LOUIS BOLK INSTITUTE

Physiology

Organphysiology from a Phenomenological Point of View

Christina van Tellingen MD

BOLK'S COMPANIONS FOR THE STUDT OF MEDICINE

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About the Author

Christina van Tellingen MD (1949) has been a general practitioner since 1982. She has educated medical students, physicians, and therapists in the United States, Canada, and Europe. She teaches medical students and physicians at the University of Witten/Herdecke, Germany. She is a member of the Medical Section of the School of Spiritual Science at the Goetheanum, Dornach, Switzerland.

About the Project

The project *Renewal of Medical Education* aims to produce Companions that demonstrate how the insights of current biomedical science can be broadened by using the Goethean phenomenological method. This method innovates current concepts and expands the understanding of biochemical, physiological, psychological, and morphological factors in living organisms and their development in time and space, and in health, illness, and therapy. The project is commissioned by the Kingfisher Foundation, which aspires the development, application, and publication of the Goethean phenomenological research method in the widest sense, to complement and innovate the accepted scientific view and research method.

BOLK'S COMPANIONS FOR THE STUDY OF MEDICINE complement current medical education, specifically disclosing human qualities in the fundamental biomedical sciences of today.

BOLK'S COMPANIONS FOR THE PRACTICE OF MEDICINE contribute to a scientific phenomenological basis for integrative medicine and integral psychiatry.

5. The Heart and Circulation

5.1. Introduction

The heart and vessels contain the moving blood. The heart and vessels are in rhythmic motion. They contribute to the movement of blood. The vessels are distributed over the whole body. At the same time they are a very differentiated system, which is formed differently in different organs and areas, related to the needs of the tissues in question and their function.

We will consider the physiological morphology and embryology, blood supply, physiology, regulation, and function, of the heart and circulation to gain a view of their characteristic place in the organism.

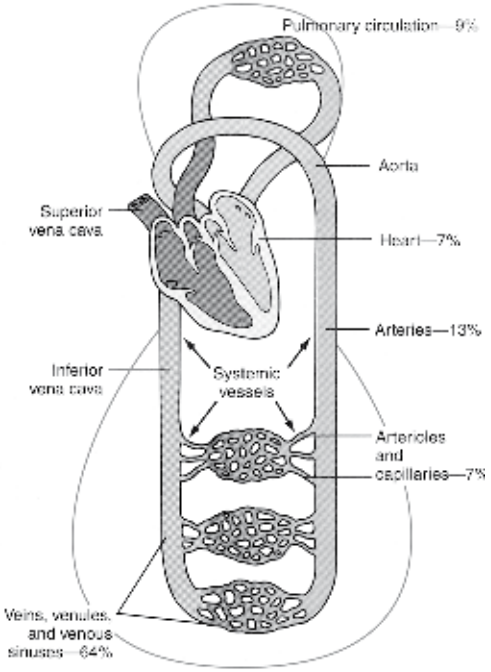


Fig. 5.1. The heart and the pulmonary and systemic circulation. The two circulations with the heart at the center together form a lemniscate (adapted from Guyton 2000)

5.2. Physiological Morphology of the Heart and Circulation

5.2.1. The Shape of Heart and Circulation

The heart and vessels are hollow, tubular-shaped organs. However, their tubular shape does not result from folding the disc-shaped embryo into a tubular shape, which is the basis of respiratory and digestive tract development, nor from outgrowths of the intraembryonic coelom like in the kidney system, but the tubular

lumen arises anew during embryological development (see section 5.2.3.).

The Circulation

The vessels build an intricate branching system, becoming ever smaller the closer they come to the functioning tissue. In the tissue itself, the three billion capillaries of the human body become so small that the blood content (especially the blood cells) can only just move through them. In the capillaries, the vessels have their smallest diameter. There are a great number of capillaries in every body tissue. The blood flow to the capillaries is supplied by the arterial system and leaves the tissue by way of the venous system.

Two separate circulations may be distinguished in the circulation, which each originate in the heart, go to the target organ(s), and then return back to the heart (fig. 5.1.):

- The oxygenated blood in the *systemic circulation* flows from the left side of the heart to all tissues of the organism. From there, the blood, which is now low in oxygen saturation, flows back to the right side of the heart
- The blood that has low oxygen saturation flows from the right heart via the *pulmonary circulation* through the lungs, where the blood is oxygenated, and from there the blood flows back to the left side of the heart.

The circulation could be seen to have two foci: one of the foci is in the capillaries, which are supplied by arterial blood and from whence the venous blood leaves. The heart is the other circulatory focus. The circulation consists of two circuits, the systemic and pulmonary circulations.

The Heart

In the heart, the vessels have their largest diameter, both internally and externally. The heart is approximately as big as our fist, and the vessels are arranged such that the two circulations meet there. The vessels of the two circulations lie alongside each other near the heart and cross each other (see fig. 5.1.).

The heart has four chambers, two atria and two ventricles (fig. 5.2.). The four chambers are separated by the interatrial and interventricular septa between atria and ventricles

respectively, and a fibrous skeleton (the base of the heart) between the atria and the ventricles that holds the four valves and is suspended from the large vessels, aorta and pulmonary artery. The tricuspid and mitral valves, on the right and left side of the heart respectively, are in the outflow tracts of the atria into the ventricles. The ventricles also have valves in their outflow tracts, on the right side the pulmonary valve to the lung circulation, on the left the aortic valve to the systemic circulation. The muscle fibers of the ventricles arise from the fibrous skeleton such that the ventricles are suspended from the large vessels.

