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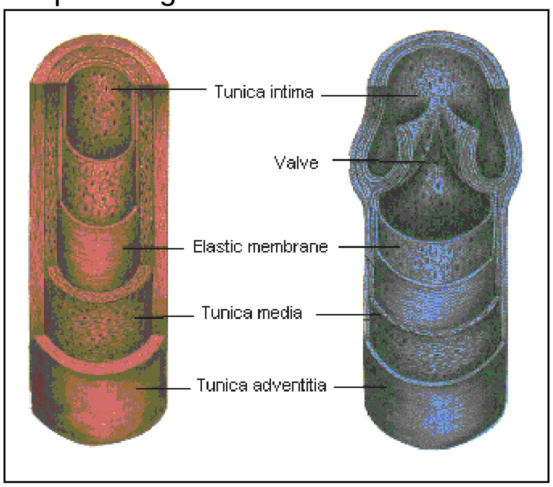
Arterial Anatomy and Hemodynamics

ARTERIAL ANATOMY

The architectural arrangement and structure of arteries and veins are important in the distribution of blood to and from the capillary beds where the real work of the vascular system is accomplished. The arteries deliver blood to the capillaries and the veins return it to the heart.

The arteries are distributed throughout the body in a systematic manner. The vessels leaving the heart are large but soon divide into branches. This division continues until minute branches are distributed to all parts of the body. At each division the branches are smaller, but since they are numerous, the total of their diameters is much greater than that of the artery from which they sprang. This means that as the blood flows from the heart toward the capillaries it flows in an ever-widening bed. The diameter of the aorta at the heart is about 2-3cm. The branches of the large arteries leave them at abrupt angles; the branches of the smaller arteries take progressively less abrupt changes of direction.



Three layers of vascular tissue.

An inner coat ***(tunica intima)*** consists of three layers—a layer of endothelial cells, a layer of delicate connective tissue, which is found only in vessels of considerable size, and an elastic layer consisting of a membrane or network of elastic fibers.

A middle coat *(**tunica media**)* consists mainly of smooth-muscle fibers with various amounts of elastic and collagenous tissue. In the larger arteries elastic fibers form layers which alternate with the layers of muscle fibers. In the largest arteries white connective-tissue fibers have been found in this coat. The external coat *(tunica externa,* or *adventitia)* is composed of loose connective tissue in which there are scattered smooth muscle cells or bundles of cells arranged longitudinally. In all but the smallest arteries this coat contains some elastic tissue. The structure and relative thickness vary with the size of the artery.

The great extensibility of the arteries enables them to receive the additional amount of blood forced into them at each contraction of the heart. Elasticity of arteries serves as a buffer to the large volume of blood forced into the system by the heartbeat. If these vessels were rigid (as is true in arteriosclerosis), the systolic blood pressure would be markedly increased. The strength of an artery depends largely upon the outer coat; it is far less easily cut or torn than the other coats and serves to resist undue expansion of the vessel.

The arteries do not *collapse* when empty, and when an artery is severed, the orifice remains open. The muscular coat, however, contracts somewhat in the region of the opening, and the elastic fibers cause the artery to retract a little within its sheath, so as to diminish its caliber and permit a blood clot to plug the orifice. This property of a severed artery is an important factor in the arrest of hemorrhage. Most of the arteries are accompanied by a *nerve* and *one or two veins,* all surrounded by a sheath of connective tissue, which helps to support and hold these structures in position.

SIZE OF THE ARTERIES The largest arteries in the body, the aorta and pulmonary artery, measure more than 3 cm in diameter at their connection with the heart. These arteries give off branches, which divide and subdivide into smaller branches. The smallest arteries are called *arterioles,* and at their distal ends, where only the internal coat remains, the capillaries begin. The arteriolar walls contain a great proportion of smooth muscle in relation to elastic tissue, and they are to be thought of as muscular rather than elastic.

THE ELASTIC ARTERIES. These include the large arteries and are called *conducting arteries* because they conduct blood from the heart to the *medium-sized arteries.* The middle coat contains a large amount of elastic tissue, and the wall is comparatively thin for the size of the vessel.

THE MUSCULAR ARTERIES. These include the arteries of medium size, and their middle coat is chiefly muscular. Muscular arteries are also called *distributing* arteries because they distribute the blood to the various organs and by contraction or relaxation they aid in regulating the volume of blood passing to structures to meet varying functional demands.

DIVISION OF ARTERIES: The way in which the arteries divide varies. (1) An artery may give off several branches in succession and still continue as a main trunk, e.g., the thoracic or abdominal portion of the aorta. (2) A short trunk may subdivide into several branches at the same point, e.g., the celiac artery. (3) An artery may divide into two branches of nearly equal size, e.g., the division of the aorta into the two common iliacs.

BLOOD SUPPLY OF THE ARTERIES. The blood which flows through the arteries nourishes only the inner coat. The external and middle coats are supplied with arteries, capillaries, and veins, called *vasa vasorum,* or blood vessels of the blood vessels.

