The blood vessels are a closed system of conduits that carry blood from the heart to the tissues and back to the heart. Some of the interstitial fluid enters the lymphatics and passes via these vessels to the vascular system. Blood flows through the vessels primarily because of the forward motion imparted to it by the pumping of the heart, although, in the case of the systemic circulation, diastolic recoil of the walls of the arteries, compression of the veins by skeletal muscles during exercise, and the negative pressure in the thorax during inspiration also move the blood forward. The resistance to flow depends to a minor degree on the viscosity of the blood but mostly upon the diameter of, principally the arterioles. The blood flow to each tissue is regulated by local chemical and general neural mechanisms that dilate or constrict the vessels of the tissue. All of the blood flows through the lungs, but the systemic circulation is made up of numerous different channels in parallel, an arrangement that permits wide variations in regional blood flow without changing total systemic flow.

**Definition of Hemodynamics**

Hemodynamics relates the **forces** and **motion** of **blood** flow and the science concerned with the study of the circulation of blood. The sole function of the circulatory system is transportation. It carries a variety of substances to and from all living cells. These substances include:

1. Oxygen
2. Nutrients
3. Metabolic wastes
4. Hormones
5. Antibodies
6. Leukocytes
7. Medications
8. Heat

The **forces** involved with the movement of blood throughout the human circulatory system include:

1. Kinetic and potential energy provided by the cardiac pump
2. Gravity
3. Hydrostatic Pressure
4. Pressure gradients, or differences, between two any points
Properties of blood itself that affect its flow characteristics through the heart, arteries and veins include its:
1. Viscosity
2. Inertial mass
3. Volume of blood to be moved

Factors that affect the motion of blood through the vascular conduits include:
1. Size of blood vessel
2. Condition of blood vessel
3. Smoothness of lumen
4. Elasticity of muscular layer (tunica media)
5. Destination of blood (distal vascular bed)

**Definition of Physical Concepts**

1. **PRESSURE**: the ratio of a force acting on a surface to the area of the surface (force per unit area). Units include: Newtons/m², pascal (Pa), atmospheres (atm), mmHg.

2. **FLOW RATE**: Amount of fluid passing a given point over a given period of time. It is described in vascular hemodynamics as either flow volume or flow velocity. **Flow volume** is measured in ml/mm or cm³/sec and is defined by Poiseuille’s law. **Flow velocity** is measured in cm/sec or m/sec and is described by Bernoulli’s principle.

3. **VISCOSITY**: The internal friction between adjacent layers of fluid. Blood is 1.5 times as viscous as water and its viscosity is directly related to hematocrit level.

4. **INERTIA**: The tendency of a body at rest to remain at rest or of a body in motion to remain in motion unless acted upon by an external force. In blood flow disturbances, inertia describes the inability of viscous blood to move spontaneously. The introduction of kinetic energy into the fluid column is required to induce motion of blood.

5. **KINETIC ENERGY**: active energy, the energy of motion. In hemodynamics, it may be described as the forward movement of blood.

6. **POTENTIAL ENERGY**: stored energy. Kinetic energy is transferred into potential energy when it produces a lateral pressure or stretching of vessel walls during systole. The potential energy is converted back into kinetic energy when the arterial walls rebound during diastole.
1. Pressure

PRESSURE IN STATIC FLUIDS

In liquids at rest the pressure caused by liquid is proportional to the depth of the liquid and its density. Because there is a distribution of pressure in static liquids it is possible to use fluid to transmit pressure. If a tiny droplet of the liquid at a particular depth could be examined, it would be found that the droplet is in equilibrium but that it has forces exerted upon it from all directions. Stated in another way, pressure is exerted equally in all directions in a static liquid.

In addition to the pressure caused by the weight and depth of a liquid, external pressures exerted on enclosed liquid must be added to the initial pressure to get the total pressure. External pressure exerted on an enclosed liquid changes the overall pressure. Pascal’s Principle states that any change of pressure in an enclosed fluid is transmitted undiminished to all parts of the fluid.

HYDROSTATIC PRESSURE

The pressure at a given depth in a static liquid is a result of the weight of the liquid acting on a unit area at that depth plus any pressure acting on the surface of the liquid. In the human body, the best example of practical applications of the principles of hydrostatic pressure can be found in the lower extremity venous systems. (See Chapter 13, p.169).