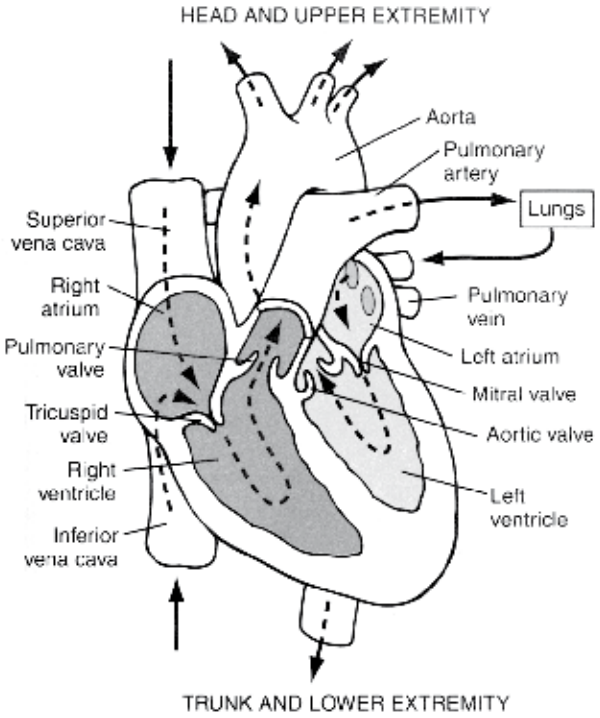


Fig. 5.2. Blood flow in the heart (from Guyton 2000)

In the systemic circulation, blood flows through the superior and inferior caval veins to the right atrium and leaves the right ventricle through the pulmonary artery of the pulmonary circulation. The pulmonary circulation empties through the right and left pulmonary veins into the left atrium and the blood leaves the left ventricle through the aorta to the systemic circulation. This means that these two circulations intersect and that the blood flow makes a somewhat complicated *figure-eight or lemniscate* shape as it passes from the one into the other circulation (see fig. 5.1.).

The shape of the heart is actively formed; the lungs develop around it. The heart is suspended from the large vessels and rests on the diaphragm.

5.2.2. Structure of the Heart and Vessels

Blood in the vessels is contained in endothelium. True capillaries are devoid of smooth muscle fibers. In the larger vessels, one or more smooth muscle layers surround the endothelium. These are especially developed in the arterial circulation and culminate in the heart, where, instead of smooth muscle cells, more differentiated heart muscle tissue develops. The heart muscle cells actually form a functional syncytium of branching and interconnecting striated muscle fibers. The smooth muscle cells and heart muscle cells in heart and circulation are arranged in spiraling or circular layers. Cardiac muscle forms a double spiral that has fibrous septa between the spiraling layers (fig. 5.3.). Ventricular muscle is thicker than atrial muscle, and the left ventricle is thicker than the right. The muscle layers in the ventricles are thickest at the base of the heart, where the outflow tracts are located. At the apex of the heart the layers are very thin. The heart is surrounded by the epicardium and pericardium. The coronary vessels are situated in subepicardial tissue. *Phylogenetically*, the heart develops from two types of heart muscle tissue, trabecular and compact myocardium. In fish, we find only trabecular tissue. It receives its blood supply from sinusoids, and there are no coronary vessels. From the amphibians

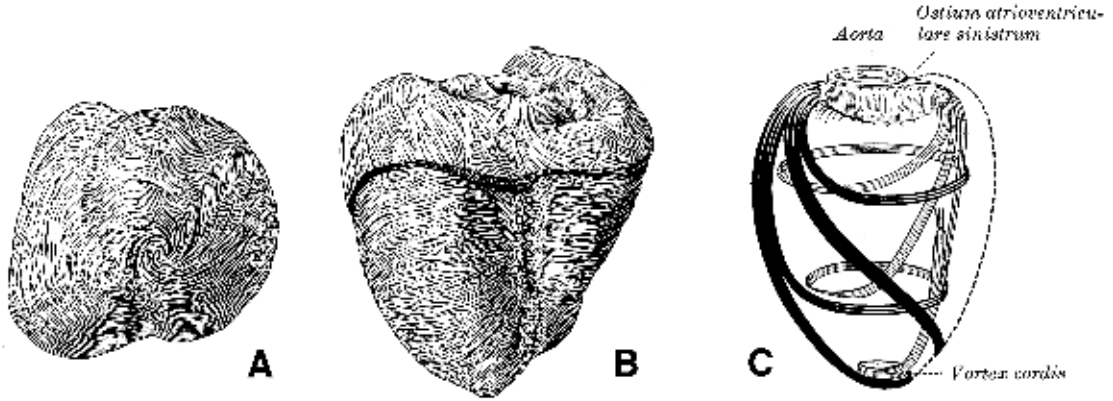


Fig. 5.3. The double spiral layers of heart musculature from the apex (A) and from a dorsal view in which the superficial spiral layer is partially removed (B), and a schematic representation of the spiral layers of the left ventricle (C) (from Benninghoff-Goerttler 1967)

onwards, compact myocardial tissue starts to develop around the trabecular tissue and with it coronary vessels form. The thebesian vessels (section 5.3.) are leftovers from the sinusoids. In vertebrates that move more actively and in those that are larger in size, the thickness of the compact layer becomes relatively greater. This allows a greater blood pressure and more tone in the circulation. Only humans have just compact myocardium.

The valves in the fibrous skeleton at the base of the heart are made up of endothelium covered fibrous tissue and move *passively*. The fibrous skeleton with the fibrous heart valves and the fibrous septa between the spiraling layers in the heart form a structural basis and create areas of relative rest in this organ that is constantly moving. The heart is not a tubular organ in the true sense of the word, neither is it a parenchymatous organ in the true sense of the word. The tubular-shaped lumen develops *de novo* (section 5.2.3.) and the "parenchyme" consists of actively moving muscular tissue.

The smooth muscle cells of the circulation and the morphologically more differentiated heart muscle cells have a spiral or circular configuration. The heart muscle cells form a functional syncytium of striated heart muscle fibers that is in constant, rhythmic motion. The fibrous parts are passively moved along and give the heart a structural basis.

5.2.3. Embryology

Angioblasts

At the start of the 3rd week of embryological development, the pericardial cavity becomes visible above the cephalic area of the embryo (fig. 5.5.). Capillary-size vessels are the first to appear in the embryo from day 17 on. They originate from angioblasts that are also the forerunners of blood cells.

