Subject III CARDIOVASCULAR SYSTEM

Program of lecture

- **General morpho-functional features.**
- **Relations between hemodynamic condition and structure of vascular wall.**
- **Heart.**
- **Arteries.**
- **Microcirculation**
- **Capillaries**
- **Venous network**
- **Anastomoses**
- **Neuro-humoral regulation of cardiovascular system functioning**
- **Lymphatic system**.

The cardiovascular system comprises the **heart,** a muscular organ that pumps the blood into two separated circuits: the **pulmonary circuit,** which carries blood to and from the lungs, and the **systemic circuit,** which distributes blood to and from all of the organs and tissues of the body. These circuits consist of:

- **Arteries-**a series of vessels that transport blood away from the heart by branching into vessels of smaller and smaller diameter, eventually branching into capillaries to supply all regions of the body with blood
- **Capillaries-**thin-walled vessels with the smallest diameter, form capillary beds, where gases, nutrients, metabolic wastes, hormones, and signaling substances are interchanged or passed between the blood and the tissues of the body to sustain normal metabolic activities
- **Veins-**vessels that drain capillary beds and form larger and larger vessels returning blood to the heart

Most blood vessels have several features that are structurally similar, although dissimilarities exist and are the bases for classifying the vessels into different identifiable groups. For example, the walls of high-pressure vessels (e.g., subclavian arteries) are thicker than vessels conducting blood at low pressure (e.g., subclavian veins). However, arterial diameters continue to decrease at each branching, whereas vein diameters increase at each convergence, thus altering the respective layers of the walls of the vessels. Therefore, the descriptions used as distinguishing characteristics for a particular type of artery or vein are not always absolute. Indeed, the walls of the capillaries and venules are completely modified and less complex compared with those of larger vessels. Generally, arteries have thicker walls and are smaller in diameter than are the corresponding veins. Moreover, in histological sections, arteries are round and usually have no blood in their lumina.

Three separate concentric layers of tissue, or tunics, make up the wall of the typical blood vessel (Fig. 1). The innermost layer, the **tunica intima,** is composed of a single layer of flattened, squamous endothelial cells, which form a tube lining the lumen of the vessel, and the

underlying subendothelial connective tissue. The intermediate layer, the **tunica media,** is composed mostly of smooth muscle cells oriented concentrically around the lumen. The outermost layer, the **tunica adventitia,** is composed mainly of fibroelastic connective tissue arranged longitudinally (Fig. 1).

The tunica intima houses in its outermost layer the **internal elastic lamina,** a thin band of elastic fibers that is well developed in medium-sized arteries. The outermost layer of the tunica media houses another band of elastic fibers, the **external elastic lamina,** although it is not distinguishable in all arteries. The deeper cells of the tunica media and tunica adventitia are nourished by the **vasa vasorum.**

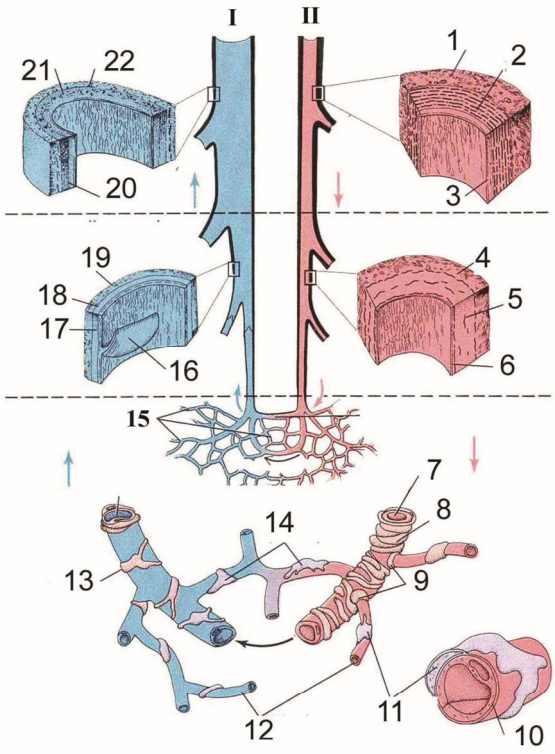

Fig. 1.

The endothelial cells (simple squamous epithelium) lining the lumen of the blood vessel rest on a basal lamina. These flattened cells are elongated into a sheet such that their long axis is more or less parallel to the long axis of the vessel, which permits each endothelial cell to nearly surround the lumen of a small-caliber vessel. In larger-bore vessels, several to many individual endothelial cells are required to line the circumference of the lumen. Endothelial cells not only provide an exceptionally smooth surface but also function in secreting types II, IV, and V collagens, lamin, endothelin, nitric oxide , and von Willebrand factor. Moreover, they possess membrane-bound enzymes, such as **angiotensin-converting enzyme (ACE),** which cleaves **angiotensin I** to generate **angiotensin II**, as well as enzymes that inactivate bradykinin, serotonin, prostaglandins, thrombin , and norepinephrine; moreover, they also bind lipoprotein lipase, the enzyme that degrades lipoproteins

A network of **vasomotor nerves** of the sympathetic component of the autonomic nervous system supplies smooth muscle cells of blood vessels. These unmyelinated, postganglionic sympathetic nerves are responsible for **vasoconstriction** of the vessel walls. Because the nerves seldom enter the tunica media of the vessel, they do not synapse directly on the smooth muscle cells. Instead, they release the neurotransmitter **norepinephrine,** which diffuses into the media and acts on smooth muscle cells nearby. These impulses are propagated throughout all of the smooth muscle

cells via their gap junctions, thereby orchestrating contractions of the entire smooth muscle cell layer and thus reducing the diameter of the vessel lumen.
Arteries are more heavily endowed with vasomotor nerves than are veins, but veins also receive vasomotor nerve endings in the tunica adventitia. The arteries supplying skeletal muscles also receive cholinergic (parasympathetic) nerves to bring about vasodilation.

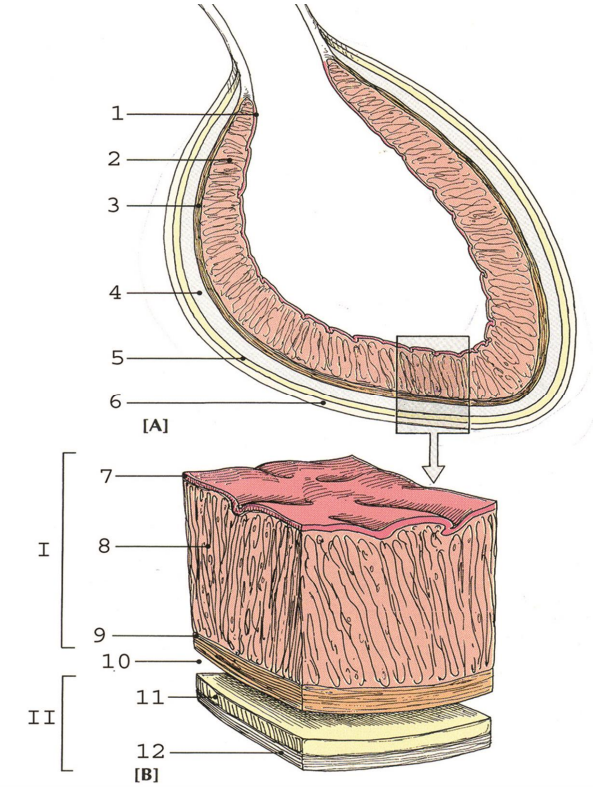

Fig. 2

A **subendothelial layer** lies immediately beneath the endothelial cells. It is composed of loose connective tissue and a few scattered smooth muscle cells, both arranged longitudinally. Beneath the subendothelial layer is an **internal elastic lamina** that is especially well developed in muscular arteries. Separating the tunica intima from the tunica media, the internal elastic lamina is composed of **elastin,** which is a fenestrated sheet that permits the diffusion of substances into the deeper regions of the arterial wall to nourish the cells there.

