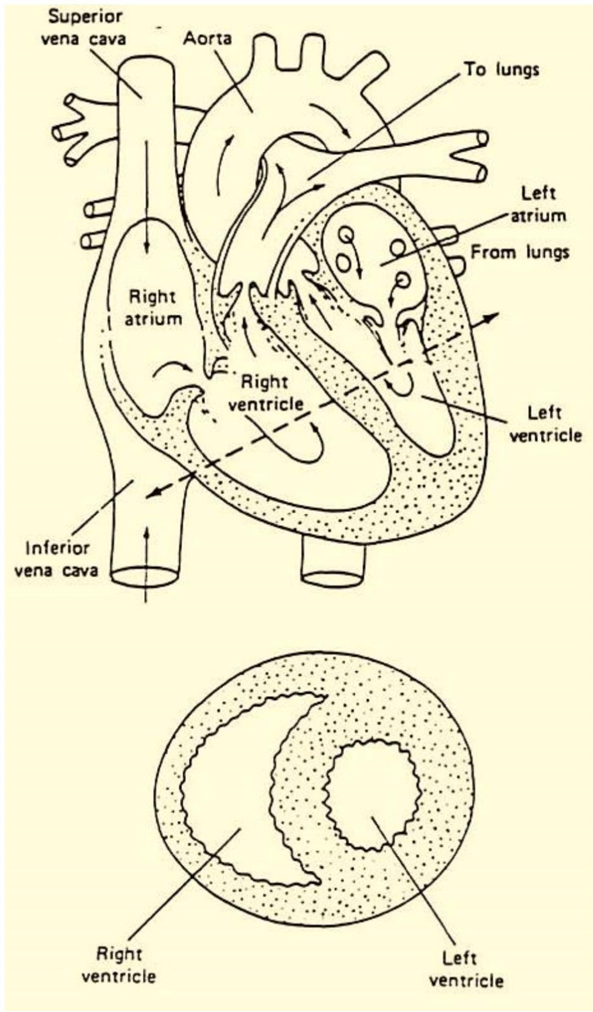
Physics of the Cardiovascular System

The cardiovascular system (CVS) consists of the heart, blood vessels. The system's primary role is for the transportation of oxygen, nutrients, hormones, and cellular waste throughout the body.

Blood is a complex mixture involving:

1. Plasma (whitish liquid) / ≈ 55-60% of the blood's volume.
2. Red blood cell (erythrocytes) / determines the fluid characteristic of blood.
3. White blood cells (leukocytes) / important for the human immune system.
4. Platelets (thrombocytes) / important for blood clotting.

It serves for distribution of food contents (from the digestive system) and of oxygen (from the respiratory system) to the body cells and it serves also as transport system for disposing the by-products (like CO_2) of the combustion process.



The heart

-The heart has 4 chambers. The upper chambers are called the left and right atria (LA & RA), and the lower chambers are called the, left and right ventricles (LV & RV).

-A wall of muscle called the ***septum*** separates the left and right atria and the-left and right ventricles.

-The left ventricle is the largest and strongest chamber in the heart. LV is about three times thicker than that of the right ventricle. In addition, the circular shape of LV is more efficient for producing high pressure than the elliptical shape of RV.

-The left ventricle's chamber walls are only about a half-inch thick, but they have enough force to push blood through the aortic valve and into the body.

The Heart Valves Four types of valves regulate blood flow through the heart:

-The **tricuspid valve** regulates blood flow between the right atrium and right ventricle.

-The **pulmonary valve** controls blood flow' from the right ventricle into the pulmonary arteries, which carry blood to the lungs to pick up oxygen.

