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1 Anatomy and Physiology of the Circulation of Blood

1.1 Blood

Blood can be regarded as a liquid tissue. It circulates in the body, driven by a pump, the heart. Our blood accounts for 7 to 8% of our body weight, which in a person of 70 kg (154 lb) body weight amounts to about 4.5 to 6 L of blood. Blood is made up of **blood plasma** and **blood**

cells (erythrocytes, leukocytes, and thrombocytes; ► **Fig. 1.1**).

Red blood cells (erythrocytes) develop like all other blood cells from pluripotent stem cells in the bone marrow (► **Fig. 1.2**). Erythrocytes contain hemoglobin, which transports oxygen. They are not motile (i.e., they cannot move on their own), but are carried along in the bloodstream.

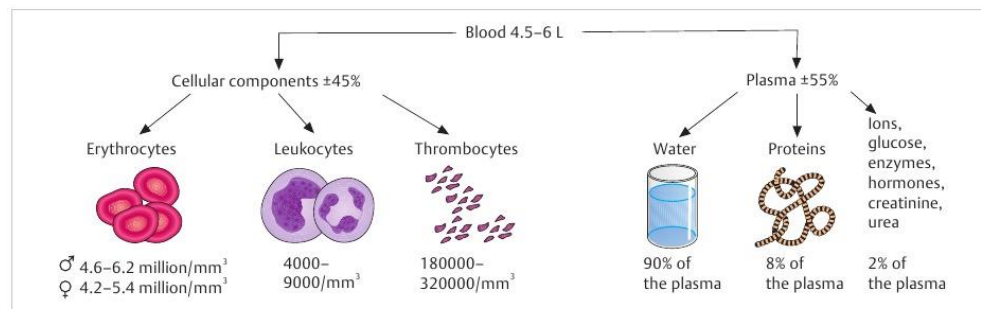


Fig. 1.1 Solid and liquid blood components.

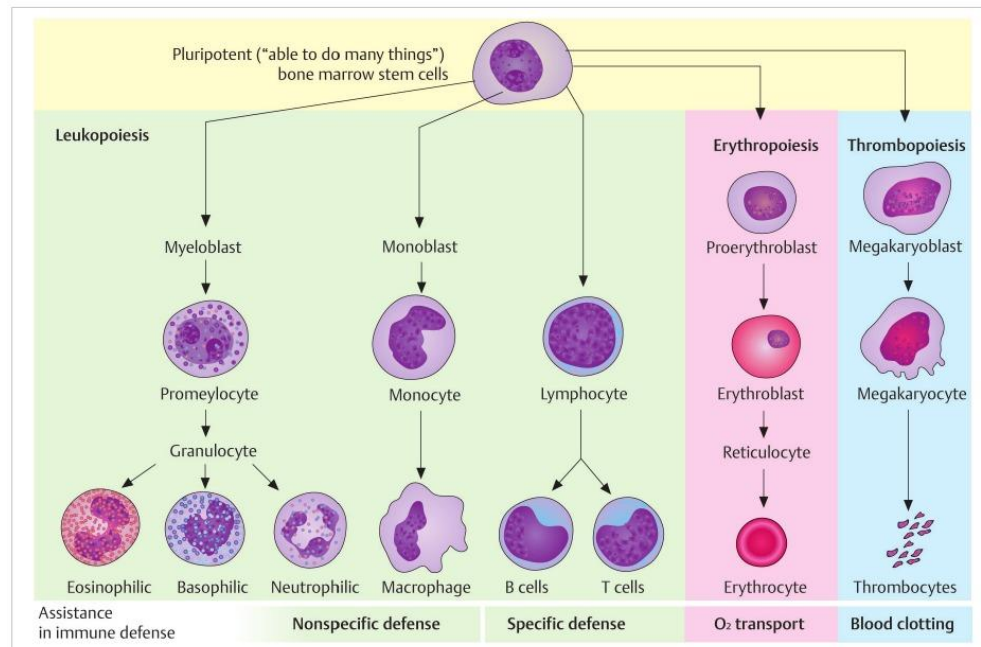


Fig. 1.2 Family tree of blood cells.

White blood cells (leukocytes) include granulocytes (neutrophilic, basophilic, and eosinophilic), lymphocytes, plasma cells, and monocytes.