The pressure in any blood vessel below the level of the heart is increased, and the pressure in any vessel above heart level is decreased by the effect of gravity. The magnitude of the gravitational effect (ΔP) is the product of the specific gravity or density of the blood (ρ), the acceleration due to gravity (980 cm/s/s) (g), and the vertical distance above or below the heart (Δh) which is 0.77 mm Hg/cm at the density of normal blood. This relationship can be stated mathematically as:

\[ \Delta P = \rho g \Delta h \]

Thus, in the upright position, when the mean arterial pressure at heart level is 100 mm Hg, the mean pressure in a large artery in the head (50 cm above the heart) is 62 mm Hg (100 - [0.77 x 50]) and the pressure in a large artery in the foot (105 cm below the heart) is 180 mm Hg (100 + [0.77 x 105]).

PRESSURE IN FLOWING FLUIDS

The pressure in a flowing liquid depends on the details of the flow process, in contrast to the case of the static liquid, where the pressure depends only upon the depth and density of the fluid and the externally applied pressure. When a liquid flows through a tube, there will be a pressure drop; the pressure at the exit point of a length of uniform tubing will be lower than the entrance to the tube. This difference in pressure is referred to as pressure gradient, which is defined as a pressure drop per unit length.
Pressure gradient = $P_1 - P_2/L$

Where: $P_1$ = entry pressure  
      $P_2$ = exit pressure  
      $L$ = length of tubing

For a uniform horizontal tube the pressure gradient will be the same at all points in the tube if a perfectly uniform flow pattern is maintained. Drops in pressure during flow represent losses in energy. These losses are largely attributable to friction effects. One type of friction is that between the fluid and the walls of the tubing. This friction increases the fluid resistance and thus impedes the flow. Frictional forces also exist within the fluid. These forces, which oppose the flow, are referred to as viscosity.

**LAW OF LAPLACE**

It is perhaps surprising that structures as thin-walled and delicate as the capillaries are not more prone to rupture. The principal reason for their relative invulnerability is their small diameter. The protective effect of small size in this case is an example of the operation of the law of LaPlace, an important physical principle with several other applications in physiology. This law states that the distending pressure ($P$) in a distensible hollow object is equal at equilibrium to the tension in the wall ($T$) divided by the 2 principal radii of curvature of the object ($R_1$ and $R_2$):

$$P = \frac{T}{1/R_1 + 1/R_2}$$

In the equation, $P$ is actually the transmural pressure, the pressure on one side of the wall minus that on the other. $T$ is expressed in dynes/cm and $R_1$ and $R_2$ in cm, so $P$ is expressed in dynes/cm$^2$. Consequently, the smaller the radius of a blood vessel, the less the tension in the wall necessary to balance the distending pressure. In the human aorta, for example, the tension at normal pressures is about 170,000 dynes/cm, and in the vena cava, it is about 21,000 dynes/cm. In the capillaries, it is approximately 16 dynes/cm.

**2. Flow Rate**

**POISEUILLE’S LAW**

Poiseuille’s law predicts the volume of flow in moving fluids. The relation between the flow volume in a long narrow tube, the viscosity of the fluid, and the radius of the tube is expressed mathematically in the Poiseuille-Hagen formula. Since flow volume varies directly and resistance inversely with the fourth power of the radius, blood flow and resistance in vivo are markedly affected by small changes in
the caliber of the vessels. Thus, for example, flow through a vessel is doubled by an increase of only 19% in its radius; and when the radius is doubled, resistance is reduced to 6% of its previous value. This is why organ blood flow is so effectively regulated by small changes in the caliber of the arterioles and why variations in arteriolar diameter have such a pronounced effect on systemic arterial pressure.

\[
Q = \left( P_1 - P_2 \right) \frac{\pi R^4}{8 \eta L}
\]

where:
- \( Q \) = volume flow
- \( P_1 \) = entry pressure
- \( P_2 \) = exit pressure
- \( L \) = length of tubing
- \( R \) = radius of tube
- \( \eta \) = viscosity of fluid

- As pressure difference or diameter of vessel ↑, volume flow ↑
- As length or viscosity ↑, volume ↓

Example: Suppose a given tube had an initial volume flow rate of 100 cm\(^2\)/s. Doubling the individual parameters in Poiseuille’s Law would have the following effect:

- Initial volume flow rate = 100 cm\(^2\)/s
- double pressure = 200 cm\(^2\)/s
- double viscosity = 50 cm\(^2\)/s
- double length = 50 cm\(^2\)/s
- double radius = 1600 cm\(^2\)/s

Poiseuille’s Law predicts volume flow under laminar flow conditions in straight tubes where wall friction is not a significant factor. In looking at the above formula perhaps most surprising is that volume flow rate is exponentially related by the fourth power to the radius of the tubing. This relationship shows that increasing the size (diameter) of the tubing is much more efficient than increasing the pressure gradient to effect a volume flow increase. Conversely, small reductions in the diameter of a vessel yield a substantial reduction (\( r^4 \))

**The Bernoulli Effect**

When fluid flows steadily (without acceleration or deceleration) from one point in a system to another further downstream, its total energy content along any given streamline remains constant, provided there are no frictional losses.