The tunica media is the thickest layer of the blood vessel. The **concentric cell layers** forming the tunica media comprise mostly helically arranged smooth muscle cells. Interspersed within the layers of smooth muscle are some elastic fibers, type III collagen, and proteoglycans. The fibrous elements form lamellae within the ground substance secreted by smooth muscle cells. Larger muscular arteries have an **external elastic lamina,** which is more delicate than the internal elastic lamina and separates the tunica media from the overlying tunica adventitia. Capillaries and postcapillary venules do not have a tunica media; in these small vessels, **pericytes** replace the tunica media

Covering the vessels on their outside surface is the **tunica adventitia,** composed mostly of fibroblasts, type I collagen fibers, and longitudinally oriented elastic fibers. This layer becomes continuous with the connective tissue elements surrounding the vessel.

HEART

The muscular wall **(myocardium)** of the heart is composed of cardiac muscle. The heart consists of four chambers: two atria, which receive blood, and two ventricles, which discharge blood from the heart. The **superior** and **inferior venae cavae** return systemic venous blood to the **right atrium** of the heart. From here, the blood passes through the **right atrioventricular valve (tricuspid valve)** into the **right ventricle.** As the ventricles contract, blood from the right ventricle is pumped out the **pulmonary trunk,** a large vessel that bifurcates into the right and left pulmonary arteries to deliver deoxygenated blood to the lungs for gaseous exchange. Oxygenated blood from the lungs returns to the heart via the **pulmonary veins,** which empty into the **left atrium**. From here, the blood passes through the **left atrioventricular valve (bicuspid or mitral valve)** to enter the **left ventricle.** Again, ventricular contraction expels the blood from the left ventricle into the aorta, from which many branches emanate to deliver blood to the tissues of the body.

The atrioventricular valves prevent regurgitation of the ventricular blood back into the atria, whereas the **semilunar valves,** located in the pulmonary trunk and the aorta near their origins, prevent backflow from these vessels into the heart.

The endocardium is continuous with the tunica intima of the blood vessels entering and leaving the heart. It is composed of an **endothelium,** consisting of a simple squamous epithelium and an underlying layer of fibroelastic connective tissue with scattered fibroblasts. Lying deeper is a layer of dense connective tissue, heavily endowed with elastic fibers interspersed with smooth muscle cells. Deep to the endocardium is a **subendocardial layer** of loose connective tissue that contains small blood vessels, nerves, and Purkinje fibers from the conduction system of the heart. The subendocardial layer forms the boundary of the endocardium as it attaches to the endomysium of the cardiac muscle.

The myocardium, the middle and thickest of the three layers of the heart, contains cardiac muscle cells arranged in complex spirals around the orifices of the chambers. Certain cardiac muscle cells attach the myocardium to the fibrous cardiac skeleton, others are specialized for endocrine secretions, and still others are specialized for impulse generation or impulse conduction (Fig. 2, 3).

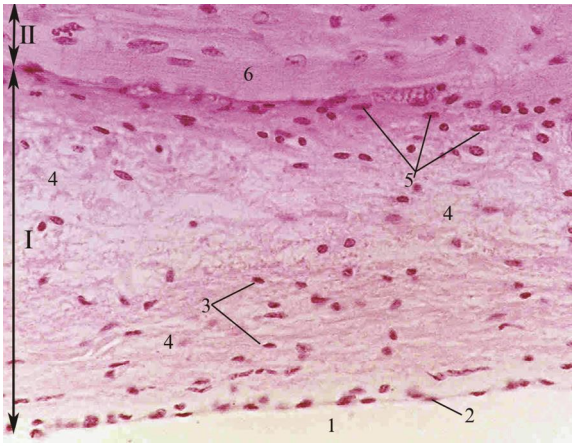

Fig. 3.

The heart rate (~70 beats per minute) is controlled by the **sinoatrial node (pacemaker)** located at the junction of the superior vena cava and the right atrium. These specialized nodal cardiac muscle cells can spontaneously depolarize 70 times per minute, creating an impulse that spreads over the atrial chamber walls by internodal pathways to the **atrioventricular node,** located in the septal wall just above the tricuspid valve. Modified cardiac muscle cells of the

atrioventricular node, regulated by impulses arriving from the sinoatrial node, transmit signals to the myocardium of the atria via the **atrioventricular bundle (bundle of His).** Fibers from the atrioventricular bundle pass down the interventricular septum to conduct the impulse to the cardiac muscle, thus producing a rhythmic contraction. The atrioventricular bundle travels in the subendocardial connective tissue as large, modified cardiac muscle cells, forming **Purkinje fibers**, which transmit impulses to the cardiac muscle cells located at the apex of the heart (Purkinje fibers are not be confused with the *Purkinje cells* in the cerebellar cortex). It should be noted that although the autonomic nervous system does not initiate the heartbeat, it does modulate the rate and stroke volume of the heartbeat. Stimulation of sympathetic nerves accelerates the heart rate, whereas stimulation of the parasympathetic nerves serving the heart slows the heart rate (Fig. 4).

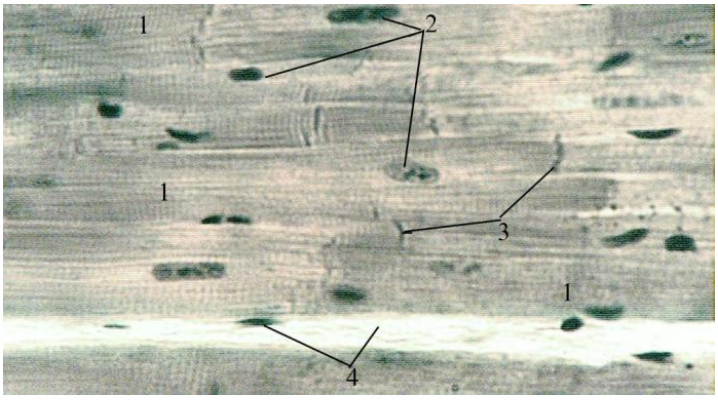

Fig. 4.

Specialized cardiac muscle cells, located primarily in the atrial wall and in the interventricular septum, produce an array of small secreted peptides. These include **atriopeptin, atrial natriuretic polypeptide, cardiodilatin,** and **cardionatrin**, which are released into the surrounding capillaries. These hormones aid fluid maintenance and electrolyte balance and decrease blood pressure (Fig. 5).

