survival and functioning of the cells (see *Homeodynamics*).

Healthy functioning of the circulatory system is determined by several physiological factors including especially normal arterial blood pressure, blood flow, blood viscosity, vascular elasticity, capillary permeability (see *Microcirculation*), and local as well as systemic control.

In most developed and developing countries, cardiovascular diseases are the leading cause of death; mortality rate is around 50% or above. Scientific investigations have proved that the incidence of cardiovascular diseases can be significantly reduced by an adequate healthy attitude and life conduct, minimizing the many risk factors attacking the human organism from the environment.

1. Introduction

Blood is the connecting link between the outside environment and the internal environment of the cells in our body. To maintain homeostasis throughout the body (see *Homeodynamics*), blood must flow continuously with various velocities adapted to the actual needs of the cells. Circulation (called also cardiovascular or circulatory system) is a complete circuit of vessels which distributes the blood via the arterial system to the capillaries of different tissues where the major exchange of materials and heat energy takes place, and collecting the blood from the capillary region via the venous system. It is divided into two major parts: one is the pulmonary circulation which partly supplies the lung tissues and serves the exchange of gases in the lungs, and the other one is the systemic circulation which supplies the tissues of all the other organs in the organism (Figure 1). The blood is propelled by the cyclic (pulsatile) pumping activity of the heart in the circulatory system. It is operating under complex hierarchical and heterarchical adaptive control.

The complete circuit of blood was first described by William Harvey (1578-1657) in his famous work entitled “*Exercitatio Anatomica de Motu Cordis et Sanguinis*” (Frankfurt, 1628). He is regarded as the discoverer of the circulation.

The main function of the circulation is to maintain homeostatic conditions in the tissue for optimal function and survival of the cells. These needs are served by transporting different nutrient molecules in water solution (amino acids, fatty acids, glucose, vitamins, minerals, oxygen, etc.) to the tissues, transporting away waste products, carrying chemical informational molecules (e.g. hormones and vitamins) from one part of the organism to another, and distributing heat energy in the body.

The hemodynamic performance of the cardiovascular system is normally extremely high. The resting value of the cardiac output in adults is 5 to 5.5 liters/min, but this can go up to 25 to 35 in heavy exercise (see *Heart, Muscle Energy Metabolism and Physiological Basis of Exercise*), depending upon the trained state of the body. In the 60 years of an average adult life span, approximately 200 000 m³ of blood is pumped by the heart into the circulation, 5000 to 6000 m³ fluid is filtered across the capillary wall, and 8 000 000 liters of oxygen is supplied for metabolic processes in the body (see *Arterial Blood Supply and Tissue Needs*). The average capillary density in the body is 600 vessels/mm³ tissue (see *Microcirculation and Lymphatics*). Their total length is a match for that of the Equator of the Earth (40 000 km). About 1000 m² surface area is available for exchange of materials at the level of capillaries. The number of circulating red blood cells (erythrocytes) amounts to 2-3 x 10¹³.