Bernoulli’s equation is instructive in that it establishes a relationship between kinetic energy, gravitational potential energy, and pressure in a frictionless fluid system. Several apparent paradoxes of fluid flow are readily explained, for example, if fluid with the specific gravity of blood enters an inclined tube at a pressure of 100 mm Hg and flows out at a pressure of 178 mm Hg. Thus, fluid moves against the
pressure gradient from a point of low pressure to a point where its pressure is high. The total fluid energy remains the same, however, since the gravitational potential energy decreases by an amount exactly equal to the increase in pressure. This situation is analogous to that which exists in the arterial tree of an upright person in which blood pressure in the arteries at ankle level is greater than that in the aortic arch.

The Bernoulli equation also predicts flow velocity and explains the presence of high-velocity jets obtained with Doppler instruments in arterial disease states characterized by lumenal narrowing (stenosis). For example, as the cross-sectional area of a straight tube decreases (narrows), it results in a comparable increase in fluid velocity through the narrowed area. It’s like putting your thumb over the opening of a flowing garden hose. High-velocity jets are created. A modification of the standard Bernoulli equation demonstrates this inverse relationship between velocity and fluid pressure. Assume that the total energy present in a fluid column remains constant \(E\). A reduction in the pressure distal to the narrowed area creates an increase in the pressure gradient (seen clinically across arterial stenoses). Higher-pressure blood proximal to the stenosis speeds up as it is pumped into the area of lower pressure beyond the stenosis. The relationships in the Bernoulli effect can be expressed mathematically as:

\[
E = \frac{1}{2} \Gamma v^2 + P
\]

where:  
\(E\) = energy per unit volume  
\(\Gamma\) = viscosity of fluid  
\(v\) = velocity of fluid  
\(P\) = fluid pressure

Bernoulli effects can also be appreciated when considering human blood pressure. The pressure in the aorta and in the brachial and other large arteries in a young adult human rises to a peak value (systolic pressure) of about 120 mm Hg during each heart cycle and falls to a minimum value (diastolic pressure) of about 70 mm Hg. The arterial pressure is conventionally written as systolic pressure over diastolic pressure, e.g., 120/70 mm Hg. The pulse pressure, which is the difference between the systolic and diastolic pressure, is normally about 50 mm Hg. The mean pressure is the average pressure throughout the cardiac cycle. Because systole is shorter than diastole, mean pressure is slightly less than the value halfway between systolic and diastolic pressure. It can actually be determined only by integrating the area of the pressure curve; however, as an approximation, the diastolic pressure plus one-third of the pulse pressure is reasonably accurate.

The pressure falls very slightly in the large- and medium-sized arteries because their resistance to flow is small, but it falls rapidly in the small arteries and arterioles, which are the main sites of the peripheral resistance against which the heart pumps. The mean pressure at the end of the arterioles is 30 - 38 mm Hg. Pulse pressure also declines rapidly to about 5 mm Hg at the ends of the arterioles. The magnitude of the pressure drop along the arterioles varies considerably depending upon whether they are constricted or dilated.
LAMINAR FLOW AND TURBULENCE

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 stream. 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**.

More on laminar flow patterns and disruptions of this normal flow state in the human circulatory system is present in Chapter 13 Hemodynamics in situ.

AVERAGE VELOCITY - TIME AVERAGE VELOCITY (TAV)

When considering flow in a system of tubes, it is important to distinguish between velocity, which is displacement per unit time (e.g., cm/s), and flow, which is volume per unit time (e.g., cm³/s). Velocity (V) is proportionate to flow (Q) divided by the area of the conduit (A): $V = \frac{Q}{A}$.

The average velocity of fluid movement at any point in a system of tubes is inversely proportionate to the total cross-sectional area at that point in space. Therefore, the average velocity of the blood is rapid in the aorta, declines steadily in the smaller vessels, and is slowest in the capillaries, which have 1000 times the total cross-sectional area of the aorta. The average velocity of blood flow increases again as the blood enters the veins and is relatively rapid in the vena cava, although not so rapid as in the aorta.