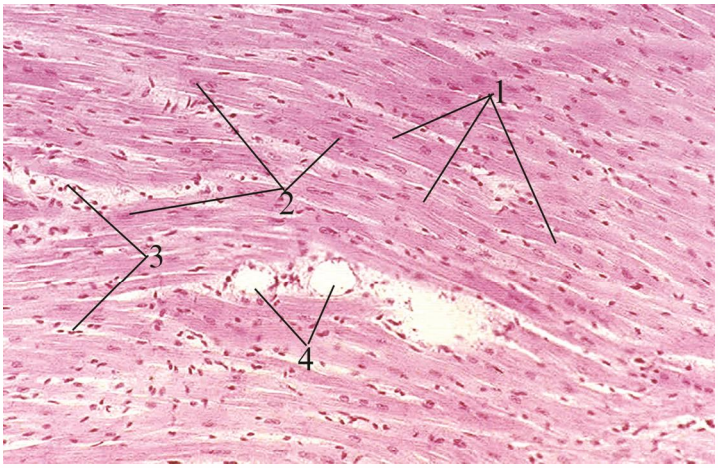

Fig. 5.

Epicardium, the outermost layer of the heart wall, is also called the **visceral layer of the pericardium** (composed of a simple squamous epithelium known as a **mesothelium**). The

subepicardial layer of loose connective tissue contains the coronary vessels, nerves, and ganglia. It also is the region where fat is stored on the surface of the heart. At the roots of the vessels entering and leaving the heart, the visceral pericardium becomes continuous with the serous layer of the parietal pericardium. These two layers of the pericardium enclose the pericardial cavity, a space containing a small amount of serous fluid for lubricating the serous layer of the pericardium and the visceral pericardium (Fig. 6, 7, 8).

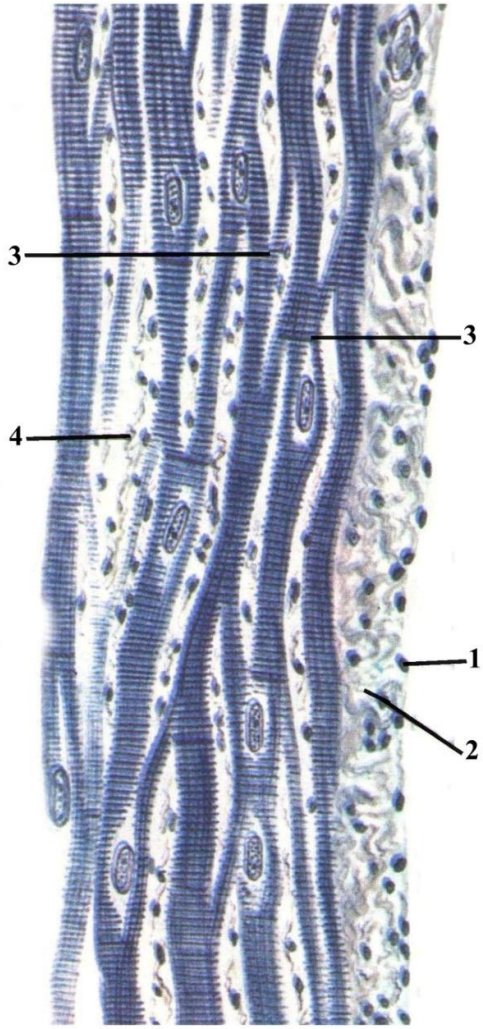

Fig. 6.

Specialized cardiac muscle cells, located primarily in the atrial wall and in the interventricular septum, produce an array of small secreted peptides.

These include **atriopeptin, atrial natriuretic polypeptide, cardiodilatin,** and **cardionatrin**, which are released into the surrounding capillaries. These hormones aid fluid maintenance and electrolyte balance and decrease blood pressure (Fig. 7, 8, 9).

Arteries

Arteries are efferent vessels that transport blood away from the heart to the capillary beds. The two major arteries that arise from the right and left ventricles of the heart are the pulmonary trunk and the aorta, respectively (Fig. 10).

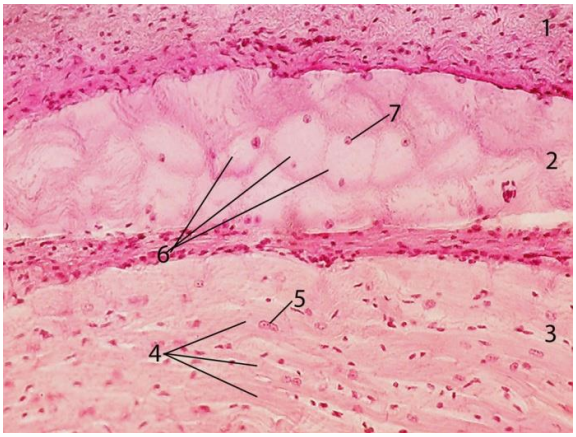

Fig. 7

The **pulmonary trunk** branches, shortly after exiting the heart, into right and left pulmonary arteries that enter the lungs for distribution. The right and left coronary arteries, which supply the heart muscle, arise from the aorta as it exits the left ventricle.

The **aorta,** upon leaving the heart, courses in an obliquely posterior arch to descend in the thoracic cavity, where it sends branches to the body wall and the viscera; it then enters the abdominal cavity, where it sends branches to the body wall and viscera. The abdominal aorta terminates by bifurcating into the right and left common iliac arteries in the pelvis.

Three major arterial trunks-the right brachiocephalic artery, the left common carotid artery, and the left subclavian artery-arise from the arch of the aorta to supply the superior extremities and the head and neck.

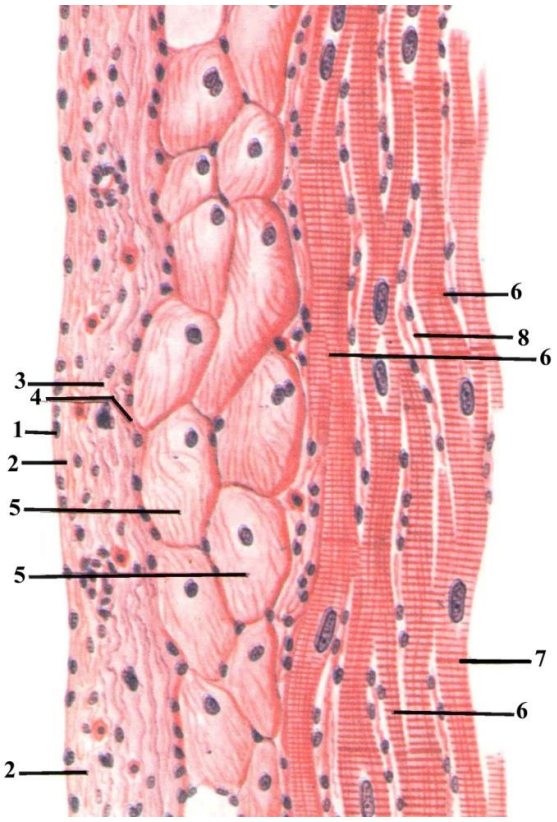

Fig. 8.

It is interesting to note that the right common carotid artery arises from the right brachiocephalic trunk, whereas the left common carotid artery arises directly from the aortic arch. Branching of all of these arteries into large numbers of smaller and smaller arteries continues until the vessel walls contain a single layer of endothelial cells. The resulting vessels, called **capillaries,** are the smallest functional vascular elements of the cardiovascular system.