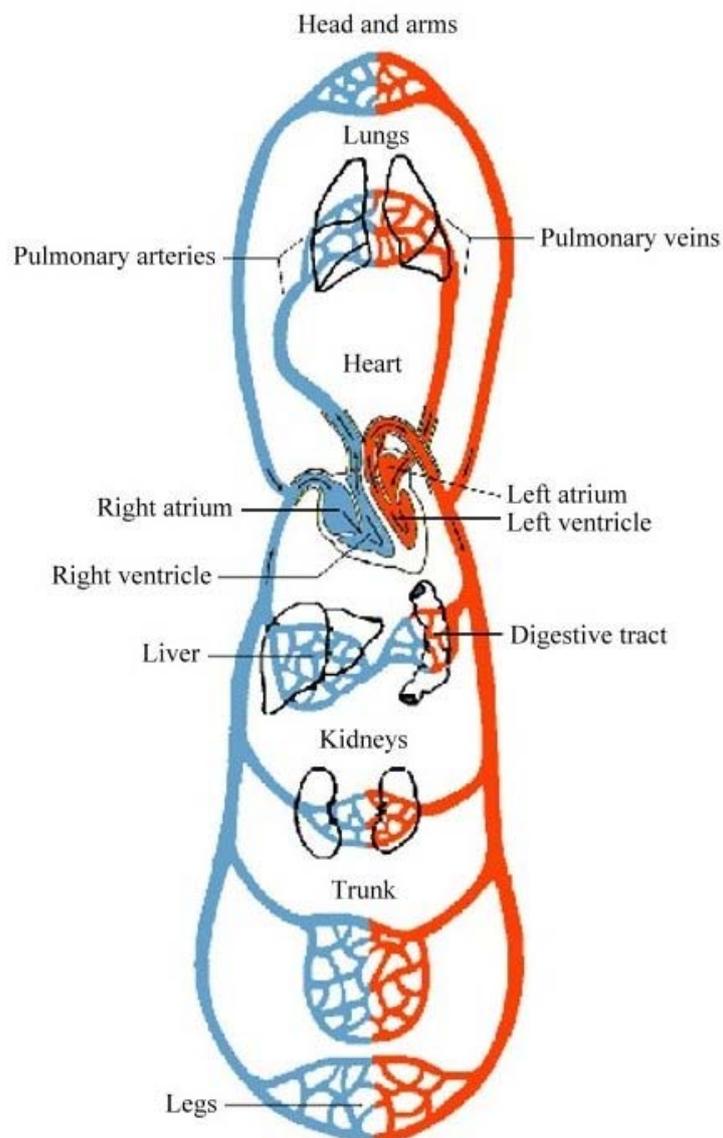


Figure 1. The cardiovascular system – the systemic and the pulmonary circulation.
 (Modified after J.W. Hole Jr. (1993). *Human Anatomy and Physiology, Sixth Edition*, Dubuque, IA: Wm.C. Brown Publ.).

There are a few basic principles that underlie the major functions of the cardiovascular system, as follows:

- The system is a complete circuit (see above).
- It is built up from elements (units) of composite hemodynamic functions—blood vessels and the heart chambers—coupled in series as well as in parallel.
- The whole circulation is functioning as a ubiquitous canalicular communicating system supplying each tissue of the body with blood according to the instantaneous needs of the cells.
- The cardiac output normally is the sum of all local tissue flows, i.e. the same amount of blood pumped by the left heart returns to the right heart, which propels this blood further to the pulmonary circulation.
- The circulatory system is provided with multiple, hierarchically and heterarchically organized systemic (neural, hormonal) and local (myogenic, endothelial, etc.) control systems. In most instances the major controlled variables—arterial pressure, cardiac output, local blood flow—are regulated independently of each other.

2. Functional Organization of the Circulatory System

2.1. The Two Separate Pumps of the Circulation: Left Heart and Right Heart

The human heart is composed of two pumps driving the blood around in the circulatory system (see *Heart as an Endocrine Organ*). One of them is the left heart, which receives oxygenated blood from the pulmonary system (lungs) and pumps it cyclically to the peripheral organs via the aorta and its branches, the arterial system. The other one is the right heart, which receives the venous blood from the peripheral organs via the venous system including its terminal section, the superior and inferior caval veins, and pumps it through the lungs (pulmonary circulation) toward the left heart. Each pump is composed of an atrium and a ventricle. Cuspidal valves separate the atria and the ventricles from each other. The major function of atria is to accelerate the filling of ventricles with blood during diastole. The ventricular contractions provide the energy to maintain appropriate blood pressure head in the systemic circulation (appr. 13.3 kPa, 100 mmHg, at rest) and in the pulmonary circulation (appr. 2.7 kPa, 20 mmHg). The amount of blood in liters pumped by one ventricle in one minute is called cardiac output. Its normal value under resting condition is 5 to 5.5 l/min. The heart is equipped with a special signal generating and conducting system that distributes electric action potentials throughout the cardiac muscles while maintains its own rhythmicity (pace-maker function).

The series of physical events (blood pressure, volume, flow, electrical, and acoustic changes) that start at the beginning of a heartbeat and last until the beginning of the next one is called the cardiac cycle. It can be divided into two major parts: systolic (simultaneous with the cardiac contraction) and diastolic (cardiac relaxation) events.