Thrombocytes are blood platelets, which play an important part in blood coagulation.

Blood plasma contains dissolved organic and inorganic molecules. Albumins make up the majority of **plasma proteins**. They are metabolized in the liver and have a role as transporters, for example, of hormones. Like all plasma proteins, albumins are water soluble and are thus responsible for the colloid osmotic pressure. The immunoglobulins (also called antibodies) are the molecular front of the body's defense system. They are released into the blood by certain lymphocytes, called plasma cells.

Both blood and lymph contain **fibrinogen**, which has a role in coagulation. Examples of organic substances found in blood are lipids, lipid-protein compounds (lipoproteins), hormones, vitamins, amino acids, and bile pigments. "Organic substances" is the name given collectively to all molecules containing the carbon atom C, except for CO (carbon monoxide) and CO₂ (carbon dioxide).

Examples of inorganic substances are phosphate, iodine (I), iron (Fe), potassium (K), and sodium (Na).

The main task of blood is as a transporter. Oxygen is carried from the lungs directly to all tissues via the red blood corpuscles (erythrocytes), and carbon dioxide is carried back from the tissues to the lungs. The only structures excluded from this direct exchange are joint cartilage, a small section of the bone-tendon connection, and parts of the intervertebral disk. In addition, as a liquid medium, the bloodstream transports nutrients from the intestines to the tissues and metabolic waste to the organs of excretion.

1.1.1 Red Blood Cells (Erythrocytes)

Erythrocytes, which are non-nucleated, make up 99% of the corpuscular components of the blood. Their function is to transport oxygen, which bonds in the cell, to hemoglobin, the ferrous blood pigment.

Erythrocytes are formed in the bone marrow and have a life cycle of 120 days. They are broken down in the spleen. At maturity, they are 6 to 7 μm in size, which means they are larger than the diameter of the capillaries. Because they cannot move on their own, they have to be very pliable so that they can be pushed through the capillaries ($\Rightarrow$ Fig. 1.3).

1.1.2 White Blood Cells (Leukocytes)

Leukocytes are not a uniform group of cells. Their three main groups comprise such differing cells as lymphocytes, granulocytes, and monocytes. **Q 50**

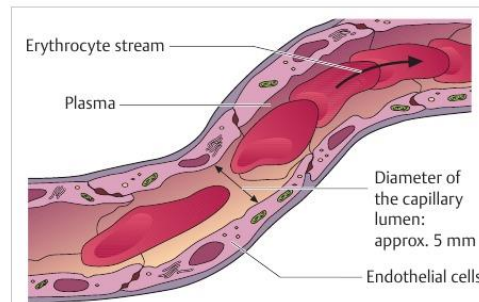


Fig. 1.3 Deformation of red blood cells as they pass through capillaries.

Granulocytes, which are nonspecific defense cells, make up 60% of leukocytes. They are divided into three groups ($\Rightarrow$ Fig. 1.4a–c):

- Neutrophilic granulocytes (95%).
- Eosinophilic granulocytes (3%).
- Basophilic granulocytes (2%).

With a diameter of 10 to 17 μm , they are considerably larger than the erythrocytes. Granulocytes remain in the blood only for a short period of time, moving on from there to the tissues, especially the mucous membranes, where they fulfill their defense function by destroying bacteria through phagocytosis.

Approximately 30% of white blood cells are lymphocytes. They are 7 to 12 μm in diameter, between erythrocytes and granulocytes in size. Only 4% of lymphocytes circulate in the blood. Most of them are to be found in the lymphatic organs: spleen, thymus, lymphatic intestinal tissue, and lymph nodes.

Lymphocytes are subdivided into two groups: **T lymphocytes**, which are formed in the thymus, and **B lymphocytes**, formed in the bone marrow. These two groups have reciprocal effects. Certain T cells, the T helper cells, can stimulate B lymphocytes after an antigen has sensitized the latter. These B lymphocytes develop into plasma cells, which specialize in producing antibodies. T suppressor cells inhibit the immune response of B lymphocytes and other T cells. Specialized B lymphocytes represent the body's antigen memory. **Q 39**