Classification of Arteries

Arteries are classified into three major types based on their relative size, morphological characteristics, or both. From largest to smallest, they are as follows:

- Elastic (conducting) arteries
- Muscular (distributing) arteries
- Arterioles

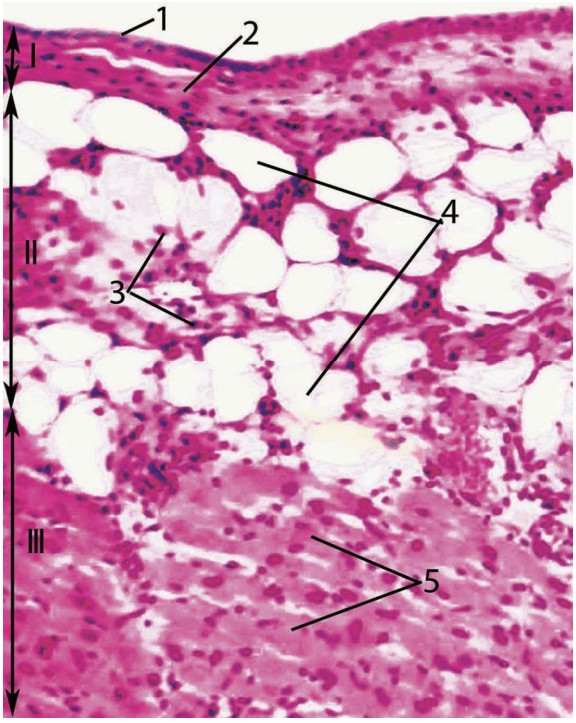

Fig. 9.

Because the vessels decrease in diameter in a continuous fashion, there are gradual changes in morphological characteristics as they morph from one type to another. Therefore, some vessels having characteristics of two categories cannot be assigned to a specific category with certainty (Fig. 10).

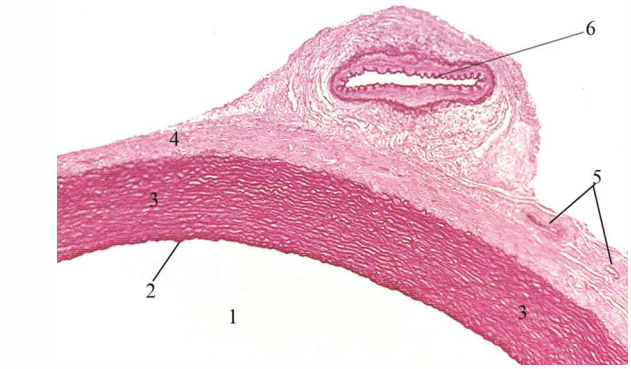

Fig. 10.

The aorta and the branches originating from the aortic arch (the common carotid artery and the subclavian artery), the common iliac arteries, and the pulmonary trunk are elastic **(conducting)** arteries (Fig. 10). The walls of these vessels may be yellow in the fresh state because of the abundance of elastin.

The **tunica intima** of the elastic arteries is composed of an endothelium that is supported by a narrow layer of underlying connective tissue containing a few fibroblasts, occasional smooth muscle cells, and collagen fibers. Thin laminae of elastic fibers, the **internal elastic laminae,** are also present.

The endothelial cells of the elastic arteries are 10 to 15εm wide and 25 to 50εm long; their long axes are oriented parallel to the longitudinal axis of the vessel. These cells are connected to each other mostly by occluding junctions. Their plasma membranes contain small vesicles thought to be related to transport of water, macromolecules, and electrolytes. Occasional blunt processes may extend from the plasma membrane through the internal elastic lamina to form gap junctions with smooth muscle cells located in the tunica media. The endothelial cells contain **Weibel-Palade bodies,** membrane-bound inclusions 0.1εm in diameter and 3εm long, that have a dense matrix housing tubular elements containing the glycoprotein **von Willebrand factor.** This factor, which facilitates the coagulation of platelets during clot formation, is manufactured by most endothelial cells but is stored only in arteries (Fig. 11).

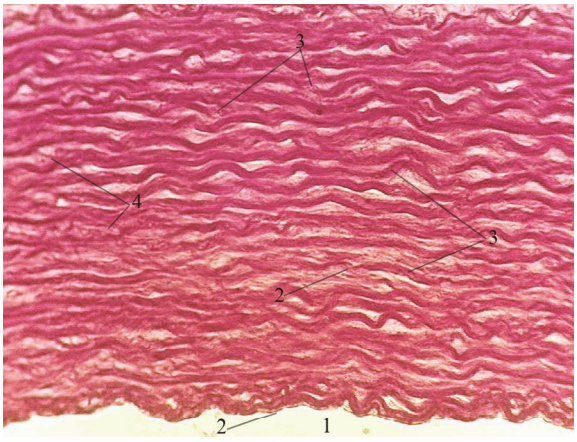

Fig. 11

The **tunica media** of the elastic arteries consists of many fenestrated lamellae of elastin, known as **fenestrated membranes,** alternating with circularly oriented layers of smooth muscle cells. The number of lamellae of elastin increases with age; there are approximately 40 in newborns and 70 in adults. These fenestrated membranes also increase in thickness because of the continued deposition of elastin, which constitutes much of the tunica media; smooth muscles

cells are less abundant in elastic arteries than in some of the muscular arteries. The extracellular matrix, secreted by the smooth muscle cells, is composed mostly of chondroitin sulfate, collagen, and reticular and elastin fibers. An **external elastic lamina** is also present in the tunica media (Fig. 12).

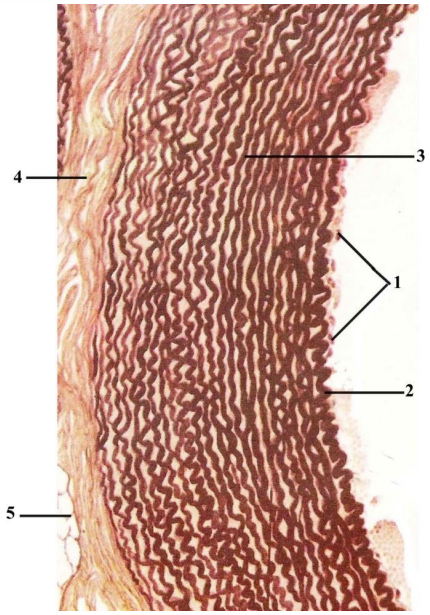

Fig. 12

The **tunica adventitia** of elastic arteries is relatively thin and is composed of loose fibroelastic connective tissue housing some fibroblasts. Vasa vasorum also are abundant throughout the adventitia. Capillary beds arise from the vasa vasorum and extend to the tissues of the tunica media, where they supply the connective tissue and smooth muscle cells with oxygen and nutrients. Fenestrations in the elastic laminae permit some diffusion of oxygen and nutrients to the cells in the tunica media from the blood flowing through the lumen, although most of the nourishment is derived from branches of the vasa vasorum (Fig. 13).