2.2. Functional Units of Systemic Blood Vessels Coupled in Series

According to the major hemodynamic functions the systemic circulation can be divided into the following vascular units (Figure 2): Windkessel or impedance vessels (see

Arterial Blood Supply and Tissue Needs), precapillary resistance vessels, precapillary sphincters, exchange vessels, postcapillary resistance vessels (see *Microcirculation*), shunt vessels, and capacity or volume vessels (see *Venous System*). The series vascular build-up of the pulmonary circulation is similar to the systemic one with the major exception that its total flow resistance is only about one fifth of that of the systemic circulation.

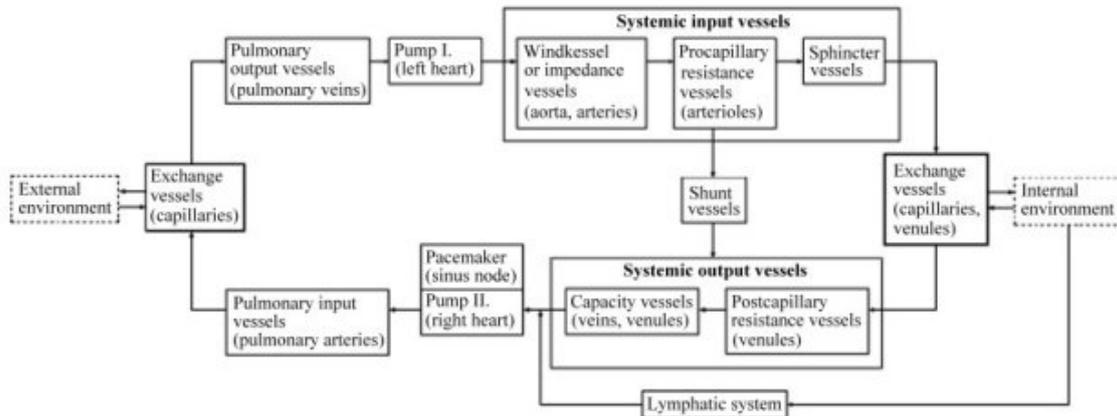


Figure 2. Block diagram illustration of the circulation: functional units coupled in series.

Windkessel vessels (aorta and its large branches) provide relatively little resistance to blood flow but they are much more distensible than the peripheral arteries, consequently they dump the pulsatile systolic pressure generated by the left ventricle. (This mechanism is similar to the operation of the mechanical device called *Windkessel* in German, which still can be seen in some old blacksmith workshops.) With the closure of the aortic semilunar valves, separating the aorta and the left ventricle, the elastic aorta and its branches recoil, thereby sustaining the pressure head in the systemic circulation and rendering the blood flow to the periphery steadier than it would otherwise be (see *Arterial Blood Supply and Tissue Needs*). The alternating current (AC) resistance which is “seen” by the left ventricle, that is the input-impedance of the systemic circulation, is determined dominantly by these *Windkessel* vessels. Aging results in deterioration of the elastic tissue elements in the wall of the aorta and large arteries, causing increased flow impedance and thus increased pulse pressure. This symptom is called systolic hypertension.

Precapillary resistance vessels are represented essentially by the small arteries and the arterioli. They provide most of the total peripheral resistance against blood flow (Figure 3). This is a direct current (DC) resistance. These vessels usually exhibit a substantial intrinsic myogenic tone which is modulated purposefully by the intravascular pressure, by endothelial substances and dilator metabolic products of the surrounding cells, as well as by systemic neural and hormonal effects.

In muscles static contraction compresses the vessels and depresses circulation. If the contraction level exceeds 15% of the voluntary maximum, the circulation deficiency limits the contraction time.