VASOMOTOR NERVES. The muscular tissue in the walls of the blood vessels is well supplied with nerve fibers, chiefly from the sympathetic portion of the autonomic system. These nerve fibers are called *vasomotor* and are divided into two sets: (1) vasoconstrictor and (2) vasodilator. A center in the medulla oblongata (vasoconstrictor center) is constantly sending impulses to the vessels, thus keeping them in a state of tone. The vasoconstrictor center is a *reflex center* and is connected with afferent fibers coming from all parts of the body. Vasoconstrictor fibers are *sympathetic* and are widely distributed to arteries and arterioles. They mediate constriction of vessels, and by tonic action speed of blood flow is controlled. Vasodilator nerve fibers have several origins and are found on the sympathetic, parasympathetic, and somatic sensory nerves. There is no direct evidence that they are tonically active, but they appear to "discharge selectively" when a local increase in blood flow is needed.

There is a diffuse network of sympathetic nerve fibers in the adventitia of all arteries, called the *periarterial plexus.* Nerve fibers are also present in the muscular coat. Arterioles are directly and completely under *nervous* control. Pressure from increased volume, exerted on the blood stream in the muscular arteries, causes relaxation of the arterioles and more blood can move through to the capillary bed. The exact function of vasodilator nerve fibers is not well understood. Sudden, widespread relaxation of arterioles lowers blood pressure by decreasing peripheral resistance and shock may result.

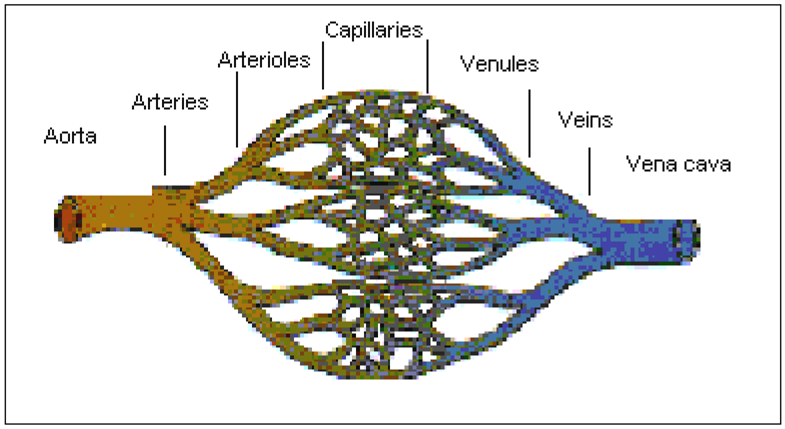
As the arteries decrease in size and approach the capillary network, they are called arterioles. Proximal to the capillary channel there are modified arterioles called metarterioles. They have a wall which contains widely separated smooth-muscle cells. A precapillary sphincter is located around the arteriole before it enters the capillary net. Arterioles are well supplied with vasoconstrictor fibers.

Capillaries

The capillaries are exceedingly minute vessels which average about 7 to 9μm in diameter. They connect the arterioles (smallest arteries) with the venules (smallest veins).

STRUCTURE. The walls of the capillaries consist of one layer of endothelial cells continuous with the layer that line the arteries, the veins, and the heart. These cells are held together by cell "cement." There is a substance called hyaluronic acid that forms a gelatinous material in the cell membrane and tissue spaces. It holds cells together and binds water in the tissues.

DISTRIBUTION. The capillaries communicate freely with one another and form interlacing networks of variable form and size in the different tissues. All the tissues, with the exception of the cartilages, hair, nails, cuticle and cornea of the eye, are traversed by networks of capillary vessels. The capillary diameter is so small that the blood cells often must pass through them in single file, and very frequently the cell is larger than the caliber of the vessel and becomes distorted as it passes through. In many parts the capillaries lie so close together that a pin's point cannot be inserted between them. They are most abundant and form the finest networks in those organs where the blood is needed for purposes other than local nutrition, such as, for example, *secretion or absorption*

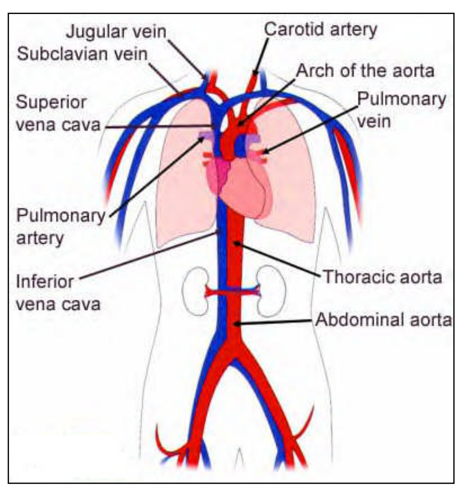


Vascular connections in the capillary bed.