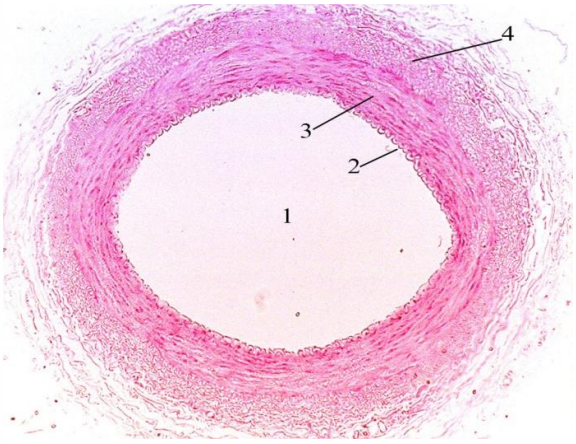

Fig. 13

Muscular **(distributing)** arteries include most vessels arising from the aorta, except for the major trunks orginating from the arch of the aorta and the terminal bifurcation of the abdominal aorta, which are identified as elastic arteries. Indeed, most of the named arteries, even those with a diameter of only 0.1 mm, are classified as muscular arteries (e.g., brachial, ulnar, renal). The

identifying characteristic of muscular arteries is a relatively thick tunica media composed mostly of smooth muscle cells (Fig. 14).

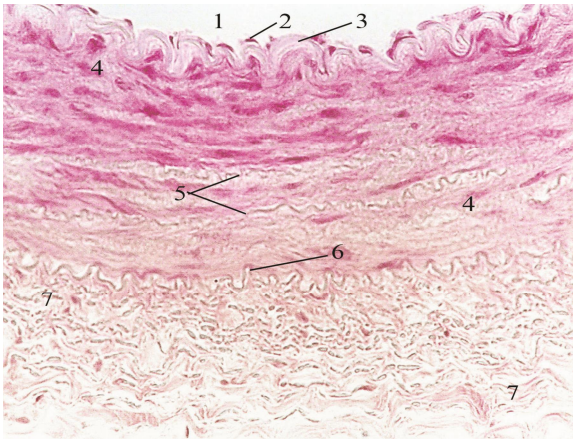

Fig. 14

The **tunica intima** in the muscular arteries is thinner than that in the elastic arteries, but the subendothelial layer contains a few smooth muscle cells; also, in contrast with that of elastic arteries, the **internal elastic lamina** of the muscular arteries is prominent and displays an undulating surface to which the endothelium conforms. Occasionally the internal elastic lamina is duplicated; this is called **bifid internal elastic lamina.** As in elastic arteries, the endothelium has processes that pass through fenestrations within the internal elastic lamina and make gap junctions with smooth muscle cells of the tunica media that are near the interface with the tunica intima. It is believed that these gap junctions may couple metabolically the endothelium and the smooth muscle cells (Fig. 15).

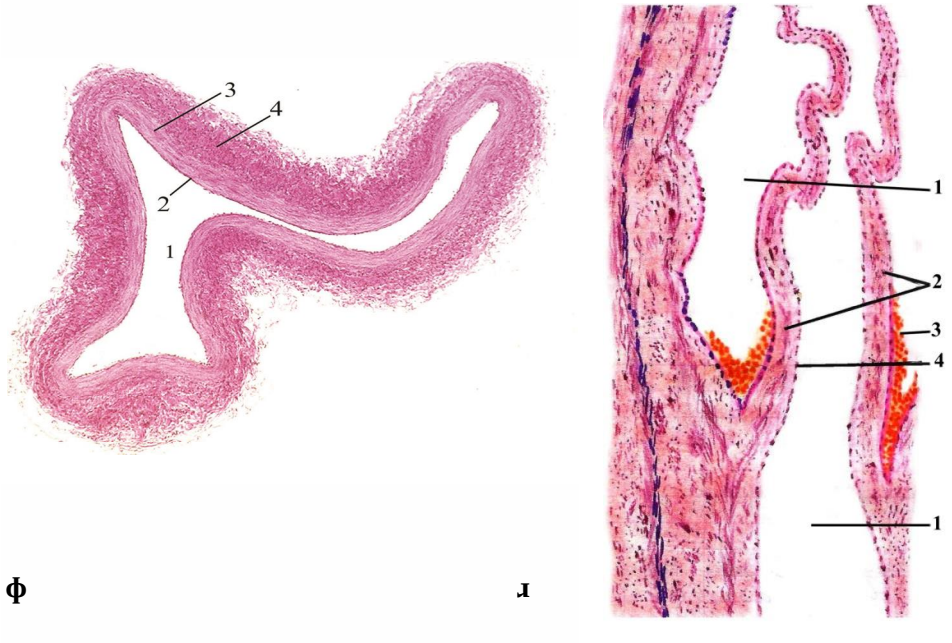

Fig. 15

Veins. At the discharging ends of capillaries are small venules, the beginning of the venous return, which conducts blood away from the organs and tissues and returns it to the heart. These venules empty their contents into larger veins, and the process continues as the vessels

become larger and larger while going back to the heart. Because veins not only outnumber arteries but also usually have larger luminal diameters, almost 70% of the total blood volume is in these vessels. In histological sections, veins parallel arteries; however, their walls are usually collapsed because they are thinner and less elastic than arterial walls because the venous return is a low-pressure system (Fig. 16).

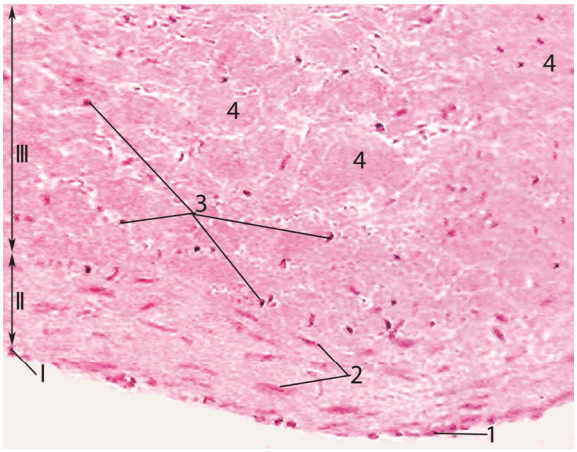

Fig. 16

Classification of Veins

The structure of veins is not necessarily uniform, even for veins of the same size or for the same vein along its entire length. Veins are described as having the same three layers (tunicae intima, media, and adventitia) as arteries. Although the muscular and elastic layers are not as well developed, the connective tissue components in veins are more pronounced than in arteries. In certain areas of the body where the structures housing the veins protect them from pressure (retina, meninges, placenta, penis), the veins have little or no smooth muscle in their walls; moreover, the boundaries between the tunica intima and the tunica media of most veins are not clearly distinguishable (Fig. 17).

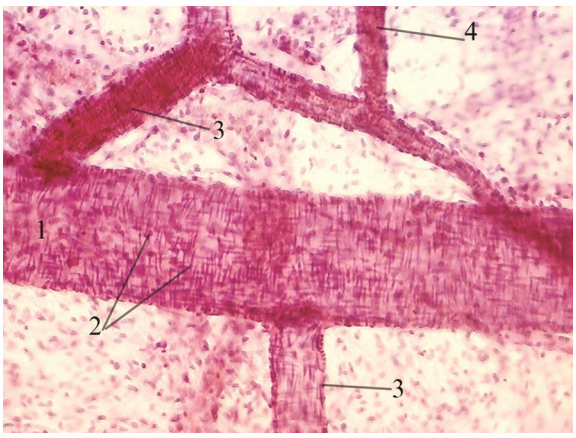

Fig. 17

Medium veins.Medium veins are those draining most of the body, including most of the regions of the extremities. Their tunica intima includes the endothelium and its basal lamina and reticular fibers. Sometimes an elastic network surrounds the endothelium, but these elastic fibers do not form laminae characteristic of an internal elastic lamina. The smooth muscle cells of the tunica media are in a loosely organized layer interwoven with collagen fibers and fibroblasts. The tunica adventitia, the thickest of the tunicas, is composed of longitudinally arranged collagen bundles and elastic fibers, as well as a few scattered smooth muscle cells (Fig. 18, 19).