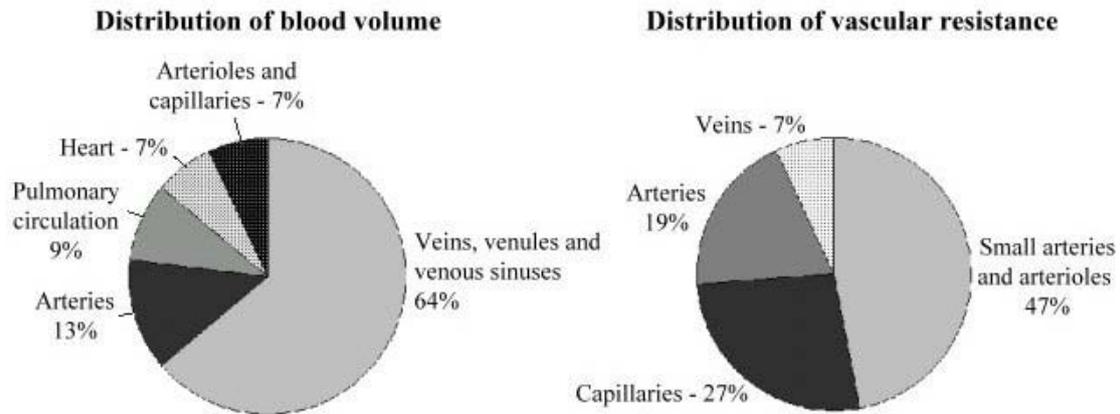


Figure 3. Distribution of the vascular resistance and volume in the circulation (modified after Despopoulos A. and Silbernagl S. (1986). *Color Atlas of Physiology, Third Edition*, Stuttgart: G.Thieme Verlag).

The *precapillary sphincter* is the terminal component of the precapillary resistance vessels. This very short vessel section at the entrance of each systemic capillary is composed of a few circular smooth muscle cells, and controls the number of open capillaries in a given moment and thereby the size of the capillary surface area available for exchange of materials across the capillary wall. The spontaneous cyclic closure and opening activity of these elements is called *vasomotion*. Local vasodilator metabolites play a major role in controlling the open phase of these vessel elements and thus the level of local blood supply.

The most obvious basic function of the circulation, namely promoting the exchange of materials between the external environment and the internal environment of the living organism, is performed at the level of capillaries, therefore they can be called *exchange vessels* by function. These miniature tubings are about 5-6 μm in diameter and 0.8 mm in (this is the average total length between the arterioli and venuli in the systemic circulation). They are formed by a single layer of endothelial cells, without the presence of smooth muscle cells. The mechanisms of transmural capillary transport involve ultrafiltration governed by the Starling-forces, diffusion, pinocytosis, and occasionally bulk flow (see *Microcirculation*).

Although the contribution of venules and small veins to the total peripheral flow resistance is little, they are still important to set properly the ratio of the pre- to postcapillary resistance. This ratio determines the instantaneous intracapillary hydrostatic pressure, which is a major component of the filtration forces driving the fluid across the capillary wall. In addition to the *postcapillary resistance* function, this vascular section contributes also to the exchange function (reabsorption of fluid) and participates significantly in the capacitance function of the venous system.

Rhythmic dynamic muscle contractions promote the return of venous blood. This has significance especially in leg muscles.

The vascular capacity of the venous system is substantially larger than that of the arterial system, thus the distribution of blood volume between them is asymmetrical (Figure 3). In addition, capacitance (or compliance) of veins is well above that of the arteries, which means, that small change in venous blood pressure is accompanied by large change in intravascular volume and vice versa. Consequently, adaptive physiological control of the venous capacitance and volume is decisive in supporting adequate venous return of blood to the heart. This is while the venous vessels are called *capacitance* or *volume vessels* by their hemodynamic function (see *Venous System*).

In certain regions of the body (e.g. ears, fingers) several direct vascular connections, so called *shunt vessels*, can be found between small arteries and veins, bypassing the capillary bed. Their function is closely related to thermoregulation (see *Thermoregulation*).

2.3. Blood Vessels Coupled in Parallel

The circulatory system is composed of several parallel-coupled vascular circuits supplying different organs and tissues each involving the series-coupled sections described above. The percentual distribution of cardiac output (see *Heart as an Endocrine Organ*) among the various circuits (Figure 4) changes substantially and purposefully in physical exercise (redistribution of cardiac output), while the magnitude of the cardiac output may increase by a factor of 5 to 7, depending on the genetic construction and the trained state of the body (see *Physiological Basis of Exercise*).