FUNCTION. It is in the capillaries that the chief work of the blood is done, and the object of the vascular mechanism is to cause the blood to flow through these vessels in a steady volume. There are an estimated 7,000 sq meters of blood capillaries in the adult body. This gives a large area for exchange of substances between the blood and tissue fluid. In the glandular organs the capillaries supply the substances requisite for secretion; in the ductless glands they also take up the products of secretion; in the alimentary canal they take up some of the digested food; in the lungs they absorb oxygen and give up carbon dioxide; in the kidneys they discharge the waste products collected from other parts; all of the time, everywhere in the body, through their walls an interchange is going on which is essential to the life of the body. The greater the metabolic activity of the tissue, the denser the capillary nets.

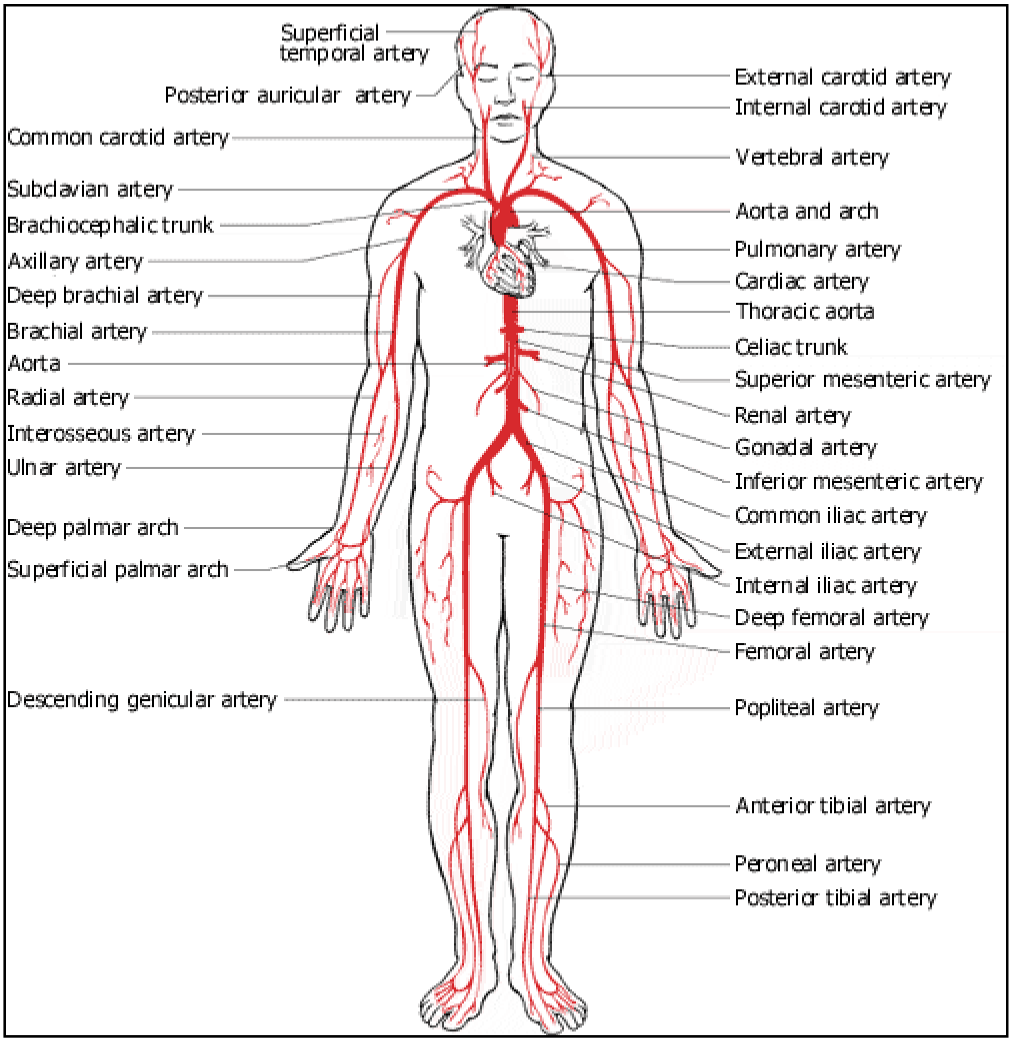
Pulmonary Circulation

The shorter circulation, from the right ventricle to the left atrium, is called the ***pulmonary circulation***. The purpose of the pulmonary circulation is to carry the blood which has been through the body, giving up oxygen and collecting carbon dioxide, to the air sacs of the lungs, where the red cells are recharged with oxygen and the carbon dioxide is reduced to the normal amount.