Large veins Large veins include the venae cavae and the pulmonary, portal, renal, internal jugular, iliac, and azygos veins. The tunica intima of the large veins is similar to that of the medium veins, except that large veins have a thick subendothelial connective tissue layer, containing fibroblasts and a network of elastic fibers. Although only a few major vessels (such as the pulmonary veins) have a well-developed smooth muscle layer, most large veins are without a tunica media; in its place is a well-developed tunica adventitia. An exception are the superficial veins of the legs, which have a well-defined muscular wall, perhaps to resist the distention caused by gravity.

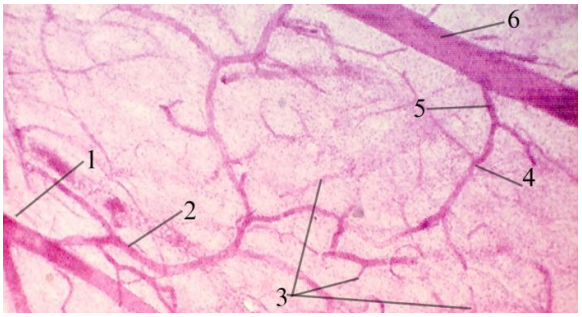

Fig. 18

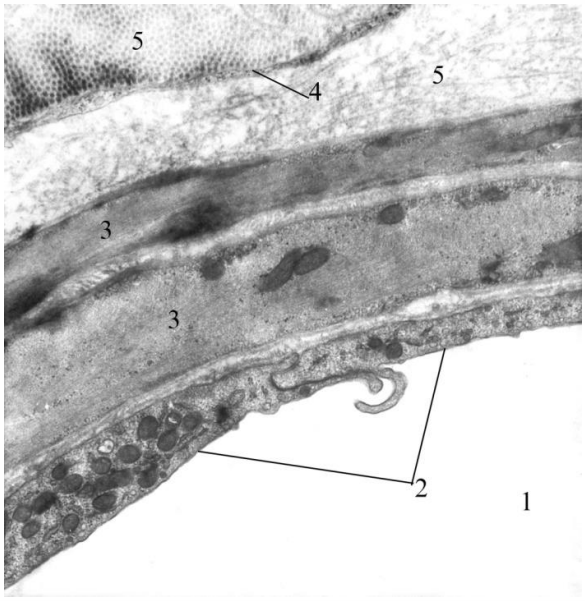

Fig. 19

CAPILLARIES

Arising from the terminal ends of the arterioles are capillaries, which form, by branching and anastomosing, a capillary bed (network) between the arterioles and the venules. Electron micrographs have revealed three types of capillaries: (1) **continuous**, (2) **fenestrated,** and (3) **sinusoidal** (Fig. 20).

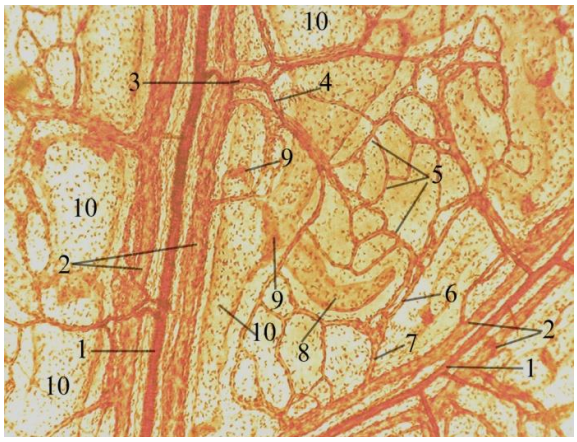

Fig. 20

Capillaries are the smallest of the vascular channels, on the average approximately 50 ɛm in length with a diameter of 8 to 10 ɛm. Capillaries are formed by a single layer of squamous endothelial cells rolled into a tube, with the long axis of these cells lying in the same direction as the blood flow. These endothelial cells are flattened, with the attenuated ends tapering to a thickness to 0.2 ɛm or less, although an elliptical nucleus bulges out into the lumen of the capillary. The cytoplasm contains a Golgi complex, a few mitochondria, some rough endoplasmic reticulum (RER), and free ribosomes (Fig. 19; also see Fig. 20). Intermediate filaments (9 to 11 nm in diameter), located around the perinuclear zone, vary in filament composition. For example, some cells contain filaments composed of **desmin,** others contain filaments composed of **vimentin,** and some endothelial cells contain both kinds of filaments. These filaments provide structural support to the endothelial cells, but the significance of their variation is unclear (Fig. 21, 23, 24).The large number of pinocytotic vesicles associated with the entire plasmalemma is an identifying characteristic of capillaries. These vesicles may be in singular array, two single vesicles may be fused together, or several vesicles may be fused, forming a transient channel. Where the endothelial cells are the thinnest, a single vesicle may span from the adluminal plasmalemma across the cytoplasm to the abluminal plasmalemma of the endothelial cell. The endothelial cells of capillaries are rolled into a tube, giving the lumen a diameter that ranges from 8 to 10 mm but remains constant throughout the entire length of a capillary. This diameter is sufficient to permit individual cells of the blood to pass without being hindered. Although not all of the capillary beds are open at any one time, increased demand initiates the opening of more beds, thus increasing blood flow to meet physiological needs. The external surfaces of the endothelial cells are surrounded by a basal lamina secreted by the endothelial cells (see Fig.21).

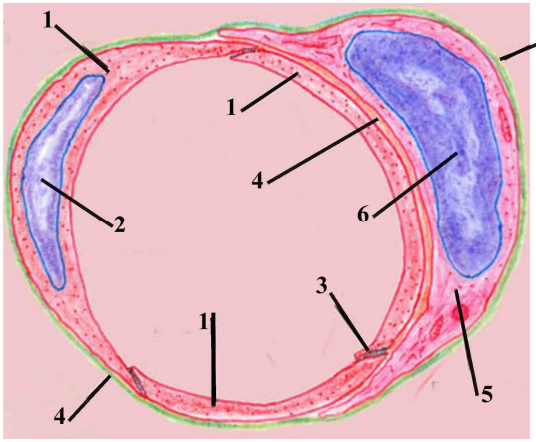

Fig. 21

When viewed in cross section, the endothelial walls making up small capillaries are formed by one endothelial cell, whereas portions of two or three endothelial cells contribute to forming

the endothelial wall of larger capillaries. At these cellular junctions, the endothelial cells tend to overlap, forming a **marginal fold** that projects into the lumen. Endothelial cells are joined together by **fasciae occludentes,** or **tight junctions (Fig. 22).**

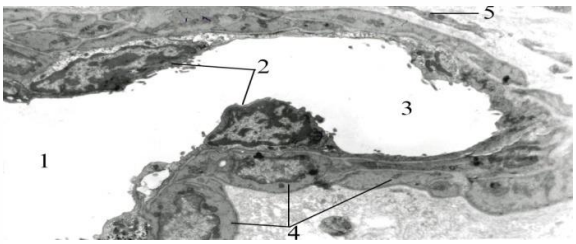

Fig. 22

Pericytes are located along the outside of the capillaries and small venules, and appear to be surrounding them (Figs. 22). These cells have long primary processes that are located along the long axis of the capillary and from which secondary processes arise to wrap around the capillary, forming a few **gap junctions** with the endothelial cells. Pericytes share the basal lamina of the endothelial cells. Pericytes possess a small Golgi complex, mitochondria, RER, microtubules, and filaments extending into the processes. These cells also contain tropomyosin, isomyosin, and protein kinase, which are all related to the contractile process that regulates blood flow through the capillaries (Fig. 22).