Angioblast cells develop in the mesenchyme of the wall of the yolk sac, and the lateral sides of the splanchnic mesoderm layer. They initially form islands of isolated cell clusters, which soon begin differentiating (fig. 5.4.). The central cells of the blood islands become round and give rise to the primitive blood cells; the peripheral cells flatten and form the

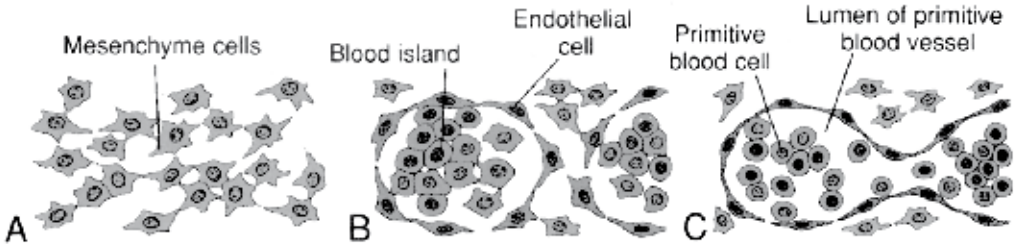


Fig. 5.4. The differentiation from mesenchyme cells (A), to angioblasts (B), and blood and vessel formation (C) (from Sadler 1995)

endothelial lining around the blood cells. The endothelial cells of different blood islands grow towards each other, fuse, and form the lining around the newly created lumen of first capillaries.

Blood and vessels originate from the same angiogenic tissue in much the same way that the embryo and its surrounding sheaths develop from the same tissue during the morula stage (see also the *Embryology Module* of **BOLK**'S COMPANIONS FOR THE STUDY OF MEDICINE). Then too, the compaction of the peripheral cells and their eventual flattening designates them as trophoblast cells, which are the forerunners of the *surrounding* embryological sheaths, in contradistinction to the *central, round* embryoblast cells. The embryoblast cells are the last ones to differentiate, and become the developing embryo itself. The central blood cells in the angiogenic areas also differentiate later and slower than the vessel walls.

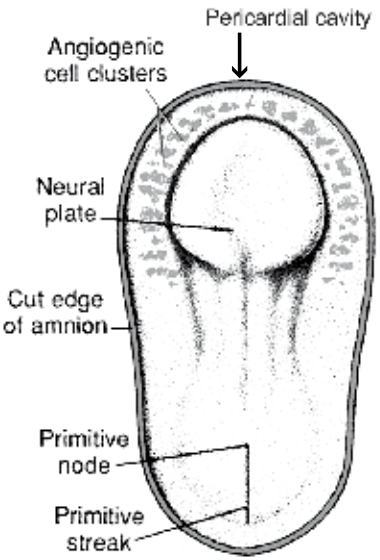


Fig. 5.5. The horseshoe shaped plexus of angiogenic cells and the position of the pericardial cavity (adapted from Sadler 1995)

In a next phase, blood islands also start to form on the cephalic end of the embryo. The capillaries on the lateral sides of the embryo and the cephalic capillaries grow to form a horseshoe-shaped plexus of small vessels around the developing embryo (fig. 5.5.). Blood is already moving in this plexus, possibly aided in its movement by the factors that also influence the slow, rhythmic vasomotion in adult vessels (see section 5.4.1.). At the cephalic bend of the horseshoe the plexus is called the cardiogenic area. The rapid growth of the central nervous system over the cardiogenic area in a cephalic direction results in the *relative descent* of this area from a location above the future head (fig. 5.5.) to the cervical and finally the chest region (see figure 5.6. and also section 4.2.3.). It becomes enclosed in the

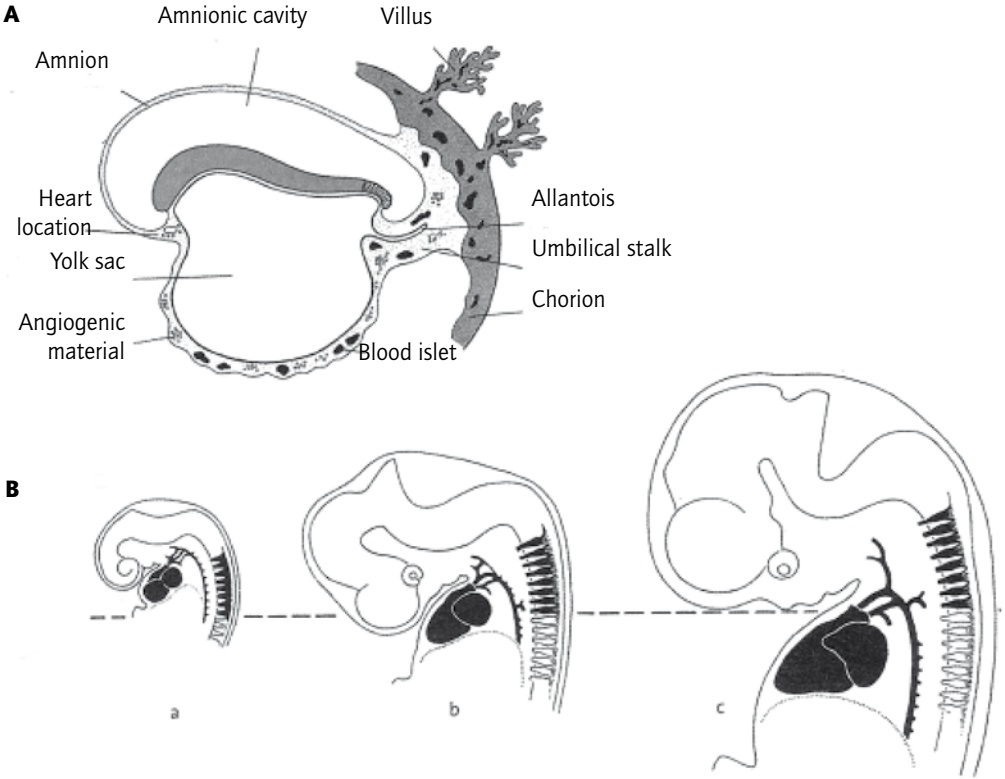


Fig. 5.6. The descent of the heart. A: Heart location in the embryo on day 19 (after Langman, 1995). B. Descent of the heart on day 29, 42, and 48 (Hinrichsen1990)

chest when the embryo folds laterally and the lateral sides fuse together anteriorly immediately after (see figure 5.6.). Initially the heart and vessels develop as a *paired, symmetric system* (see also section 4.2.1.); on day 21 the heart vessels and parts of the circulatory vessels have become fused.