Lymphocytes come in contact with an antigen in the lymph node. This contact sensitizes them and causes them to reproduce. They leave the lymph node through the efferent lymph vessels, enter the blood, enter the tissues, and then return to the lymph nodes. Lymphocytes spend most of their lifespan in lymph nodes or other lymphatic tissue and only hours (up to 24) in the blood. **Q 11**

Monocytes remain in the blood for a few days and travel from there to the tissues, where they reside as **macrophages** for months or even years. For this reason,

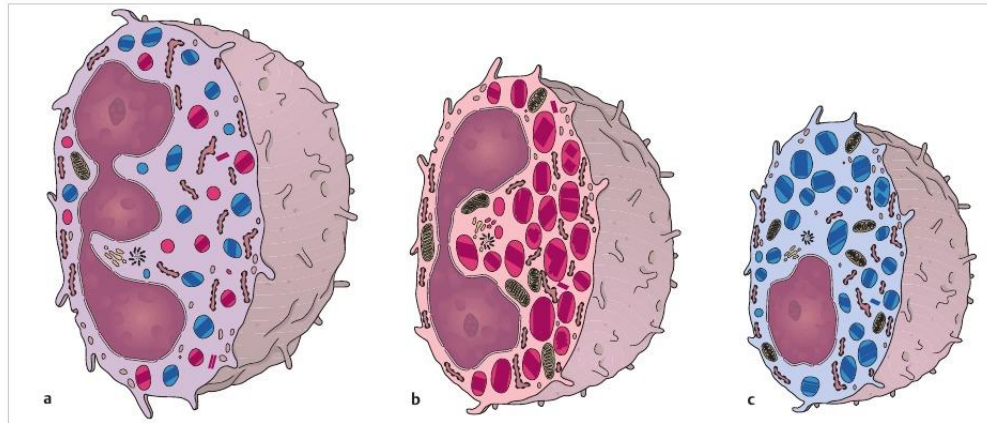


Fig. 1.4 Granulocytes: (a) neutrophilic; (b) eosinophilic; (c) basophilic.

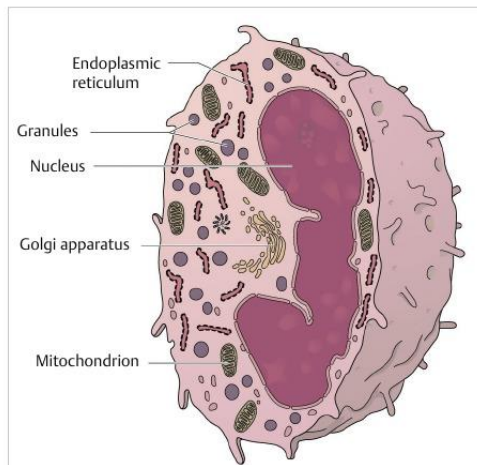


Fig. 1.5 Monocyte.

they are also called histiocytes (from the Greek *histon*, web, tissue). They have a nonspecific part in the defense system: they phagocytose cell debris and antigens. They are quite large (12–20 μm) and possess strong amoeboid motility (► Fig. 1.5). Q 50

1.1.3 Blood Platelets (Thrombocytes)

Thrombocytes are small, flat, and round non-nucleated cells, 1 to 4 μm in diameter. Their lifespan is 9 to 12 days,

during which time they remain in the blood. Their task is controlled coagulation of blood and wound sealing. If the endothelium of the inner vascular wall is damaged, platelets form a thrombus (clump) at the injury site.

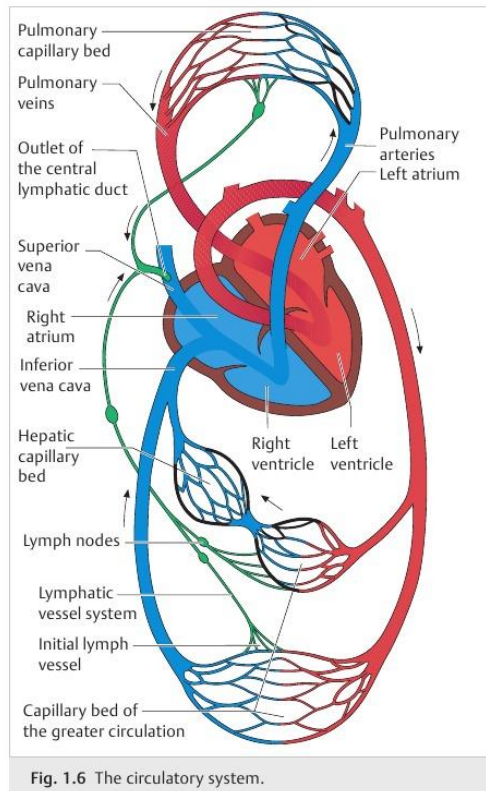
Thrombocytes contain serotonin; serotonin causes vasoconstriction, which inhibits blood loss from the damaged vessel and promotes hemostasis.