Classification of Capillaries

Capillaries are of three types: (1) continuous, (2) fenestrated, and (3) sinusoidal. They differ in their location and structure

Continuous capillaries are present in muscle, nervous, and connective tissues; in the brain tissue they are classified as modified continuous capillaries. The intercellular junctions between their endothelial cells are a type of **fasciae occludentes,** which prevent passage of many molecules. Substances such as amino acids , glucose , nucleosides, and purines move across the capillary wall via carrier-mediated transport. The cells exhibit a polarity with the transport systems, such that Na^+,K^+-ATPase is located in the adluminal cell membrane only. There is evidence that barrier regulation resides within the endothelial cells but is influenced by products formed by the astrocytes associated with the capillaries (Fig. 25).

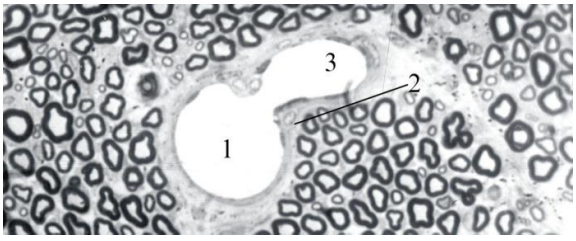

Fig. 23

Fenestrated capillaries have **pores (fenestrae)** in their walls that are 60 to 80 nm in diameter and covered by a pore diaphragm. These capillaries are found in the pancreas, intestines, and endocrine glands (Fig. 26).

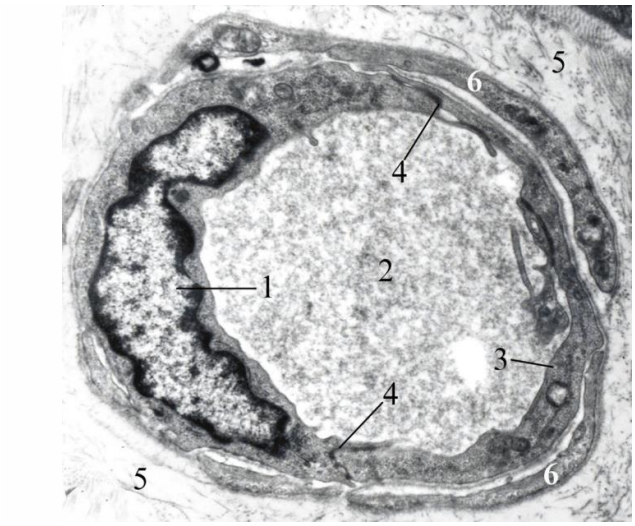

Fig. 24

The pores in fenestrated capillaries are bridged by an ultrathin diaphragm. When viewed after processing with platinum-carbon shadowing, the diaphragm displays eight fibrils radiating out from a central area and forming wedge-like channels, each with an opening of about 5.5 nm. These pore-diaphragm complexes are regularly spaced about 50 nm apart but are located in clusters; thus, most of the endothelial wall of the fenestrated capillary is without fenestrae (see Fig. 26). An exception is the **renal glomerulus,** composed of fenestrated capillaries that lack diaphragms

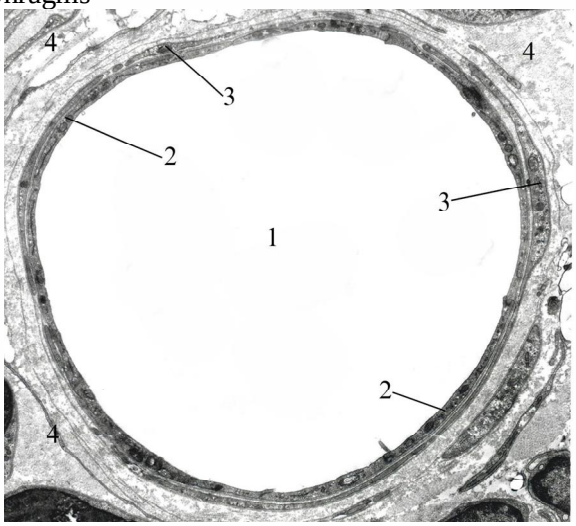

Fig. 25

The vascular channels in certain organs of the body, including the bone marrow, liver, spleen, lymphoid organs, and certain of the endocrine glands, are called **sinusoids,** irregular blood pools or channels that conform to the shape of the structure in which they are located. The peculiar conformation of a sinusoid is determined by its being shaped between the parenchymal components of the organ during organogenesis **(Fig. 21)**.

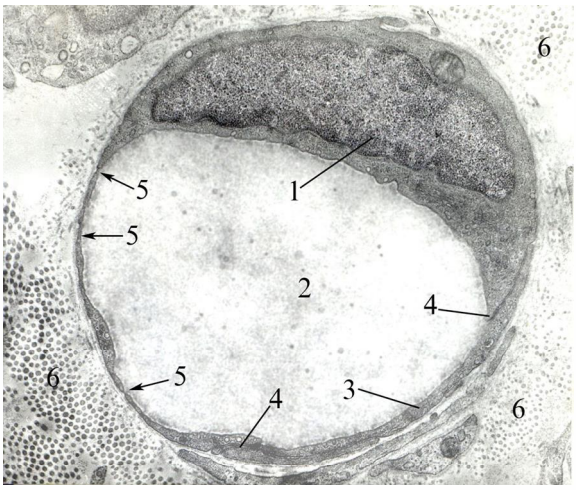

Fig. 26

Because of their location, sinusoidal capillaries have an enlarged diameter of 30 to 40εm (Fig. 26). They also contain many large fenestrae that lack diaphragms; the endothelial wall may be discontinuous, as is the basal lamina, permitting enhanced exchange between the blood and the tissues. Sinusoids are lined by endothelium. In certain organs, the endothelium is thin and continuous (as in some lymphoid organs); in others it may have continuous areas mixed with fenestrated areas (as in endocrine glands). Although the endothelial cells lack pinocytotic vesicles, macrophages may be located either in or along the outside of the endothelial wall (Fig. 25).