Systemic Circulation

The more extensive circulation, from the left ventricle to all parts of the body and the return to the right atrium, is known as the ***systemic circulation***. The purpose is to carry oxygen and nutritive material to the tissues and remove products of metabolism from the tissues. After leaving the left ventricle, portions of the blood pursue different courses; some portions enter the coronary arteries, some go to the head, some to the upper and lower extremities, and some to the different internal organs. Some portions go on shorter circuits and arrive back at the heart sooner than other portions that travel farther away from the center of the systemic circulation An example of a long circuit in the systemic circulation is the circulation from the left heart to the toes and back to the right heart, then to the lungs and to the left heart. An example of a short circuit is the circulation of blood through the walls of the heart itself.



Systemic arterial circulation

Arterial physiology

Each cell of the body is dependent on the blood for its very existence, and it is the work of the heart, arteries, capillaries, and veins that makes possible the transporting of all substances to and from cells.

The function of the heart is to adjust circulation in relation to the metabolic rate of body cells. By chemical and nervous control, the needs of these cells are met promptly through adjustments of pulse rate and pulse volume, which increase and decrease the volume of blood reaching the tissue capillaries per minute. Variable cellular needs are thus met by changes in the number, size, and area of the open capillaries and in the temperature and the minute volume of the blood in these open capillaries.

The blood is contained in a closed set of vessels, which it completely fills. Interposed in this set of vessels is the heart, which fills with blood from the veins and then contracts, thereby, forcing this blood into the capillaries of all parts of the body.

DISTRIBUTION OF BLOOD TO DIFFERENT PARTS OF THE BODY.

In healthily tissue the distribution of blood varies, as determined by the needs of the different parts. When the digestive organs are active, they need an extra supply of blood, which may be supplied by redistribution of blood from less active organs. Other causes may result in an increased supply of blood to an organ. If the skin is exposed to high temperatures, the arterioles which bring blood to it are dilated, and the blood flow near the surface is increased. This aids in the radiation of heat and in the control of body temperature. On the other hand, slight chilling causes contraction of the skin arterioles and resulting paleness. The blood supply to the brain is relatively constant. According to recent studies, blood supply to the brain is not reduced during sleep and not increased by mental activity

TONUS OF BLOOD VESSELS

Normally the blood vessels maintain a state of tonus about halfway between contraction and dilatation. It is thought that adjustments in the blood supply to various parts are brought about by increasing or decreasing the tone of the local blood vessels. Two factors are important, (1) vasomotor nerve fibers and (2) chemical stimuli.

1. The vasomotor nerve fibers consist of two antagonistic sets. The vasoconstrictors cause the muscular coats of the blood vessels to contract, lessen the diameter of the vessels, and thereby increase resistance to blood flow. The vasodilator fibers increase the diameter of the blood vessels, probably by allowing the muscular coats to relax, and thereby decrease resistance to blood flow.
2. Chemical substances, such as the lactic acid and carbon dioxide produced during muscular activity, may lessen the tonus of the blood vessels in the part affected, resulting in local dilatation and an increased supply of blood to the part needing it. At the same time, chemoreceptors convey impulses to the

vasoconstrictor center, stimulate it, and thereby increase the tonus of blood vessels in other parts of the body. On the other hand, angiotensin and hormones, such as epinephrine and vasopresssin, cause constriction of the blood vessels.

Epinephrine and many other drugs are used medicinally to cause vasoconstriction, and amyl nitrite is inhaled to bring about vasodilatation, particularly when a condition like angina pectoris makes quick relief necessary. Both the arteries and the veins are capable of dilatation or constriction under the influence of nerve fibers or chemical stimuli.

In surgical shock there is marked interference with the circulation of the blood owing to dilatation of the arteriolar bed and consequent decrease in arterial pressure, which may fall below the level essential to the welfare of the tissues. The pulse becomes rapid and weak, and respiration increases. It is thought that dilatation of the arterioles may be brought about by substances such as histamine formed in injured tissues.

Physiological Controls

Several physiological factors, which control or affect blood flow into human tissues, have a direct impact on alterations of blood flow patterns seen during sonographic evaluation of the arteries.

LOCAL CONTROL of blood flow into tissue is governed largely by nutritional needs of the tissue itself. Metabolically active tissue requires a constant supply of oxygen and nutrients and removal of waste products. Therefore perfusional demands of organs such as the brain, kidneys and heart are constant. Perfusional demands of tissue that is not constantly active at the same metabolic rate will vary; blood flow rates and patterns into these tissues will vary according to current needs.

NEURAL CONTROLof blood flow is mediated through the sympathetic nervous system that innervates arterial and venous systems. The sympathetic nervous system, which is centered in the spinal cord and ganglia innervate viscera, heart, lungs. It controls motor, vasomotor and secretory reflexes. It produces the following physiologic reactions:

1. Dilatation of pupils
2. Bronchodilation/constriction
3. Vasodilation/constriction
4. Sweating, increase/decrease salivary production
5. Increased adrenal secretions
6. Sphincter/bladder control
7. Uterine contractions
8. Hair stands on end (piloerector muscles)

HUMORAL CONTROL is the control of arterial tonus by chemical substances that typically circulate in the blood stream. Humoral regulation causes vessels to constrict or dilate for example, angiotensin and vasopressin are potent vasoconstrictors whereas histamine and bradykinin are vasodilators.