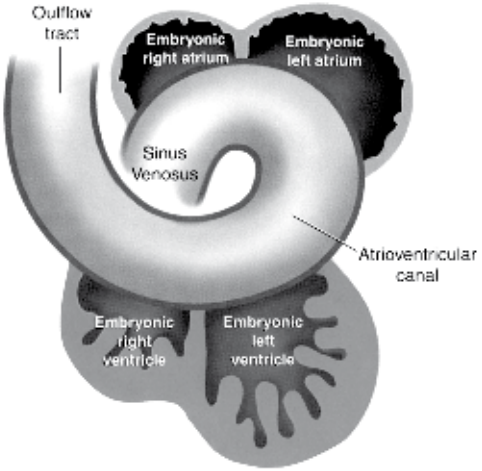


Fig. 5.7. The human embryonic heart at 4 weeks of development showing the primary heart tube with ballooning atria and ventricles (Moorman 1999)

The Cardiogenic Area

The morphological development of the heart is an autonomous process, independent of the environment. The cardiogenic area in the crescent part of the horseshoe expands and forms the cardiac loop, the forerunner of the primary heart tube, from which the future atria, ventricles, and outflow tracts develop. The cardiac loop bulges more and more into the pericardial cavity. Ballooning expansions from the primary heart tube will form the future atria and ventricles (fig. 5.7.). Research into the origin of the ballooning and the formation of septa in the primary heart tube seems to indicate that the placement of the ballooning expansions may be determined by the flow of blood through the primary heart tube (Moorman 1999 and 2000). Where the blood runs into the walls these start to balloon; outside the tract of the flow of blood, the septa develop (fig. 5.8.).

Embryologically, the *coronary arteries* originate epicardially, in the tissue surrounding the left ventricle. During heart development, they grow toward their final point of origin in the area behind the cusps of the aortic valve.

The heart is the first organ to form and function in the developing embryo. Other examples of how the flow of blood in heart and vessels initiates changes in shape are apparent at birth (see 5.4.1. The heart). Then the closure of the umbilical vessels is followed by an

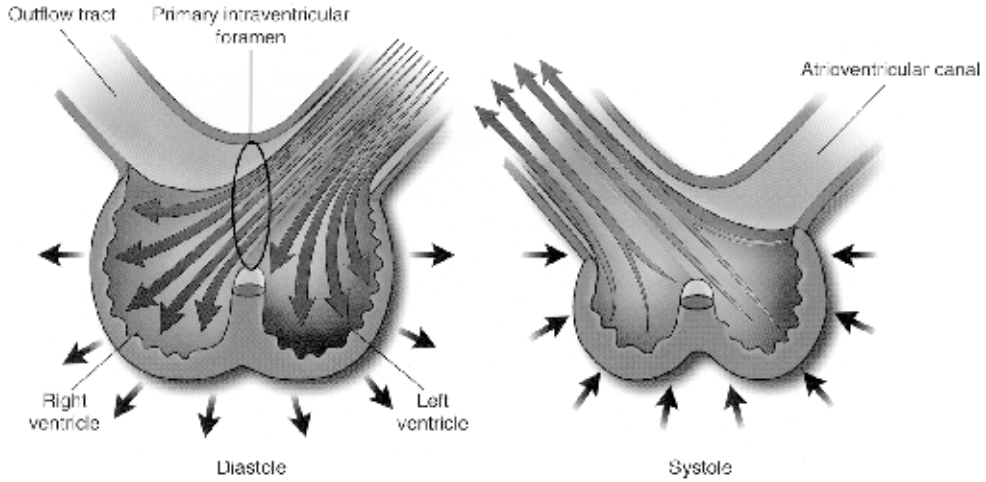


Fig. 5.8. Blood flow through the embryonic heart in diastole and systole. In diastole, blood to the right ventricle flows through the interventricular foramen, in systole blood from the left ventricle flows through the interventricular foramen (from Moorman 1999)

abrupt functional closure of the foramen ovale between the atria, as well as the closure of the ductus venosus, which had until then diverted the portal blood from flowing through the liver. Closure of the umbilical vessels and cessation of the large placenta circulation results in an acute increase in systemic vascular resistance. However, the foramen ovale also closes when the umbilical circulation is not abruptly halted. The aeration of the lungs decreases vascular resistance in the pulmonary circulation. The consequent change in flow between the atria and in the ductus venosus results in their direct functional closure, which eventually becomes anatomical. The ductus arteriosus also experiences a reversal of flow, yet its closure after birth seems to be related to increased oxygenation of the blood in the ductus.

The blood and vessels develop from the same angiogenic tissue, which is originally located at the periphery of the embryo. At first, capillaries develop and form a horseshoe shaped plexus. The heart forms in the crescent of the horseshoe as a symmetric, paired organ, and

becomes the most developed part of the vessels. The developing heart descends to its final location through growth of the central nervous system. Blood flow may have an effect on the final shape of the heart.

5.3. Blood Supply for Heart and Circulation

The heart has its own, separate blood supply, the coronary system (fig. 5.9.). The coronary circulation, in which 4-5% of the cardiac output flows, supplies the heart with blood. The right and left coronary arteries originate in the recession behind the cusps of the aortic valve. Blood flows in them during the relaxation phase (diastole) of the heart, in contrast to the systemic circulation, where blood flow is strongest during the contraction phase (systole) of the heart. During contraction of the heart, blood flow in the coronary arteries comes to a standstill and may even reverse at the end of systole.

The major determinant of coronary flow is the metabolic activity of the myocardium. Increased metabolic activity decreases coronary resistance and thus increases flow and vice versa. Only $^{1}/_{10}$th of a millimeter of the endocardial surface thickness receives its nutrients directly from the blood in the heart chambers.

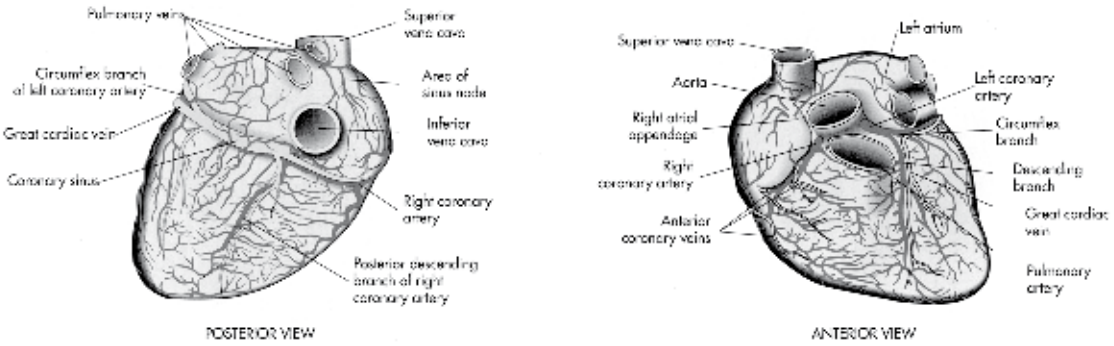


Fig. 5.9. The coronary vessels (from Berne 1998)

The right coronary veins empty into the right atrium directly, the left coronary veins empty into the coronary sinus first. A small amount of the blood can enter the heart chambers directly through the thebesian veins (see also section 5.2.2.) and the arteriosinusoidal and arterioluminal vessels.