-The **mitral valve** lets oxygen-rich blood from the lungs pass from the left atrium into the left ventricle. "

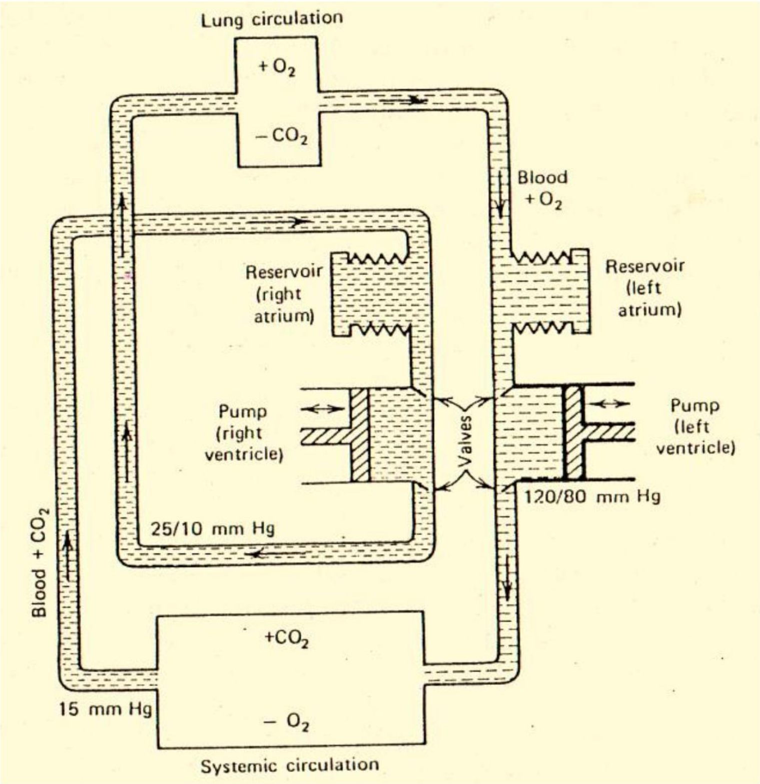
-The **aortic valve** opens the way for oxygen-rich blood to pass from the left ventricle into the aorta, where it is delivered to the rest of the body.

1-pulmonary circulation (Heart-lung)

a- **Deoxygenated blood** is pumped out of the right ventricle (25 mmHg). It travels through the pulmonary valve into the pulmonary artery, leaving the heart.

b- **Deoxygenated blood** reaches the lungs. Here, carbon dioxide is removed from the blood and oxygen is added to it. The fresh blood leaves the lungs.

c- Fresh blood enters the left atrium through the pulmonary vein (6mmHg). Then, it is pumped by contraction of LA (8mmHg) through the mitral valve into the left ventricle (80mmHg).



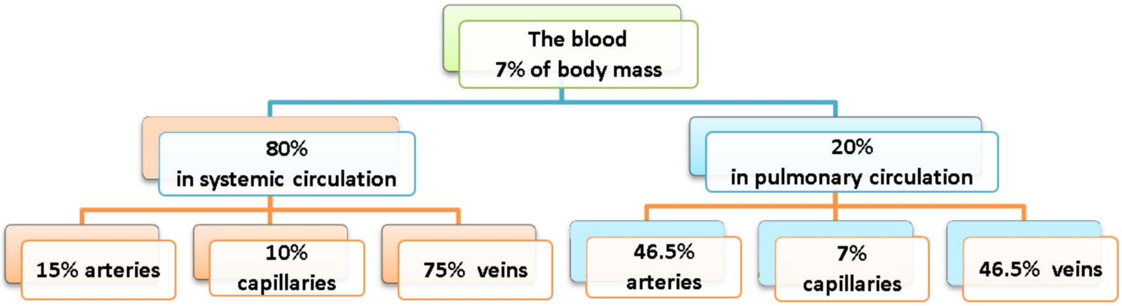
2-Systemic circulation (Heart - body)

a- **Oxygenated blood** is pumped out of the left ventricle (120mmHg). It travels through the aortic valve into the aorta, leaving the heart.

b- **Oxygenated blood** reaches the head and the body (gut, kidney, muscles), where the oxygen in it is used and replaced by carbon dioxide.

C-**Deoxygenated blood** is collected through the vena cava into the right atrium (5 mmHg) and is pumped by week contraction (6mmHg) through the tricuspid valve into the right ventricle. This ends the system circulation.

Blood represents about 7% of the body mass or about 4.5 kg (≈ 4.4 liters) in a 64kg-person.



The Heart beat: The average blood volume of an adult is about(4.5-5) liters and each section of the heart pumps about 80 ml per contraction through the lungs & a similar volume to the systemic circulation with about 70 contractions per minute (heart rate). This means that the heart pumps about 5600ml/minute.