1.2 Cardiovascular System

The cardiovascular system is made up of the heart and blood vessels. This system supplies oxygen and nutrients to all the cells in the body, and at the same time removes the waste products of metabolism, including carbon dioxide and substances excreted via the urinary system.

In the “greater” **circulatory system**, oxygen-rich blood coming from the lungs is pumped from the left cardiac ventricle, through the aorta, the arteries, the arterioles, and finally the capillaries into the periphery. Passing through the capillary system, the blood moves from the arterial into the venous system. From the venous part of the capillaries, the blood travels to the venules and veins. Propelled by various complementary mechanisms (valves that prevent the venous return), it travels to the right atrium of the heart, into the right ventricle (► Fig. 1.6). The **muscle pump**, which is activated by any movement of the body, exerts pressure on the veins, particularly in the lower extremities.

The **venous valves** steer the blood in the desired direction. In addition, inspiration creates negative pressure in the thoracic cavity relative to the abdominal cavity, producing a suction that transports the venous blood toward



the heart. The pumping action of the right side of the heart also exerts suction on the vena cava, drawing the blood through this vessel toward the heart. **Q 48**

At this point, the **pulmonary or "lesser" circulation** begins. The right cardiac ventricle pumps the blood into the lungs. Oxygen exchange takes place in the pulmonary alveoli, analogous to the exchange seen in the capillary system. In this case, carbon dioxide (CO_2) is released and oxygen (O_2) is taken up. The oxygen diffuses into the erythrocytes. There it forms a compound with hemoglobin, turning into oxyhemoglobin. The blood travels from the lungs back to the left cardiac ventricle and has come full circle. Thus, the arteries provide the blood flow into the tissues and the veins provide the blood flow out of them (**► Fig. 1.7**).

The **blood pressure** is relatively high in the arteries and drops away further down the branches of the system (e.g., the pressure in the brachial artery of the upper arm, where blood pressure is usually taken, is in the range of 120–140/80–90 mm Hg in the healthy adult). Precapillary sphincters lower the pressure in the capillaries to 30 mm Hg. The pressure in the venous system is about

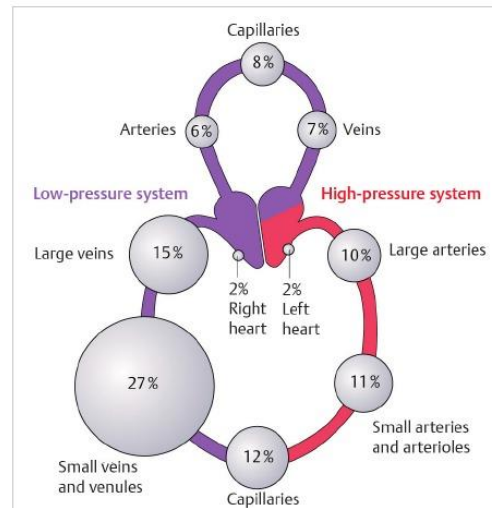


Fig. 1.7 Distribution of the blood volume in the circulatory system.

10 to 25 mm Hg; finally, in the veins close to the heart, it drops right down to 2 to 4 mm Hg.

Blood pressure is regulated by complex mechanisms, including the autonomic nervous system, hormones, and even ions. Vasoactive substances include histamine, prostaglandin, serotonin, and epinephrine. The exchange of cell nutrients takes place through the walls of the capillaries, where the flow rate is rather slow. Flow rate, blood pressure, and the diameter (caliber) of the vessels play an important role in metabolic processes. Blood flow is regulated by changes in vascular radius. The flow into the capillary areas is also regulated. At no time are all the capillaries open simultaneously. A large proportion of the blood is stored in the venous system, spleen, and liver. Vascular constriction increases the resistance to blood flow and perfusion decreases.