The coronary vessels of cold-blooded animals have a thin inner layer of endothelial tissue. In warm-blooded animals, the endothelium becomes thicker. In humans, the endothelium thickness reaches 33% of the total vessel wall thickness, which makes it equal to the thickness of the two other vessel wall layers, the muscular layer and the layer with blood vessels and nerves around the vessels. Each of these three layers comprises 33% of the total wall thickness in humans. Plaque formation and myocardial infarction occurs in the endothelial layer and is specific for humans.

The larger arteries also have their own blood supply. The small vessels can receive their nutrients directly from the blood that flows through them.

The heart has its own special circulation, in which the blood flows when the heart is in its rest phase and blood flow slows down in the pulmonary and systemic circulation; and in which the blood comes to a standstill when the pulmonary and systemic circulation have the greatest flow. This reversal is a phenomenon that is essential for the existence of rhythm. In rhythm the direction of the flow needs to be reversed constantly in order to elicit the back and forth of rhythmicity. It shows that the heart is the archetype of rhythm.

5.4. Physiology of Heart and Circulation

5.4.1. Blood Flow in Heart and Circulation

The Capillaries and Arterioles

Blood flow in the capillaries occurs *rhythmically*, even before the heart is functional. The rhythm is relatively slow, turning on and off every few seconds or minutes. The rhythmical oscillatory movement in the capillaries is accompanied by rhythmic contraction and

relaxation of the musculature of the precapillary vessels. This phenomenon is called *vasomotion*.

Vasomotion is a mostly autonomous movement and is autoregulated. Smooth muscle fibers in the whole circulation are excitable and discharge electrical impulses. In the precapillary vessels, the rhythmical electrical discharge is accompanied by contraction of the smooth muscle fibers (section 5.4.2. Smooth muscle cells). The flow of blood in the capillaries can be enhanced by local metabolic requirements. Changes in the local metabolic needs causing a decreased oxygen concentration will result in an increase in the duration and frequency of flow through the capillaries. Another factor that may influence the flow through the capillaries is the activity of the erythrocyte membrane. The erythrocyte cell membrane has very special characteristics and can roll along the hemoglobin in the cell. Special proteins serve as connecting compounds both on the inside and on the outside of the erythrocyte cell membrane to allow greater plasticity of the membrane form. This gives the erythrocyte cell membrane both more form stability as well as making it more flexible in form. The erythrocyte shape adapts itself to fit in the capillaries; the rolling membrane allows the erythrocyte to move like a caterpillar through the capillaries (Busse 1982).

Diffusion in the capillary bed
In the capillaries, many of the constituents of the blood such as nutrients, electrolytes, and blood gases diffuse *passively* from the plasma to the tissues and back. The thermal motion of water molecules and dissolved substances in the blood drives the diffusion. Water-soluble substances move 80x faster through pores in the capillary membrane to the tissue interstitial space than the plasma moves through the capillary. Lipid-soluble substances such as O_2 and CO_2 can diffuse directly through the lipid membrane. The rate of diffusion is proportional to the concentration difference of the substance between the interstitial space and the capillary lumen.

Vasomotion is an observed autonomic movement of blood accompanied by contraction of precapillary vessels. Local metabolic needs and the rolling capacity of the erythrocytes through the capillaries influence capillary blood flow. Exchange of substances between

capillary lumen and tissue happens by diffusion driven by the thermal motion of water molecules.

The Heart

The heart muscle also contracts and relaxes *rhythmically*, at a rate of approximately 72 times per minute in rest. The rhythmic self-excitatory activity of the arterioles becomes further developed in the heart, where two specific areas rhythmically discharge electrical impulses faster than the other cells of the functional syncytium. The sinus node (or sinoatrial node) in the right atrium discharges at the fastest rate and therefore normally overrules the discharges in the atrioventricular node (a-v node), which is situated at the transition of the right atrium to the right ventricle. The impulses of the sinus node set the rhythm for the contractions of the heart muscle fibers at 72 beats/minute. The contractile strength (contractility) and the rate of the heart are determined largely by the venous return of blood from the circulatory periphery (see section 5.5.). The heart uses ketone bodies from the metabolism of lipids for its energy supply.

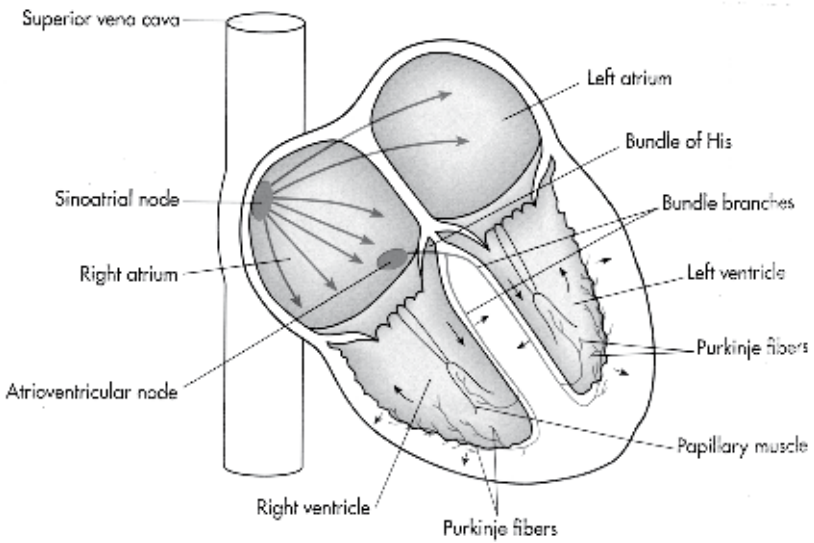


Fig. 5.10. The conduction of the nodal impulse throughout the myocardium (from Berne 1998)

Between the nodes and from the sinus node into the left atrium and from the a-v node into both ventricles, specialized myocardial cells conduct the electrical impulse to reach all heart muscle fibers at approximately the same time (fig. 5.10.). The functional syncytium of heart muscle fibers is directly connected to the cells of the sinus node and a-v-node, and to the specialized fibers that conduct the electrical excitatory impulse throughout the heart. The electrical impulse moves to the epicardial surface of the myocardium along the direction of the spiraling layers (Guyton 2000).