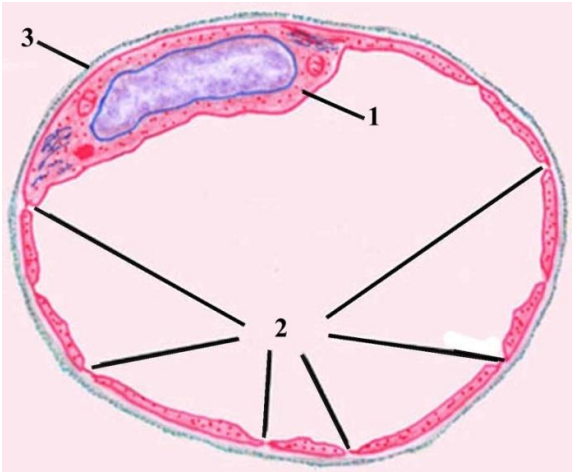

Fig. 27

Regulation of Blood Flow into a Capillary Bed

Terminals of most arteries end in capillary beds, which deliver their blood to venules for the return back to the venous side of the cardiovascular system. In many parts of the body, however, the artery simply joins with a venous channel, forming an arteriovenous anastomosis (AVA). The structures of the arterial and venous ends of the AVA are similar to those of an artery and vein, respectively, whereas the intermediate segment has a thickened tunica media and its subendothelial layer is composed of plump polygonal cells that are modified, longitudinally arranged smooth muscle cells (Fig. 29).

When the AVAs are closed, the blood passes through the capillary bed; when shunts are open, a large amount of blood bypasses the capillary bed and flows through the AVA. These shunts are useful in thermoregulation and are abundant in skin. The intermediate segments of the AVAs are richly innervated with adrenergic and cholinergic nerves. Whereas most peripheral nerves are controlled somewhat by local environmental stimuli, those nerves in the AVAs are controlled by the thermoregulatory system in the brain.

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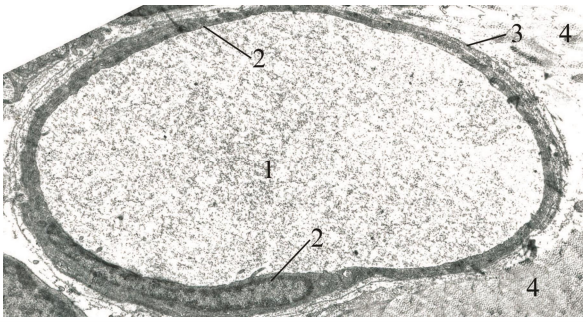

Fig. 28

A network of **vasomotor nerves** of the sympathetic component of the autonomic nervous system supplies smooth muscle cells of blood vessels. These unmyelinated, postganglionic sympathetic nerves are responsible for **vasoconstriction** of the vessel walls. Because the nerves seldom enter the tunica media of the vessel, they do not synapse directly on the smooth muscle cells. Instead, they release the neurotransmitter **norepinephrine,** which diffuses into the media and acts on smooth muscle cells nearby. These impulses are propagated throughout all of the smooth muscle cells via their gap junctions, thereby orchestrating contractions of the entire smooth muscle cell layer and thus reducing the diameter of the vessel lumen (Fig. 27).

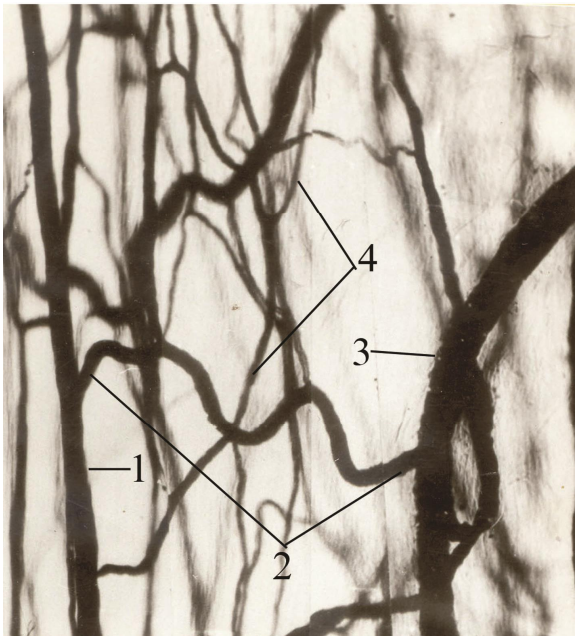

Fig. 29

Arteries are more heavily endowed with vasomotor nerves than are veins, but veins also receive vasomotor nerve endings in the tunica adventitia. The arteries supplying skeletal muscles also receive cholinergic (parasympathetic) nerves to bring about vasodilation (Fig. 28).

Many medium veins have valves that function to prevent the backflow of blood. These valves are especially abundant in the veins of the legs, where they act against the force of gravity. A venous valve is composed of two leaflets, each having a thin fold of the intima jutting out from the wall into the lumen. The thin leaflets are structurally reinforced by collagen and elastic fibers that are continuous with those of the wall. As blood flows to the heart, the valve cusps are deflected in the direction of the blood flow toward the heart. Backward flow of blood forces the cusps to approximate each other, thus blocking backflow.

LYMPHATIC VASCULAR SYSTEM

The lymphatic vascular system is composed of a series of vessels that remove excess extracellular fluid **(lymph)** from the interstitial tissue spaces and return it to the cardiovascular system. Lymphatic vessels are present throughout the body, except in the central nervous system and a few other areas, including the orbit, internal ear, epidermis, cartilage, and bone. Unlike the cardiovascular system, which contains a pump (the heart) and circulates blood in a *closed* system, the lymphatic vascular system is an *open* system in that there is no pump and no circulation of fluid (Fig. 30).

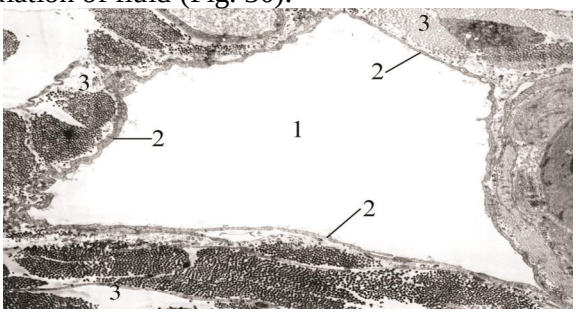

Fig. 30

The lymphatic vascular system begins in the tissues of the body as blind-ended **lymphatic capillaries**, which simply act as drain fields for excess interstitial fluid. The lymphatic capillaries empty their contents into **lymphatic vessels,** which empty into successively larger vessels until one of the two **lymphatic ducts** is reached. From either of these ducts, the lymph is emptied into the venous portion of the cardiovascular system at the junctions of the internal jugular and the subclavian veins.

The blind-ended, thin-walled lymphatic capillaries are composed of a single layer of attenuated endothelial cells with an incomplete basal lamina. The endothelial cells overlap each other in places but have intercellular clefts that permit easy access to the lumen of the vessel. These cells do not have fenestrae and do not make tight junctions with each other. Bundles of **lymphatic anchoring filaments** (5 to 10 nm in diameter) terminate on the abluminal plasma membrane. It is thought that these filaments may play a role in maintaining the luminal patency of these flimsy vessels.

Small and medium lymphatic vessels are characterized by closely spaced valves. Large lymphatic vessels resemble small veins structurally, except that their lumina are larger and their walls thinner. Large lymphatic vessels have a thin layer of elastic fibers beneath their endothelium and a thin layer of smooth muscle cells. This smooth muscle layer is then overlaid with elastic and collagen fibers that blend with the surrounding connective tissue, much like a tunica adventitia. Although some histologists describe tunics similar to those in blood vessels, most do not concur, because there are no clear boundaries between the layers and because the walls are so varied.