Stroke volume (SV): is the amount of blood pumped by each ventricle with each heartbeat, averaging 80(ml/beat) in the adult at rest. It represents the difference between end diastolic volume (EDV) and end systolic volume (ESV)

Cardiac output: **Cardiac output = heart rate x stroke volume**

Cardiac Output = the amount of blood pumped by a ventricle per minute. Units may be milliliters or Liters per minute.

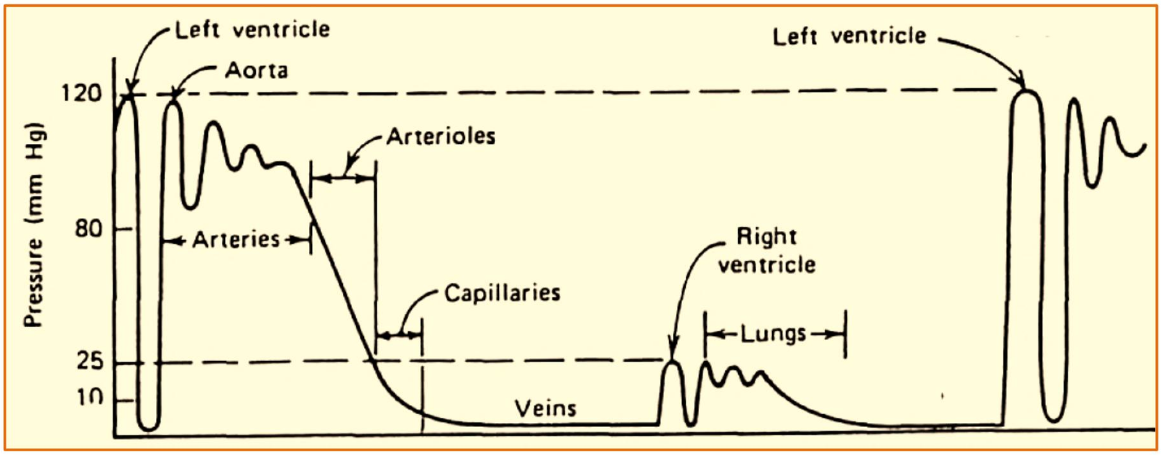
Heart Rate (HR): number of cardiac cycles per minute. Average (HR) for males (64-72/min), for females (72-80/min).

Stroke Volume: amount of blood pumped out of a ventricle each beat. Average resting stroke volume is (70-80) ml.

Work done by the heart

In the pulmonary system, the pressure is quite low because of the low resistance of the blood vessels in the lungs. The maximum pressure (systole) is typically about 25 mmHg.

In order to circulate the blood through the much larger systemic network the left side of the heart must produce a pressure that is typically about 120 mmHg at the peak (systole) of each cardiac cycle. During diastole of the cardiac cycle the pressure is typically about 80 mmHg.



Although the diameter of a single capillary is small, the number of capillaries supplied by a single arterial is so great that the total cross-sectional area available for the flow of blood is increased. Therefore, the pressure of the blood as it enters the capillaries decreases.

Average pressure -	$P_{ave} = \frac{P_s + P_d}{2}$	(≈ 100mmHg)
Pulse pressure -	$P_{pulse} = P_s - P_d$	(≈ 40 mmHg)
Mean pressure -	$\overline{P_m} = P_d + \frac{1}{3}(P_s - P_d)$	(≈ 93 mmHg)

The value of mean blood pressure ($P\bar{m}$) represents the averaged arterial pressure over the cardiac cycle or the pressure that propels the blood to the tissues. It remains almost constant.

Example: A patient with heart rates of (120\min), his pressure (180/90) mmHg. Calculate the work done by the left ventricle for 2 seconds.

Solution

$w = p_{ave} * \Delta v$

$p_{ave} = (180+90)/2 = 135$ mmHg

The pressure units must be converted from mmHg to dynes/cm^2 or N/m^2

1 mmHg = 1333dyne/cm^2 (i.e. p=ρgh=13.6*980*0.1=1333dyne/cm^2)

135 mmHg x 1333(dyne/cm^2)/(mmHg) =1.8 x10^5 dyne/cm^2 .