1.2.1 Arterial System

The arterial wall consists of three layers: the interior vascular endothelium with an elastic membrane (tunica interna or intima); the middle layer with elastic fibers and smooth muscle cells (tunica media); and the outermost connective-tissue layer, which also contains elastic fibers (tunica externa; **► Fig. 1.8**).

This three-layer structure is crucial to maintaining a steady blood flow. The volume of blood expelled with each systole briefly dilates the aorta and the arteries close to the heart. During the diastolic phase, when the heart muscle

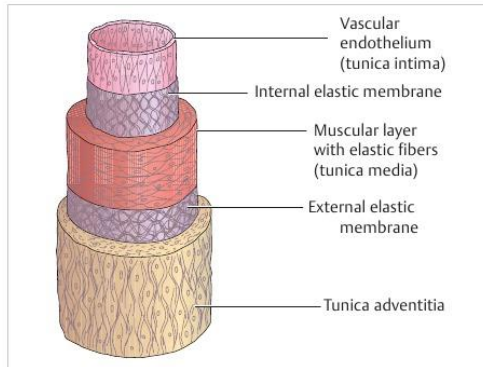


Fig. 1.8 Structure of an arterial wall of the muscular type.

relaxes, these dilated vessels recoil, pushing the blood forward. If the aorta was rigid like a pipe, the blood flow would stop after systole. This mechanism is called the **Windkessel effect**, and it is due to the relatively high percentage of elastic fibers in the vessel wall. Further toward the periphery of the body, the muscular layer is more dominant in the arterial walls. These arteries can actively contract and thus considerably increase the flow resistance of the entire system. For this reason, they are called resistance vessels; they help regulate blood distribution and blood pressure.

The resistance vessels include the arterioles, whose caliber is only 1% that of the arteries. Only about 10% of the blood volume is in the small arteries and arterioles.

The main function of these vessels is to regulate blood flow in the downstream capillary network, which they do by means of their contractility, controlled by the sympathetic nervous system (vasomotion). They therefore have a very strong effect on the function of the body parts that they supply. The precapillary sphincter has two tasks: to regulate (1) capillary blood flow and (2) blood pressure. Increased blood flow will cause active hyperemia. As mentioned earlier, precapillary sphincters can contract if energy needs are low, and send the blood directly into the venous system via an arteriovenous anastomosis. **Q 52**

1.2.2 Capillaries

The capillaries form the transition between the arterial and venous systems. With a diameter of 3 to 8 μm , they are extremely narrow. The walls of the capillaries are made of a single endothelial layer (the endothelial cells are sheathed by the endothelial glycocalyx) and a basement membrane. The wall is semipermeable; that is, depending on its structure (the size of its “windows”), certain substances can selectively pass through. The exchange of substances

is additionally supported by the flow rate in the capillaries, which is very slow. The actual exchange takes place in the capillaries and does so by diffusion, osmosis, and filtration.

1.2.3 Venous System

From the capillaries, the blood travels to the venules, whose walls are only slightly thicker than the capillary walls. They have few muscle fibers and are elastic. From the venules, the venous blood travels to the larger veins, which eventually carry it all the way to the right heart, where it restarts its journey to the lungs for oxygenation. The walls of the **veins** are structured in the same way as the walls of the arteries, but they are considerably thinner; this is adequate because the pressure in the venous system is lower. In the small and middle-sized veins, the inner layers of the walls form small flaps or pouches, called venous valves, which keep the blood from running backward. **Q 48**

The activity of the muscle pump has an important role in maintaining blood flow from the veins back to the heart. When muscles surrounding the veins contract, the blood is pushed toward the heart as long as the venous valves are functioning properly. Thus, the important veins of the legs are located deep in the tissue, where the muscle pump can propel the blood with every movement of the leg. In addition to the deep veins, superficial veins also exist in the legs, forming a close network under the skin. Perforating veins connect the deep veins with the superficial veins. They act as a one-way street and physiologically only allow blood to flow from the surface to the deep layers—not in the other direction.

If the pressure on the venous walls becomes inadequate, the blood can no longer be moved along fast enough and can become stagnant. The veins give way under the internal pressure and dilate, because they have few muscle fibers. As a result, the valves no longer seal the lumen properly, and blood travels backward—increasing the internal pressure even more. This insufficiency of the venous valves leads to **varicose veins (varices)**.