AUTOREGULATION is the ability of tissues to control their own blood flow. Lack of oxygen or accumulation of metabolites (lactic acid and carbon dioxide) causes dilatation of capillary channels in an attempt to channel more blood into the hypoxic area. There are two components of physiologic autoregulation that impact flow dynamics encountered in arterial pathology:

1. ***Hyperemia*** which is a generalized increase in blood flow to a part. This increase in flow volume may be either:

   Reactive: when blood supply to an area has been chronically diminished and is suddenly restored, increased blood volume flows into the tissue causing it to become red and warm and sometimes painful. This phenomenon is frequently seen in a condition called Reynaud's disease. Reactive hyperemia is also responsible for the red, hot fingers seen in hands that have come in from the cold.

   Functional which is an increase in flow based on physiological needs. Examples include exercising skeletal muscle and increases in metabolism in rapidly growing tissues such as cancer or early pregnancies.
2. ***Collateral circulation*** is a mechanism for long-term re-perfusion of tissues. When mechanical or physiological obstruction blocks normal perfusional channels to living tissue, anatomic anastomotic channels carry blood to that area. Over time, these channels dilate and blood flow increases to meet nutritional needs of the tissue being perfused. Collateral perfusion works best when obstruction to flow is gradual (chronic) and not sudden (acute). Examples of collateral circulatory flow can be seen in almost all major human organ systems when primary flow paths are diminished or obliterated.

Cardiovascular Function

The most important factors maintaining **arterial** circulation are:

- **Pumping action of the heart** (*See Chapter 4*, section on Hemodynamics – Cardiac Energy)
- **Elasticity and extensibility of the arterial walls**
- **Peripheral resistance in distal vascular beds**
- **Quantity of blood in the body**

Elasticity of Arterial Walls

During each systole the ventricles force blood into arteries that are already full (about 30 to 60 ml each). The extensibility of the arteries enables them to distend and receive this extra supply of blood. The period of distention corresponds to the systole of the heart. Just as soon as the force is removed, the elasticity of the arteries causes them to contract to their former diameter, and this exerts such a pressure on the contained blood that the blood is forced into the capillaries just rapidly enough to allow the arteries time to reach their usual size during diastole of the heart. The arteries thus not only serve as conducting vessels but exert a force that assists the heart in driving the blood into the capillaries.

The extensibility and elasticity of the arteries change with the health and age of the individual. Sometimes as the result of disease, and usually with age, the arterial walls become less elastic and less well adapted for the unceasing work they are called upon to perform.

Peripheral Resistance

Blood flow is opposed by frictional forces within the vessels. Friction results from the relationships between the layers of fluid wetting the vessel walls and the more central layers of the moving stream. Frictional resistance to flow varies therefore with the character of the fluid, that is, with its viscosity. This means that there is direct relationship between viscosity of the blood and peripheral resistance. The greater the viscosity, the greater the resistance to blood flow.

It is the function of the vasomotor fibers to “set” the diameters of the muscular arterioles in relation to constantly varying local needs for blood. The elastic arteries compensate for heart systole and diastole, thus maintaining a steady flow of blood in the capillaries, the arteries accommodating the extra blood forced into them during heart systole and by their contraction forcing the blood toward the capillaries during heart diastole. Inasmuch as local needs for blood vary constantly and through constantly varying limits, it is the function of the autonomic nervous system (and locally produced chemical substances such as carbon dioxide), reflecting these needs, to set the diameters of the arterioles so that the peripheral resistance meets these local needs (much blood needed, wide arterioles; less blood needed, narrower arterioles). On the basis of peripheral resistance thus established, it is the function of the arterioles, to expand and contract, changing an intermittent flow in the arteries to a steady flow in capillaries. It is easily seen that this is a fine adjustment, the elastic arteries giving a steady flow in capillaries on many bases of diameter of arterioles set by local needs. This fine adjustment (associated with optimum activity of the heart) is the mechanism by means of which homeostasis, or state of constancy, of body fluids is maintained.

The kidneys play an important role in the regulation of arterial pressure. It is known that the kidneys can regulate arterial pressure by increasing urine output, which decreases volume and lowers pressure, or by decreasing urine output, thereby increasing blood volume, which raises arterial pressure. If the kidney is deprived of part of its blood supply from any cause, blood pressure rises. When the kidney is deprived of part of its blood supply, it secretes renin. Renin activates a globulin of a plasma protein which eventually becomes a substance called angiotensin II. This is the most active vasopressor substance known. It also acts on the adrenal cortex to increase aldosterone secretion, which stimulates the kidney to retain sodium and water. The net effect is an increase in blood pressure.