Contraction of the ventricles starts at the apex. However, at the base of the heart, where the outflow tracts start, the muscle layers are thickest and contraction is strongest. If the spiral arrangement of the heart muscle layers would result in a spiral contraction pattern and this would give a spiral shape to the blood stream out of the ventricle, then the thickness of the muscle layers at the base of the heart and the thin apex would be physiologically logical (see Kilner 1993, 2000, 2002).

The *four valves* of the heart aid in maintaining the direction of the flow. Yet the direction of flow is largely maintained even in the face of mitral insufficiency, when the mitral valve between left atrium and left ventricle does not close properly. A much greater than expected volume of blood takes its normal course out of the left ventricle into the aorta in such situations, rather than flowing back into the left atrium. All valves open and close *passively*. Of the blood in the heart about 50% is oxygenated and 50% non-oxygenated.

The centrally located heart is a completely active, rhythmical organ. The quality of rhythmic, self-excitatory activity of the arterioles is especially developed in the heart. The smooth muscle cell functions of rhythmic excitability, conduction, and contraction are taken up and perfected by three differentiated cell groups in the heart, the sinus and a-v nodes, the conducting fibers (including the Purkinje fibers in the ventricles), and the myocardial cells, respectively. The heart valves aid the direction of the blood flow.

The Large Arteries

Contraction of the heart ejects the blood out of the heart into the large arteries. These have muscular walls which can dilate and contract to control the flow of blood. During the

contraction phase of the heart, the aorta dilates to accommodate the rushing in of ejected blood. During diastole, the aortic wall will contract as a result of elastic recoil, and the blood will be aided on its way to the periphery as the arterial walls convert the potential energy of stretch into blood flow. The pressure in the aorta is higher than in the left ventricle after the rapid ejection phase of the heart. Yet this reversal of the pressure gradient does not result in the return of blood to the ventricle during the last part of the ejection of blood from the ventricle because of the momentum of the blood itself.

After the blood has passed through the arterioles, the fluctuations in flow from cardiac contractions ceases, and blood flow becomes dependent on autonomous mechanisms.

The flow of blood in the large arteries is partially dependent on the momentum of the blood itself, which it is given in the heart and which is enhanced by the elastic recoil of the smooth muscle layers of the arteries. In the arterioles the cardiac impulse is more evened out, and the blood moves with a slow, rhythmic flow through the capillaries.

The Veins

Blood flow in the veins is dependent on the flow of blood through the organs, which is determined by the metabolic requirements of tissues. It is enhanced by the contraction of muscles around the veins and by the valves in the veins. The sum of venous blood flowing back from the tissues to the heart is the *venous return*. It is the main determinant of heart rate and contractility (see section 5.5).

Venous return is determined by the metabolic requirements of the peripheral organs and tissues and in turn determines heart activity.

➔ *Blood flow in the heart and circulation gets its determining impulse from the metabolic needs of the tissues.*

5.4.2. Electrophysiology of the Smooth Muscles and the Myocardium

The muscle cells in vascular walls are smooth muscle cells. All muscle cells - skeletal muscle, heart muscle, and smooth muscle cells - contain thin actin and thick myosin filaments. Shortening of the fibers by sliding of the actin and myosin filaments alongside each other is associated with the contraction of muscular tissue (fig. 5.11.).

Smooth Muscle Cells

The amount of actin is 5-10 times greater than the amount of myosin in smooth muscle cells. Due to the special arrangement of actin and myosin, smooth muscle fibers can contract to 20% of their length, whereas skeletal fibers can contract up to just 70% of their length. On the other hand, smooth muscle cell contraction is slow, yet it may be prolonged and develop high forces with low ATP usage, due to the slow metabolic cycling of the myosin cross bridges with actin. Thus, the force of contraction is great in smooth muscle, but the rapidity of contraction is slow compared to skeletal muscle. Skeletal muscle contraction, however, can be consciously controlled, in contradistinction to smooth muscle or heart muscle contractions. The influx and transport of Ca^{2+}, which is much slower than sodium transport and therefore can contribute to the slow but sustained contraction, generates the action potential in the smooth muscle cells of vascular tissue. The action potential allows the calcium influx to increase and spreads the impulse over a larger region. Graded changes in the membrane potential of the sarcolemma may accompany changes in force of contraction. Sodium participates only little in generating the action potential in smooth muscle.

In the smaller arterioles the smooth muscle fibers exhibit automaticity, because they are self-excitatory. These smooth muscle fibers have the property of generating basic slow wave rhythms in the cell membrane potential that act as pacemaker waves (section 5.4.1. The capillaries and arterioles).

The Myocardium

The *muscle cells* of the heart appear striated, like skeletal muscle, due to the arrangement of actin and myosin filaments. The ratio between actin and myosin is 2:1. The duration of

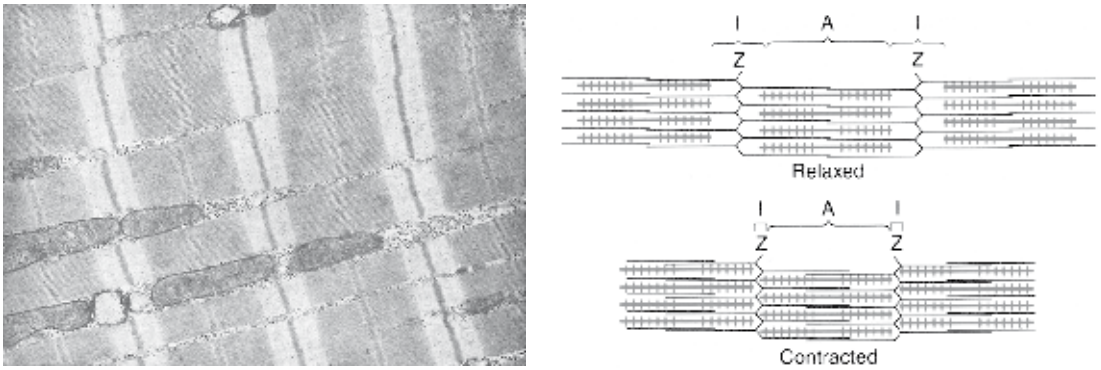


Fig. 5.11. Electron micrograph of myofibrils and schematic representation of the placement of actin filaments (light lines) and myosin filaments (dark lines) in contraction and relaxation in striated muscle (from Guyton 2000)