**Time average velocity (TAV)** is a measurement that is important in calculating flow volume in some types of vascular sonography. Operator-obtained measurements (vessel diameter and spectral waveform profile) are entered into onboard software to make this calculation.

VELOCITY AND FLOW OF BLOOD

Although the mean velocity of the blood in the proximal portion of the aorta is 40cm/s, the flow is phasic and velocity ranges from 120cm/s during systole to a negative value at the time of the transient backflow before the aortic valves close in diastole. This short-lived reduction in pressure produces a typical negative deflection of in a Doppler waveform immediately after end systole and just before early diastole called a **dicrotic notch**. In the distal portion of the aorta and in the arteries, velocity is also greater in systole than in diastole, but forward flow is continuous because of the recoil during diastole of the vessel walls that have been stretched during systole. An exception of this continuous forward flow may be found in the peripheral arteries in extremities, where a normal flow reversal is seen in early diastole. Pulsatile flow appears in some poorly understood way to maintain optimal function of the tissues. If an organ is perfused with a pump that delivers a non-pulsatile flow, there is a gradual rise in vascular resistance, and tissue perfusion fails.
3. Viscosity

VISCOSITY AND RESISTANCE

Blood flow varies inversely and resistance directly with the viscosity of the blood in vivo, but the relationship deviates from that predicted by the Poiseuille-Hagen formula. Viscosity depends for the most part on hematocrit, i.e. the percentage of blood volume occupied by red blood cells. In large vessels, increases in hematocrit cause appreciable increase in viscosity. However, in vessels smaller than 100 μm in diameter, i.e., in arterioles, capillaries, and venules, the viscosity change per unit change in hematocrit is much less than it is in large-bore vessels. This is due to a difference in the nature of flow through the small vessels. Therefore, the net change in viscosity per unit change in hematocrit is considerably less in the body than it is in vitro. This is why hematocrit changes have relatively little effect on the peripheral resistance when the changes are large. In severe polycythemia, the increase in resistance does increase the work of the heart. Conversely, in anemia, the peripheral resistance is decreased, though the decreased resistance is only partly due the decrease in viscosity. Cardiac output is increased and as a result, the work of the heart is also increased in anemia.

Viscosity is also affected by the composition of the plasma and the resistance of the cells to deformation. Clinically significant increases in viscosity are seen in diseases in which plasma proteins such as the immunoglobulins are markedly elevated and in diseases such as hereditary spherocytosis, in which the red blood cells are abnormally rigid.

In the vessels, red cells tend to accumulate in the center of the flowing stream. Consequently, the blood along the side of the vessels has a low hematocrit, and branches leaving a large vessel at right angles may receive a disproportionate amount of this red cell-poor blood. This phenomenon, which has been called plasma skimming, may be the reason the hematocrit of capillary blood is regularly about 25% lower than the whole body hematocrit.

Methods of Measuring Blood Pressure

INTRAVASCULAR METHOD

If a cannula is inserted into an artery, the arterial pressure can be measured directly with a mercury manometer or a suitably calibrated strain gauge and an oscillograph arranged to write directly on a moving strip of paper. When an artery is tied off beyond the point at which the cannula is inserted, an end pressure is recorded. Flow in the artery is interrupted, and all the kinetic energy of flow is converted into pressure energy. If, alternatively, a T tube is inserted into a vessel and the pressure is measured in the side arm of the tube, under conditions where pressure drop due to resistance is negligible, the recorded side pressure is less than the end pressure by the kinetic energy of flow. This is because in a tube or a blood vessel the total energy—the sum of the kinetic energy of flow and the pressure energy—is constant (Bernoulli’s principle).
It is worth noting that the pressure drop in any segment of the arterial system is due both to resistance and to conversion of potential into kinetic energy. The pressure drop due to energy lost in overcoming resistance is irreversible, since the energy is dissipated as heat; but the pressure drop due to conversion of potential to kinetic energy as a vessel narrows is reversed when the vessel widens out again.

Bernoulli’s principle also has a significant application in pathophysiology. According to the principle, the greater the velocity of flow in a vessel, the less the lateral pressure distending its walls. When a vessel is narrowed, the velocity of flow in the narrowed portion increases and the distending pressure decreases. Therefore, when a vessel is narrowed by a pathologic process such as an atherosclerotic plaque, the lateral pressure at the constriction is decreased and the narrowing tends to maintain itself.