Δ v = HR*80 ml/contraction

Δ v = 80*(120min/60(sec/min)) = 160 ml/sec

W =1.8 x10^5 dyne/cm^{2}x 160 ml/sec = 2.88 x 10^7 erg in one second

And W for 2 sec = 2.88 x 10^7 erg /sec x2 = 5.76 x 10^7 erg\sec

Conservation of flow rate (Bernoulli equation)

By consideration that the blood is inviscid fluid, the kinetic energy and potential energy must remain unchanged throughout system. This concept is called the *Conservation of Continuity*, where the flow (Q) of fluid in a vessel is constant and given by Bernoulli equation as following:

$$Flow_{in} = Flow_{out}$$
$$A_1 v_1 = A_2 v_2$$

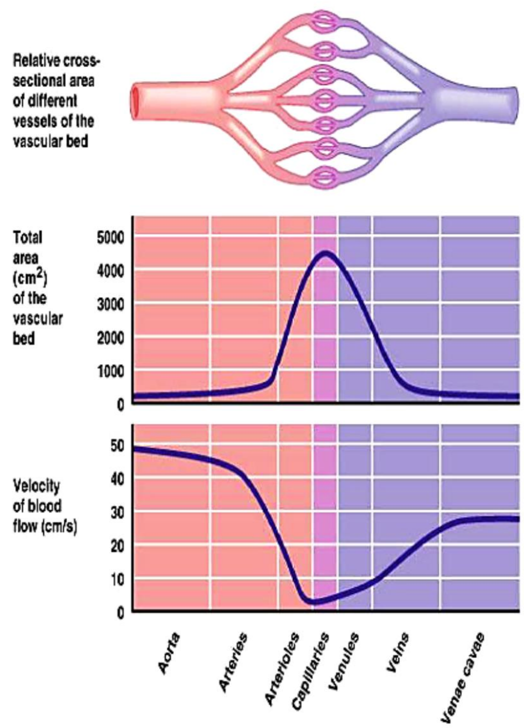
$$Q = Volume/\ time = constant$$

Where, Q= flow rate, A= Area and v = velocity

Application: From the figure;

$v_{capillaries}$ = 1 mm/sec while v_{aorta} = 45 cm/sec

This is because the cross sectional area of the aorta is small compared to the total cross sectional area of all the capillaries. This low velocity in capillaries allows time for diffusion of the gases (O_2 and CO_2) to occur.



Application: From the above equation, $\Delta P \propto \frac{1}{r^4}$. If r decreases by a factor of 2, the ΔP increases by a factor of 16 to maintain the same flow rate. Some medications for hypertension are designed around this principle, and they lower blood pressure by limiting the contraction of blood vessel walls.

Effect of viscosity on the fluid flow (Poiseuille's equation)

Viscous forces within a fluid act to dissipate energy. In this case, the fluid flow through the tube of a liquid of viscosity (η) is given by:

$$Q = \frac{\pi r^4 \Delta P}{8\eta L}$$

Viscosity (η): The frictional force that acts between adjacent portions of liquid and is inversely proportional with temperature. (η) unit is:

[in c.g.s. system = dyen/cm2.sec= Pois] **[In SI system = N/m2.sec =Pa.Sec= Kg/(m.sec) =10 Pois]**

The viscosity of blood depends on:

1-Velocity of the blood. At higher velocity the 'disc-shaped Red Blood cells (RBC's, erythrocytes) orient in the direction of the flow and viscosity is lower. For extremely low shear rates formation of RBC aggregates may occur, thereby increasing viscosity to very high values.

2-The size of blood vessel. In small blood vessels, and at higher velocities, blood viscosity apparently decreases with decreasing vessel size.

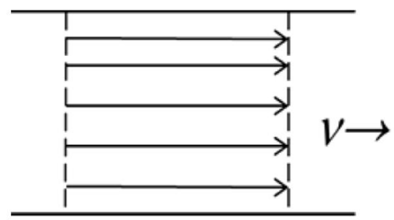
3-percentage of red blood cells in the blood (the hematocrit): as the hematocrite increases, the viscosity increases. **Application:** Persons with disease **polysythemia Vera** in which there is an overproduction of red blood cells has a high hematocrit and often has circulatory problems.