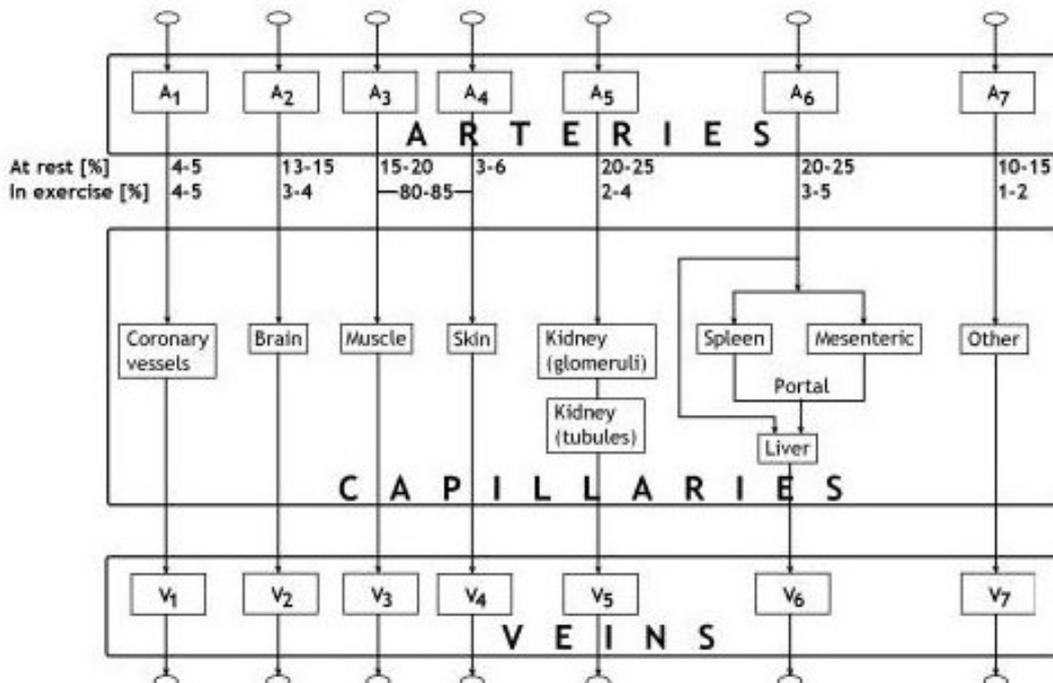


Figure 4. Redistribution of cardiac output fractions amongst the parallel coupled units of the circulation during heavy exercise in man.

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Biographical Sketch

Dr. Emil Monos studied at the Semmelweis Medical University, Budapest, and he received his MD in 1959. Since then he has consistently worked at this institution, presently called Clinical Research Department and Institute of Human Physiology, Faculty of Medicine, Semmelweis University, Budapest. He obtained his PhD and DMSci in physiology at the Hungarian Academy of Sciences in 1974 and 1982, respectively. He was appointed full professor in 1983. Dr. Monos was director of the Institute (1990-2000) and deputy-rector of the University (1995-1999). Since 1990 he has been an adjunct professor of physiology at the Department of Physiology, Medical College of Wisconsin, Milwaukee, USA, where he worked as a visiting professor for more than two years. He teaches medical physiology in Hungarian and in English for graduate and post-graduate students in medicine, pharmacy, and biomedical engineering.

Dr. Monos is author and co-author of eight books and more than 400 articles in the fields of cardiovascular physiology and pathophysiology, endocrinology, neurophysiology, and biomedical engineering. He is editor-in-chief of the *Acta Physiologica Hungarica*, and serves on the editorial board of a number of scientific journals. He was president of the Hungarian Physiological Society (1990-98). Since 1998 he has been the president of the International Society for Pathophysiology, and a full member of the American Physiological Society, the European Academy of Sciences, and the *Academia Scientiarum et Artium Europaea*. A number of university and governmental honours have been conferred upon him. Dr. Monos and his co-workers have discovered a number of important mechanisms participating in physiological control of blood vessel functions, including those of capacity autoregulation of veins. His present research interests are in the regulation of orthostatic tolerance and the adaptation of extremity vessels to long-term gravitational stress.

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