Quantity of Blood

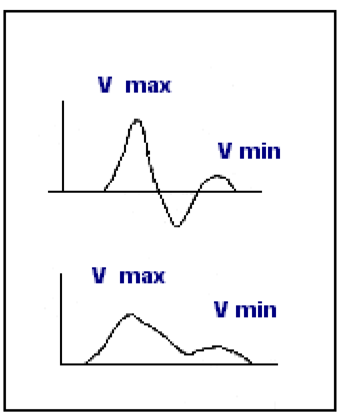
It is evident that, other things being equal, the quantity of blood to be moved is an important factor. Except in cases of severe hemorrhage, loss of blood is compensated for by a transfer of liquid from the tissues into the blood vessels.

Doppler Measurement of Arterial Flow

Spectral Doppler techniques permit a variety of measurements to be made of arterial blood flow through a particular vessel. Changes in flow velocity and volume amplitude throughout the cardiac cycle provide a great deal of information about the type of tissue the vessel is perfusing and about flow characteristic within the vessel itself. The most commonly measured parameters of arterial blood flow include **pulsatility and resistivity.**

Pulsatility

Pulsatility is a sensitive index of diastolic runoff – that is, with increased peripheral vasodilatation; diastolic runoff is expected to increase and PI to decrease. Some authors believe that PI is a better indicator of vasodilatation than of flow velocity, presumably because it reflects a combination of reduced partial pressure and lowered tissue resistance. Pulsatility is the difference between systolic peak velocity (V_{max}) and late diastolic peak velocities (V_{min}) . High systolic peak and low end-diastolic flow velocities produce good pulsatility; low systolic peak and low end-diastolic flow velocities produce poor pulsatility**.** In the schematic below, waveform A demonstrates good pulsatility; waveform B demonstrates poor pulsatility.



High pulsatility waveform

Low pulsatility waveform

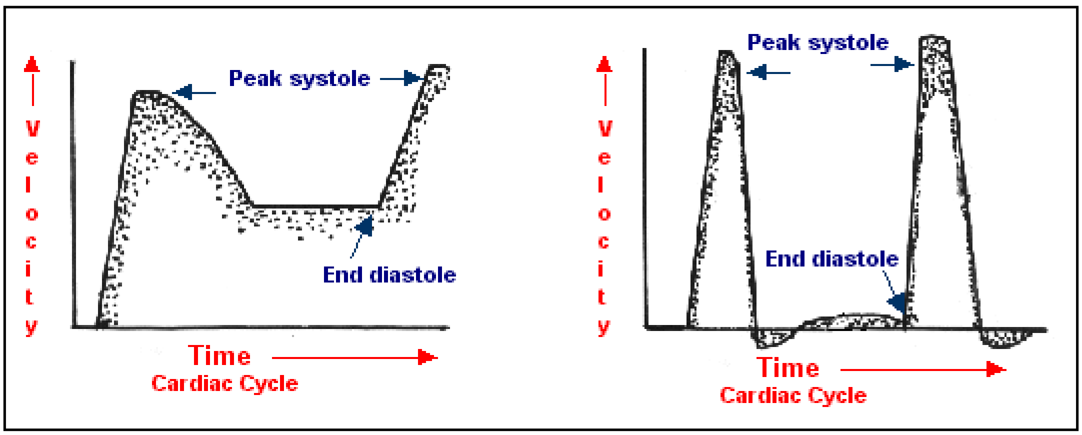
Pulsatility Index (**PI) = (V_{max} – V_{min})** ÷ **V_{mean}**

RESISTIVITY

Resistivity is a measure of difficulty in forcing blood through vessels into tissue.

LOWLY RESISITVE tissue provides little resistance to blood flow. Consequently, there is antegrade flow into the tissue throughout the cardiac cycle. Tissue and organs that require a constant supply of oxygen and nutrients to meet metabolic needs usually possess a large number of small blood vessels which create a low resistance vascular bed. Examples include the brain, kidneys, trophoblastic and malignant tissue.

HIGHLY RESISTIVE tissue and organs do not require a constant flow of oxygen and nutrients and typically contain far fewer blood vessels. Blood has a difficult time flowing easily into them, especially during diastole. Examples include skeletal muscle at rest and the non-dominant ovary.



5.5 Low Resistance Waveform
Velocities accelerate during systole and begin to slowly taper off during diastole. Forward flow is maintained throughout the cardiac cycle.