Approximately 60% of the entire blood volume is located in the venous system; this is why veins are also called **capacitance vessels**. The body can take quite large amounts of blood from this system and send them to any other region if needed, for example, to muscle tissue during physical exercise. **Q 52**

The **lymphatic system** consists of lymph vessels (also called simply “lymphatics”), lymph nodes, and organs, such as tonsils, spleen, thymus, lymphatic mucous membrane tissue, and the tissue of the appendix. Structures lacking lymphatics are epidermis, glandular epithelium, bone marrow, brain, cartilage, nails, lens, and the vitreous body. The last four of these do not contain blood vessels either.

2 Anatomy of Lymph Vessels and Lymph Nodes

The lymphatic system can be divided into a superficial system and a deep system. The superficial (epifascial) system removes the interstitial fluid of the skin. The deep (subfascial) system removes interstitial fluid from muscles, joints, organs, and vessels. The two systems are interconnected via perforating lymph vessels.

The vessels of the deep system empty into the large lymph trunks.

With regard to the lymph system, the skin is divided in sections. Initial lymph vessels (lymph capillaries) drain the lymph-obligatory load of one of the small, overlapping, circular areas of skin (1–3 cm in diameter) into which the entire covering of the body is divided. From the **initial lymph vessel**, the lymph moves to the precollectors. Several adjacent skin areas constitute a skin zone, the **precollectors** of which are interconnected and empty into a common lymph collector. **Collectors** drain lymph from strip like skin zones. Several skin zones together form a **lymph vessel bundle**, also called a **territory**. There are no anastomoses between the bundles, only between collectors within a bundle.

The vessel bundles drain into the lymph node stations (inguinal and axillary), and ultimately into the thoracic duct and the venous angle.

The superficial (epifascial) lymph vessels are spread out like a network and frequently run parallel to the superficial veins. The subfascial lymph vessels of muscles, joints, bones, and organs run with the blood vessels (in the neurovascular sheath) and do not have their own names.

Note

The **lymph-obligatory load** is the name given to all the substances that have to be removed from the interstitium via the lymphatic vascular system. **Q 9**

The lymphatic vascular system is a second drainage system that supports the venous system in removing substances from the interstitium. Because of its particular anatomy, the lymph vessels can absorb and remove all those molecules that are too large or too many to enter the venous system. These substances are called the “lymph-obligatory load” and consist mainly of proteins, long-chain fatty acids, cells and cell debris, and water. Exogenous substances such as viruses, bacteria, coal dust, and glass dust (silica) are also removed in this way. **Q 9**

The lymph from the entire body drains into the subclavian vein at the venous angle (terminus) and travels together with the venous blood into the right heart. Just as

in the arterial and venous systems, there is a hierarchy of scale (size) in the channels of the lymphatic system.

Note

Lymph-obligatory loads: Q 10

- Water (also serves transportation).
- Protein.
- Lipids.
- Cells.
- Exogenous substances.

2.1 Initial Lymph Vessels

Prelymphatics are small channels found in the loose connective tissue. They do not have a vascular structure, but they do carry lymph-obligatory substances.

The initial lymph vessels (also known as lymph sinus, formerly called lymph capillaries) are the smallest vessels and form the beginning of the lymphatic vascular system. The lymph vessels of interest for manual lymph drainage (MLD) are those of the skin. The initial lymph vessels can be found in the entire dermis and drain the lymph-obligatory load from the connective tissue or interstitium.

Initial lymph vessels are reticulated. Some have a blind origin in the tissue. They consist of a single oak-leaf-shaped layer of endothelial cells that connect with adjacent cells. Some overlap at the edges and do not close tightly, so they can open like shutter valves (► **Fig. 2.1**). **Q 1, Q 2**

The vessel is surrounded by a basement membrane (fiber network), which is much thinner than the basement membrane of blood capillaries. This reticular fiber network and the anchor filaments, which insert directly at the endothelial cells and the fiber network, are connected to the fibers of the surrounding tissue. When tissue pressure is low, the intercellular openings (open junctions) are closed. When the pressure in the connective tissue changes or more water enters the tissue, tissue pressure rises. The connective tissue swells and the collagen fibers of the connective tissue pull on the fiber network (matrix) and the anchor filaments, creating an opening from the endothelial cells into the initial lymph vessel. Through this opening, water, large molecules, cell debris, and cells can enter the initial lymph vessel. The exact mechanism and process of how the lymph-obligatory load flows into the initial lymph vessel is still not fully understood.