contraction in cardiac muscle is also longer than in skeletal muscle. The specialized excitatory muscle cells in the sinus and a-v nodes hardly contract but have rhythmicity and generate the action potentials that induce the rhythmical beating of the heart. The action potential in cardiac *muscle* is due to opening of fast sodium channels as well as slow calcium channels. By comparison, skeletal muscle cells operate solely under the influence of fast sodium channels. The fast sodium channels cause a phase of rapid depolarization (a few 10,000ths of a second); the slow calcium channels sustain and prolong polarization (several 10ths of a second). There is excitation/contraction coupling in the myocardium, like in skeletal muscle, and unlike in smooth muscle. The self-excitatory effect of the *nodal cells* is related to the constant slow leaking of sodium during relaxation, which lays the basis for the next action potential. The fast sodium channels are not operative in these cells. The actual quantity of sodium that enters the cell is so small that it does not affect the intracellular sodium concentration. The action potential in skeletal muscle is also based on sodium influx and transport, like the action potential in the nerves that innervate skeletal muscles.

➔ *Smooth muscle cells are the most primitive muscle cells. Their electrical activity is*

mainly based on calcium metabolism. Cardiac muscle cells differentiate and specialize to take on the different functions of self-excitation, conduction, and contraction. Their electrical activity is chiefly based on calcium transport in muscular tissue and sodium transport in nodal tissue. Skeletal muscles have the most specialized and most developed muscle cells. They can be moved consciously, with the help of the nervous system, in contradistinction to smooth muscle and heart muscle. Their electrical activity is mainly based on sodium transport. Cardiac muscle takes in a middle position between smooth muscle and skeletal muscle.

5.5. Regulation in Heart and Vessels

5.5.1. The Heart

The Frank-Starling Mechanism and Regulation of Heart Rate

Regulation of the flow of blood through the heart is normally almost entirely done by an intrinsic mechanism, the Frank-Starling mechanism (fig. 5.12.). This mechanism implies that venous return to the heart controls the force of contraction of the ventricles. Venous return also regulates the rate of firing of the sinus node through stretching of the atrial wall. The stretching of the ventricles and atria, through increased filling as venous return increases, results in an increase in the amount of blood that is ejected by the heart through increased contractile strength and increased heart rate.

Venous return to the heart is dependent on the return of blood from the tissues. Each peripheral tissue controls its own blood flow and venous return to the heart is the total of all local blood flow to the right atrium.

Autonomic Influence

Heart rate and contractility can also be modified by the autonomic nervous system. Sympathetic stimulation increases cardiac output by increasing both heart rate and force of contraction. Parasympathetic stimulation mainly decreases the heart rate. When the

heart is denervated, as is the case in heart transplant patients, cardiac reaction to stress is still quite adequate. This demonstrates the autonomous nature of the heart and the effectiveness of the Frank-Starling mechanism. *Intrinsic regulation of cardiac output through venous return is the main determinant of heart activity.*

Temperature

Contractility and heart rate are also regulated by temperature. In fever the contractility is greater and the heart rate may be doubled.

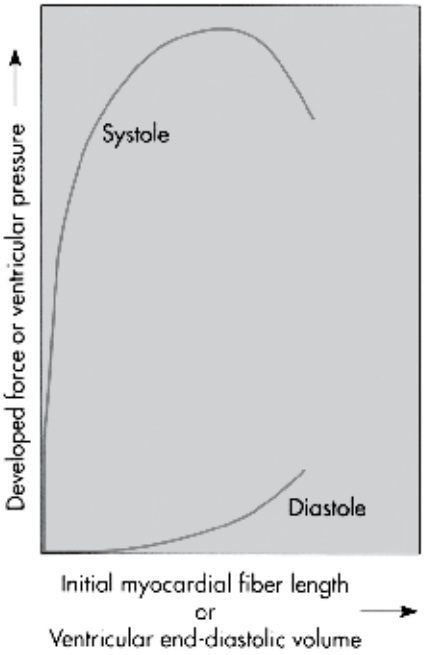


Fig. 5.12. The Frank-Starling mechanism: increased end-diastolic volume (i.e. increased myocardial fiber length) results in increased contractile force in systole (from Berne 1998)

5.5.2. The Vessels

Blood flow in the larger arteries is regulated by the cardiac output and the contractility and elasticity of the vessels. Blood flow in the smaller vessels is determined by the metabolic activity of the organ or tissue in question. In humans, the perfusion of the subcutaneous capillary network is influenced by soul states, such as shame (blushing). Subcutaneous capillary perfusion changes can also be used to regulate heat loss through the skin. The human subcutaneous capillary network is unique in this respect and both of these processes are only possible in the human organism.

Regulation of the flow in the heart and vessels is mainly intrinsic and autonomic.

➔ *The central organ of the heart is totally dependent on the periphery to regulate its activity. The movement of heart and vessels is determined by the flow of the blood as much as the heart and vessels' movement determines the flow of the blood.*

5.6. The Function of the Heart and Circulation for the Organism

The heart and circulation bring rhythmic movement to the fluids of the body. They impart their own intrinsic movement to the blood they carry, which imparts this movement to the whole organism. The heart and circulation carry warmth throughout the organism by means of the blood and effect a differentiated warmth organism by individualizing the blood supply to different tissues. The heart and circulation are intimately related to the blood.

The heartbeat has two components: the first and the second heart sound. Each human being's heartbeat is unique. The tone and the rhythmic relation of the first and second heart sounds are different for everyone. The blood carries the heartbeat and rhythm into the organism. The heart and circulation, together with the blood, ensure that the organism can function as a *rhythmic whole*. In contrast, the hormonal substances, which are secreted and carried in the blood, ensure the *metabolic* unity of the organism; and the nervous system, the fibers of which often run next to the vessels, ensures that the organism functions as a whole in regard to *sensory* impulses. Embryologically, the heart and circulation are functional before the hormonal and nervous systems, and heart and circulation therefore carry the first responsibility to maintain unity in the growing organism of the embryo. (For a more detailed description of the three areas mentioned here and their characteristics and functions see the *Anatomy Module* of **BOLK**'S COMPANIONS FOR THE STUDY OF MEDICINE.)