5.6 High Resistance Waveform
Velocities accelerate rapidly during systole and decelerate quickly. Little or no forward flow is present throughout diastole.

$$\textbf{Resistivity Index (RI)} = (V_{\text{peak systole}} - V_{\text{end diastole}}) \div V_{\text{peak systole}}$$

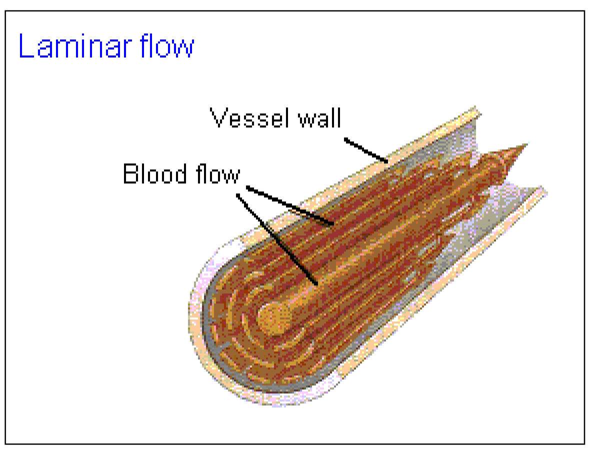
Arterial Hemodynamic Patterns

The flow of blood in the arterial circulation is governed by the basic laws of fluid dynamics. Hemodynamics relates the forces and motion of blood flow and the science concerned with the study of the circulation of blood. The forces found on the arterial side of the human circulatory system include: the cardiac pump, gravity, hydrostatic pressure and the presence of pressure differences, or gradients, between two points in a column of flowing fluid. Some of the physical characteristics of blood, such as viscosity and inertial mass, also play an important role in flow patterns in arteries, as do the physical characteristics of the arteries themselves. Diameter of the blood vessel, smoothness of the vascular lumen, the elasticity of the muscular layer, and the vascular bed being supplied by the artery determine, to a great extent, the volume velocity and laminarity of blood flow within each vessel.

Typical Arterial Flow Patterns

The following are the basic types of blood flow patterns found in normal and diseased human arteries.

LAMINAR FLOW is smooth flow in which the blood components are layered so that the plasma is adjacent to the smooth surface of the vessel wall and the cellular components are in the center of the blood stream. This reduces friction by allowing the blood layers to slide smoothly over each other in concentric layers, or laminae. Each very thin layer flows at a different velocity with higher velocities in the center of the stream and slower velocities toward the vessel wall. All flow is in the same direction and laminar flow is stable with “streamline” formations staying intact. Friction and energy losses, as described below, increase to the extent that laminar flow is disturbed. Laminar flow is sometimes referred to as *parabolic flow* because the velocity profile takes on the shape of a parabola.

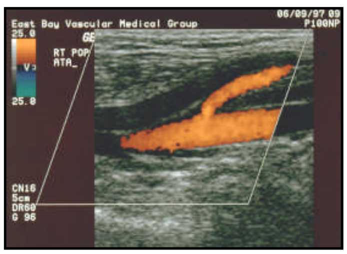


Concentric laminae in normal arterial laminar flow patterns.

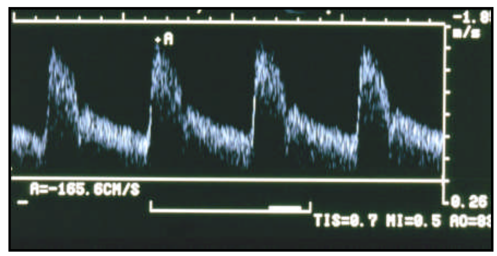
The flow of blood in the blood vessels, like the flow of liquids in narrow rigid tubes, is normally laminar (streamline). Within the blood vessels, an infinitely thin layer of blood in contact with the wall of the vessel does not move. The next layer within the vessel has a small velocity, the next a higher velocity, and so forth, velocity being greatest in the center of the.

Laminar flow occurs at velocities up to a certain critical velocity. At or above this velocity, flow is turbulent. Streamline flow is silent but turbulent flow creates sound, frequently presenting in clinical practice as a ***bruit***

The probability of turbulence is also related to the diameter of the vessel and the viscosity of the blood. This probability can be expressed by the ratio of inertial to viscous forces. The mathematical relationship of these forces yields a unitless number called the Reynolds number, named for the man who described the relationship. Basically, the higher the value of the Reynolds, the greater the probability of turbulence. In humans, critical velocity is sometimes exceeded in the ascending aorta at the peak of systolic ejection, but it is usually exceeded only when an artery is constricted. Turbulence occurs more frequently in anemia because the viscosity of the blood is lower. This may be the explanation of the systolic murmurs that are common in anemia.



CDI demonstration of normal arterial laminar flow in the aorta and superior mesenteric artery.



Spectral waveform showing good laminar flow. Spectral window is clear; spectral envelope is crisp.

Plug Flow

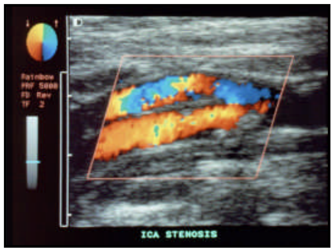
Plug flow is a hemodynamic pattern where all layers of blood move along at the same velocity. All flow is in the same direction. Plug flow is frequently seen in arterial vessels close to the heart that have low resistance, i.e., renals, vertebrals, aorta.