**AUSCULTATORY METHOD (Stethoscope and cuff)**

The arterial blood pressure in humans is routinely measured by the auscultatory method. An inflatable cuff (sphygmomanometer) is wrapped around the arm and a stethoscope is placed over the brachial artery at the elbow. The cuff is rapidly inflated until the pressure in it is well above the expected systolic pressure in the brachial artery. The artery is occluded by the cuff, and no sound is heard with the stethoscope. The pressure in the cuff is then lowered slowly. At the point at which systolic pressure in artery just exceeds the cuff pressure, a spurt of blood passes through with each heartbeat and, synchronously with each beat, a tapping sound is heard below the cuff. The cuff pressure at which the sounds are first heard is the systolic pressure. As the cuff is deflated further, the sounds become louder, then dull and muffled, and finally, in most individuals, they disappear. These are the sounds of Korotkow. When direct and indirect blood pressures are taken simultaneously, the diastolic pressure correlates better with the pressure at which the sounds muffled than with the pressure at which they disappear.

The sounds of Korotkow are produced by turbulent flow in the brachial artery. The streamline flow in the unconstricted artery is silent, but when the artery is narrowed the velocity through the constriction exceeds the critical velocity, and turbulent flow results. At cuff pressures just below the systolic pressure, flow through the artery occurs only at the peak of systole, and the intermittent turbulence produces a tapping sound. As long as the pressure in the cuff is above the diastolic pressure in the artery, flow is interrupted at least during part of diastole, and the intermittent sounds have a staccato quality. When the cuff pressure is just below the arterial diastolic pressure, the vessel is still constricted, but the turbulent flow is continuous. Continuous sounds have a muffled rather than a staccato quality.

The auscultatory method is accurate when used properly, but a number of precautions must be observed. The cuff must be at heart level to obtain a pressure that is uninfluenced by gravity. The blood pressure in the thighs can be measured with the cuff around the thigh and the stethoscope over the popliteal artery, but there is more tissue between the cuff and the artery in the leg than there is in the arm, and some of the cuff pressure is dissipated. Therefore, pressures obtained using the
standard arm cuff are falsely high. The same thing is true when brachial arterial
pressures are measured in individuals with obese arms, because the blanket of fat
dissipates some of the cuff pressure. In both situations, accurate pressures can be
obtained by using a cuff that is wider than the standard arm cuff. If the cuff is left
inflated for sometime, the discomfort may cause generalized reflex vasoconstriction,
raising the blood pressure. It is always wise to compare the blood pressure in both
arms when examining an individual for the first time. Persistent major differences
between the pressures on the two sides indicate the presence of vascular
obstruction, usually in the subclavian artery on the side with the diminished pressure.

PALPATION METHOD (Pulses)
The systolic pressure can be determined by inflating an arm cuff and then letting
the pressure fall and determining the pressure at which the radial pulse first becomes
detectable. Because of the difficulty in determining exactly when the first beat is felt,
pressures obtained by this palpation method are usually 2-5 mm Hg lower than those
measured by the auscultatory method.

It is wise to form a habit of palpating the radial pulse while inflating the blood
pressure cuff during measurement of the blood pressure by the auscultatory method.
When the cuff pressure is lowered, the sounds of Korotkow sometimes disappear at
pressures well above diastolic pressure, and then reappear at a lower pre-
auscultatory gap. If the cuff is initially inflated until the radial pulse disappears, the
examiner is sure that the cuff pressure is above systolic pressure and falsely low-
pressure values will be avoided.

Normal Arterial Blood Pressure

The blood pressure in the brachial artery in young adults in the sitting or lying
position at rest is approximately 120/70 mm Hg. Since the arterial pressure is the
product of the cardiac output and the peripheral resistance, it is affected by
conditions that affect either or both of these factors. Emotion, for example, increases
the cardiac output, and it may be difficult to obtain a truly resting blood pressure in an
excited or tense individual. In general, increases in cardiac output increase the
systolic pressure whereas increases in peripheral resistance increase the diastolic
pressure. There is a good deal of controversy about where to draw the line between
normal and elevated blood pressure levels (hypertension) particularly in older pa-
tients. However, the evidence seems incontrovertible that in apparently healthy
humans both the systolic and the diastolic pressure rise with age. The systolic
pressure increase is greater than the diastolic. An important cause of the rise in
systolic pressure is decreased distensibility of the arteries as their walls become
increasingly more rigid. At the same level of cardiac output, the systolic pressure is
higher in older subjects than in young ones because there is less increase in the
volume of the arterial system to accommodate the same amount of blood.