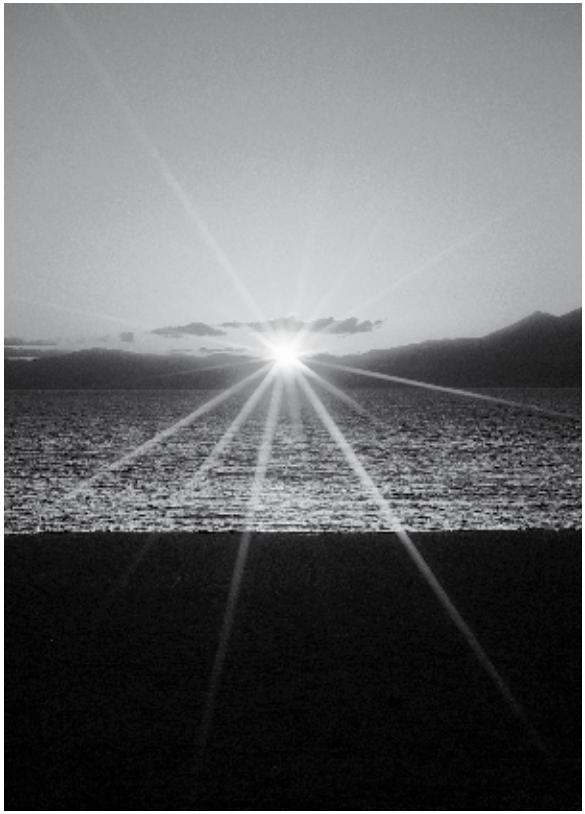
➔ *The function of the heart, blood, and vessels is to bring unity to the organism. The blood warms the organism, enabling it to function as a rhythmic whole.*

5.7. Conclusion

- Morphology:
  Heart and circulation have their *own strong form*. The systemic and pulmonary circulations together form a *lemniscate*. The heart muscle fibers form a double spiral.
- Embryology*:*
  The *heart and circulation as well as the blood* originate from the same angioblast cells at the beginning of the third week of embryological development. The relation between the two becomes functional as they act together to deliver and collect substances, rhythm, and warmth to and from the tissues.
- Blood supply:
  The heart has its *own special coronary circulation* that functions in opposite phase to the pulmonary and systemic circulations. This reversal reveals the *archetypal rhythmic* quality of the heart.
- Physiology:
  The heart is an *active, autonomous* organ that generates its own rhythmicity. Blood flow is mainly determined by the metabolic needs of the tissues. The flow of blood is individualized in peripheral tissues according to their metabolic needs. *Passive* diffusion enhanced by *thermal* motion of molecules is the main mechanism for the exchange between the plasma and the tissues in the periphery.
- Regulation*:*
  The output of the heart is mainly determined by the *venous return* from all the tissues of the body. The blood that flows from the heart supplies the tissues. In this way the heart is in living, active interrelation with the peripheral tissues. This relation could be represented by a *lemniscate*. The heart is largely *autonomous*.
- Function:
  The heart exhibits its own *activity* in the beating of the heart and *imparts this activity to the whole organism* through the rhythm of the flowing blood and makes the organism into a unity.

	Lung + Respiratory Tract	Liver + Intestinal Tract	Kidneys + Urogenital Tract	Heart + Circulation
Morphology	Shape from without, tubular organ, **membranous structure**	Mostly shaped from without, uniform parenchyme, tubular organs	Own active form, differentiated parenchyme with cortex and medulla, tubular parts specialized	Own active form, **newly formed tubular lumen**
Blood supply	50% of *weight* is blood, largely O_2 unsaturated, capillary blood in thin film	Largest *flow*, special *venous portal system*, ¼ is O_2 saturated, ¾ has low O_2 saturation, capillary blood in thin layer	Second largest flow, *unique arterial system*, high O_2 saturation, capillaries in tufts	**Own circulation in reverse phase,** ½ O_2 saturated, ½ O_2 unsaturated
Physiology	Passive diffusion	**Great activity in metabolic cycles**	Both active and passive processes	**Imparts rhythmic activity and warmth to the whole organism**
Regulation	Mainly from without, via the central nervous system	Both through local hormones and local autonomic plexuses, some via central nervous system	Both local and external hormones and buffering processes, kidneys secrete regulatory hormones for functions in organism	**Mainly determined by the periphery,** autonomous
Function	Passively supplying	Passively supplying, maintaining, and storing	**Actively regulating the internal milieu of the organism**	**Makes the organism into a unity**
Characteristic	Membrane-like tubular structure, *diffusion of gases* (O_2 and CO_2) and water	Physiologically active in metabolic cycles, diffusion and *absorption of fluid nutrients* in tubular part	Active regulatory function in the organism, diffusion and *resorption of blood constituents* in tubular parts	Middle position in organism, *makes the organism a unity*

➔ *The characteristic feature of heart and circulation is that they are not only constantly active, autonomous organs, but that they also permeate the whole organism with their rhythmic activity and warmth. The "tubular shape" of the vessels arises anew in the angiogenic tissue during embryological development. The "parenchyme" of the heart is actively moving muscular tissue. The heart has its own special circulation that reveals its rhythmic nature. The heart takes in a middle position in the organism morphologically and functionally. Heart and circulation contribute to the integrated functioning of the organism as a unity.*



Physiology

Organphysiology from a Phenomenological Point of View

Can physiology give more insight into the living human organism than the mere facts reveal at first? Is the level of activity the same for all organs? Are the vital qualities at work in organs unique for organisms and limited to biological activity? Can we find a scientific basis to research the coherence between organ systems?

By enhancing the current scientific method with phenomenological points of view we can find meaning in the facts and understand them as an expression of life itself. The phenomenological method makes the relation between organs visible and comprehensible. It approaches scientific facts from the point of view of their coherence and can give totally new insights this way.

What emerges is a grasp of the interrelations between biological processes, consciousness, and nature.