4-Viscosity is strongly dependent on temperature: A decrease of 1°C in temperature yields a 2% increase in viscosity. Thus in a cold foot blood viscosity is much higher than in the brain.

Fluid flow

1. Ideal fluid:

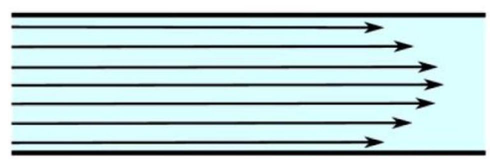
- Having no internal fractional forces acting on it.
- All particles flow in parallel layers with equal velocity,
- The mechanical energy is conserved.



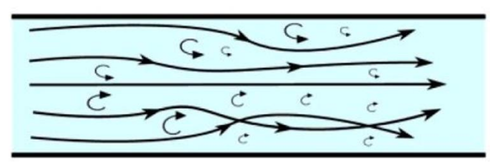
2. Real fluid:

- There are internal frictional forces (viscous forces)
- All particles of the fluid intersect with different velocities
- There is a loss of mechanical energy.

laminar flow



turbulent flow



Real fluid can be subdivided into two kinds:

Laminar flow:

Fluid particles flow in parallel layers with streamlines that do not intersect.

The greatest velocity of the center of the tube and decreases to zero at the wall.

It is silent.

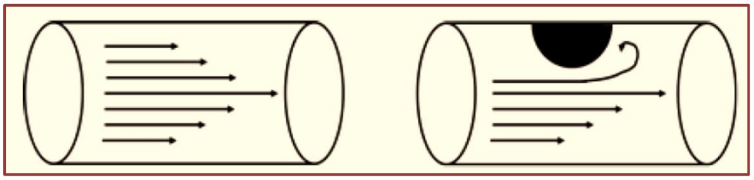
Turbulent flow:

-Flow pressure and velocity show random variation in both time and space (called as eddy current).

-It has a sound.

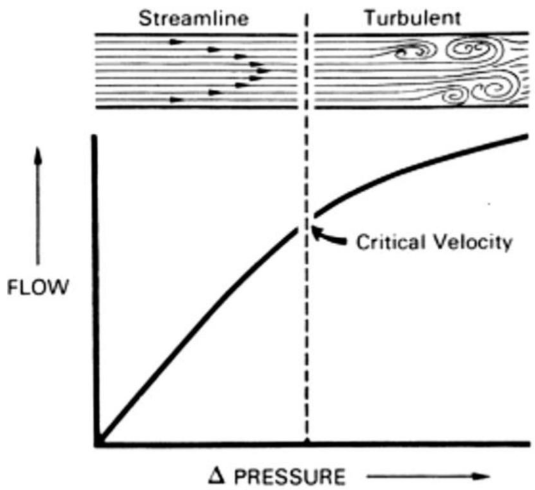
Effect of constriction on flow rate

The velocity of blood increases by reducing the radius of the tube, it will reach a critical velocity (vc) when Laminar flow changes into turbulent flow.



-At some critical velocity (vc), the flow will become turbulent with the formation of eddies and chaotic motion which do not contribute to the volume flow rate.

-This turbulence increases the resistance dramatically so that large increases in pressure will be required to further increase the volume flowrate.



The critical velocity for a long straight tube with radius (r) and cross section area (A) is given by:

$$v_c = \frac{R\eta}{\rho r} = \frac{Q_c}{A}$$

ρ density of fluid
R Reynolds number = 1000 for many fluids
Qc critical flow

Application:
From the above figure, one can notice that the flow as a function of pressure in the laminar region is relatively greater than turbulent region. So, the laminar flow is more efficient than turbulent flow. As a result, obstructed vessel may not be able to deliver which causes chest pain and heart attack.

Example: The aorta has a radius of ≈1cm in adult; the critical velocity will be;

$v_c = \frac{R\eta}{\rho r}$ $=1000*(4*10^{-3}\ Pas)/(10^{3}\ kg/m^{3})(10^{-2}m) = 0.4\ cm/sec$

.

The velocity in the aorta ranges from 0 to 0.5m/sec, and thus the flow is turbulent during of the systole. During heavy exercise the critical velocity will be exceeded for a longer period of time.