Disturbed Flow

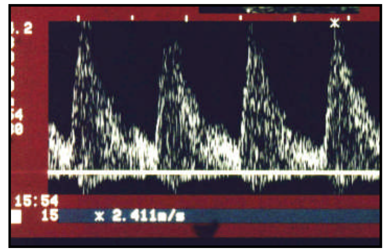
Wall roughening or non-obstructive plaques causes alteration of normal laminar flow with random irregularities in velocities throughout the vessel. There may be mild alterations in flow direction. Doppler audio signal is mildly gruff. Spectrum demonstrates random irregularities in the upper maximum frequency range. A soft bruit may or may not be auscultated with the stethoscope.

Turbulent Flow

Flow disturbances characterized by multi-directional, multi-velocity streams and eddies of blood within an arterial lumen are called ***turbulent***. Common causes of turbulence include vessel tortuosity and the collapse of high velocity jets distal to an arterial stenosis. In clinical practice, this phenomenon is commonly seen just distal (downstream) to a critical arterial stenosis. These jets create excessive wall vibrations and the presence of many different velocities flowing through the vessel in many different directions. Doppler audio signal is gruff and whining. Doppler frequency spectrum shows spectral broadening, non-laminar profile, flow separation and/or reverse flow. It may also be heard as a gruff, moderately loud bruit with a stethoscope.



CDI demonstration of turbulent flow in the carotid artery. Random flow directions and velocities are present.



Spectral waveform demonstrating turbulent flow. Filling in of spectral window; shaggy spectral envelope.

Stenotic Flow Patterns:

Definition of a hemodynamically significant, or critical, stenosis:

- 75% cross-sectional area reduction
- 50% diameter reduction

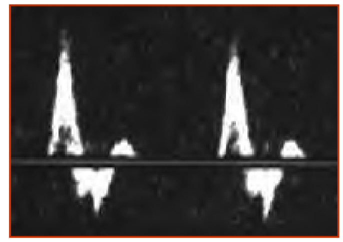
A critically stenosis channel produces higher velocities consistent with Bernoulli's Principle that relates vessel diameter and flow velocity. According to Bernoulli, fluid will flow ***faster*** through a narrower vessel than it will through a wider vessel. This assumes that other factors influencing hemodynamics remain constant such as pressure and viscosity of blood. Doppler audio signal is typically high-pitched and clean. Doppler frequency spectrum shows elevated peak systolic velocities (>140 cm/sec) with flow usually in one direction. There may be flow reversals and turbulence distal to the stenotic site. High velocity flow patterns may be heard with the stethoscope as a loud, harsh or wheezing bruit. As the degree of narrowing increases, peak systolic velocities continue to increase.

Pre-occlusive Flow:

As blood strikes a pre-occlusive lesion (less than 1 mm in diameter) kinetic energy is transmitted to the arterial walls during systole causing excessive vessel motion. Doppler audio signal demonstrates a characteristic dampened thumping. Doppler frequency spectrum shows very high velocity signal with elevated peak systolic (>200 cm/sec) and end diastolic components (>140 cm/sec), and complete spectral broadening. The Doppler signals distal to the stenosis may demonstrate decreased velocities and absent diastolic flow. The audible bruit is usually "sea-gull" in nature.

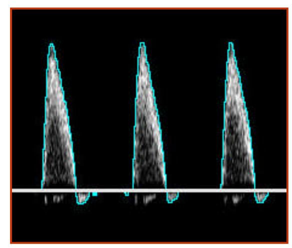
Arterial Phasicity Patterns

Triphasic: Each waveform consists of three components: 1) **forward flow**, usually with rapid acceleration and deceleration rates corresponding to systolic myocardial contraction; 2) a short, low velocity **flow reversal** during which blood is ejected back up the artery as a result of vascular wall rebound during early diastole; and 3) a second **forward flow** component during late diastole. Triphasic waveforms represent normal blood flow in the arteries in the extremities at rest. Loss of triphasicity suggests decreased peripheral resistance in the distal vascular bed or loss of vascular wall compliance.



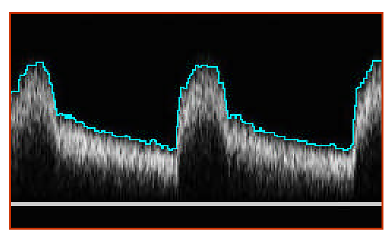
Triphasic waveform

Biphasic: Biphasic waveforms consist of two components as described above: **forward flow** followed by a **flow reversal.** In the peripheral arterial tree, biphasic flow suggests mild loss of vascular wall compliance.



Biphasic waveform

Monophasic: Flow in a single direction throughout the cardiac cycle is called monophasic flow. It is normal in arterial vessels supplying a lowly resistive distal vascular bed, such as the brain. In arteries that normally display a triphasic pattern, monophasic flow suggests significant loss of vascular wall compliance and reduced pressure from a proximal flow disturbance (significant stenosis or occlusion).



Monophasic waveform