According to Zoeltzer (2003), opening and closing of the open junctions is an active process of the endothelial cell.

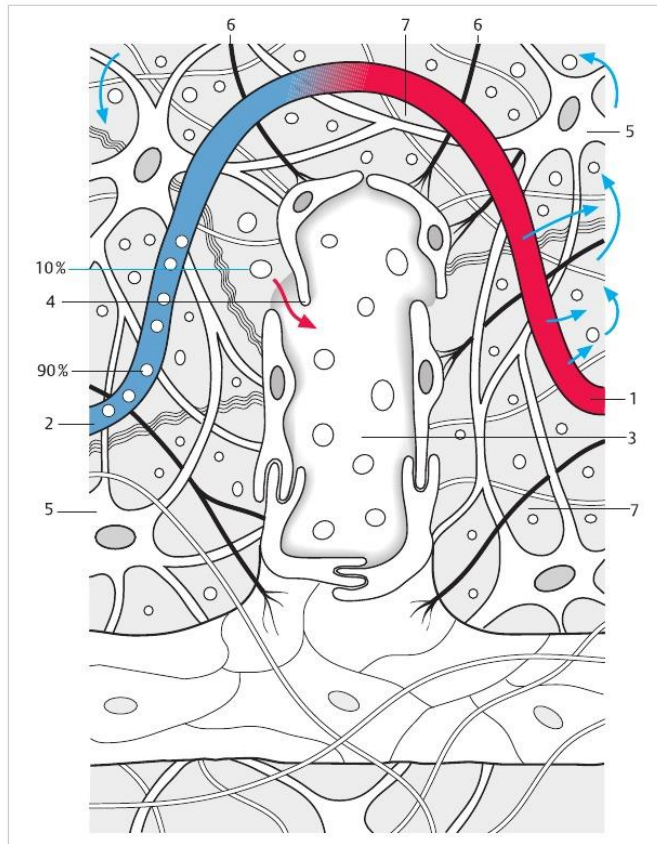


Fig. 2.1 Longitudinal section along a glove-finger-shaped initial lymph vessel with a blind origin in the tissue. 1, arterial limb of capillary; 2, venous limb of capillary; 3, initial lymph vessel; 4, swinging tip of an endothelial cell of the initial lymph vessel allowing influx of interstitial fluid (arrow to the left and right of 4); 5, fibrocyte; 6, anchor filaments; 7, intercellular space.

This would indicate a much more complex process than has been assumed so far. Diffusion, osmosis, or suction created through contraction of the deeper lymph vessels are considered to be a part of the mechanism. During influx into the initial lymph vessel, pressure in the vessel increases and pressure in the interstitium correspondingly decreases, while the shutter valves close. The initial lymph vessel is also called a collecting vessel and empties into the precollectors. Precollectors are often closely connected with arteries and their pulsation results in an acceleration of lymph flow. [Q 1](#), [Q 2](#)

2.2 Precollectors

Initial lymph vessels turn without noticeable transition into precollectors, which pass the collected lymph on to the next vessels (the collectors). In the skin (and also in the mucous membranes), they run vertically into the deep tissues.

The precollectors show similarities to both the smaller and the larger lymph vessels. They have rudimentary

valves that determine the direction of flow and also prevent reflux. There are some isolated muscle fibers and openings in the walls that allow them to absorb fluid from the connective tissue.

Precollectors have a transitional character. On the one hand, they are transport vessels and form the link between the initial lymph vessels and the collectors. In addition, though, like the initial lymph vessels they are able to absorb a small amount of lymph-obligatory substances from the interstitium and are therefore also regarded as collecting vessels. The collectors to some extent have a suction effect on the content of the precollectors, which speeds up the transport. As mentioned earlier, this suction can continue to have an effect all the way into the initial lymph vessels. [Q 3](#), [Q 4](#)

2.3 Lymph Collectors

The lymph collectors are the next size up from the lymph vessels. Along their course from the periphery to the venous