Karbala University-College of Dentistry
Medical Physics-Lecture (6)

Physics of the Cardiovascular System

Work done by the heart

In a typical adult each contraction of the heart muscles forces about 80ml (**about one-third of a cup**) of blood through the lungs from the right ventricle and a similar volume to the systemic circulation from the left ventricle. In the process the heart does work.
The pressure in two pumps of the heart are not the same. In the pulmonary system the pressure is quite low because of low resistance. The maximum pressure (**systole**), typically about **25mmHg**, is about **one-fifth** of that in the systemic circulation. In order to circulate the blood through the much larger systemic network the left side of the heart must produce pressures that are typically about **120mmHg** at the peak (**systole**) of each cardiac cycle. During the resting phase (**diastole**) of the cardiac cycle the pressure is typically about **80mmHg**.
The work done W by a pump working at a constant pressure P is equal to the product of the pressure and the volume pumped ΔV, or $W=P\Delta V$.
<u>We can estimate the physical work done by the heart by multiplying its average pressure by the volume of blood that is pumped.</u>
Actually the pumping action takes place in less than **one-third** of the cardiac cycle and the heart muscle rests for over **two-thirds** of the cycle.

Example(1): The heart rate of a person is 72 pulse/min; calculate the action time and the resting time of heart muscle.

72pulse/1min = 72 pulse/60sec
= 1pulse/0.833sec
1pulse = 1/3contraction + 2/3 relaxation
0.833x1/3 = 0.277sec (the time of contraction)
0.833x2/3 = 0.555sec (the time of relaxation)

Example(2): Person has a systolic pressure 150mmHg, diastolic pressure 100mmHg, heart rate 90/min. Calculate the work done and the efficiency of the lower left half of the heart if the energy consume is 6 Watt.

Work done = $P\Delta V$

P average = (systolic +diastolic)/2

P average = (150+100)/2

P average = 125 mmHg

1 mmHg = 1330 dyne/cm^2

125 mmHg = 166250 dyne/cm^2

ΔV = 80ml/beat × (90beats/min)/(60sec/min)

ΔV = 120 cm^3/sec

$\boldsymbol{W = P\Delta V}$

Work = 166250 dyne/cm^2 × 120 cm^3/sec

Work = 19950000 dyne. cm/sec

1 erg = 1 dyne. cm

Work = 19950000 erg/sec

1 erg = 10^{-7} Joule

Work = 1.995 Joule/sec

Efficiency = (Work done/Energy consume) x 100%

Efficiency = (1.995/6) × 100% = 33.25 %

Blood pressure and its measurement

One of the most common clinical measurements is of blood pressure. During ventricular systole, the heart pushes blood n to the arteries and the pressure reaches a maximum value which is called **systolic pressure**. When the ventricle relax between beats, blood presser falls to a minimum value called **diastolic pressure**. These two pressures are expressed in millimeters of mercury (mm Hg), because the original device that measured blood pressure contains a column of mercury.

Principle

A blood pressure measurement is taken by temporarily stopping the flow of blood in an artery (usually by inflating a cuff around the upper arm) and then listening for the sound of the blood beginning to flow through the artery again as air released from the cuff(as shown in figure 1). As blood flows through the artery, it can be heard through a stethoscope placed on the skin over the artery.

Equipment

1.Sphygmomanometer

2.Cuff

3.Stethoscope (a device that magnifies the sound made by the body).

Procedure

1. Applying the cuff around the arm above the elbow for about four fingers and ensure that the cuff is empty of air.
2. Open the mercury pool and put the stethoscope over the brachial artery distal the cuff.
3. Close the valve of the bulb and inflate the cuff by the squeezing the bulb of several time until the pressure lifts to the 200mmHg, this pressure closes the brachial artery(الشريان العضدي), so that no blood flows pass the cuff (figure2b) and no sound can be heard through the stethoscope at this point.
4. Gradually and slowly deflate the cuff by opening the valve of the bulb with the thumb and forefinger of the same hand and notice that the mercury column begins to fall and the blood beings to flow into the forearm and the sound can be heard, so that the number pointed by the sphygmomanometer at the first hearing is the systolic pressure (figure2 c)
5. Continue hearing the sound and notice the sound become louder and starts to disappear gradually as the cuff deflated and the level of the mercury decline until the sound disappear completely. The number pointed by the sphygmomanometer at which the sound disappeared represents the diastolic pressure (figure2 d).

Blood pressure measurements are recorded as systolic/diastolic. If systolic pressure is 120 mmHg and diastolic pressure is 80 mmHg , it will be recorded as 120/80 mmHg and we read as 120 over 80.

Reference ranges:

Newborn	90/70 mmHg
Juvenile	120/80 mmHg
Adults	130/90 mmHg
Old	150/120 mmHg

Note

The patient should not ingest any caffeine or tobacco for at least 30 minutes before the test. Elevated blood pressure detecting requires a confirmation by at least two other readings on separated occasions. The average of all three tests is then used as the patients' blood pressure. Home monitoring of blood pressure considered valuable as long as the equipment is properly calibrated and test is performed correctly.

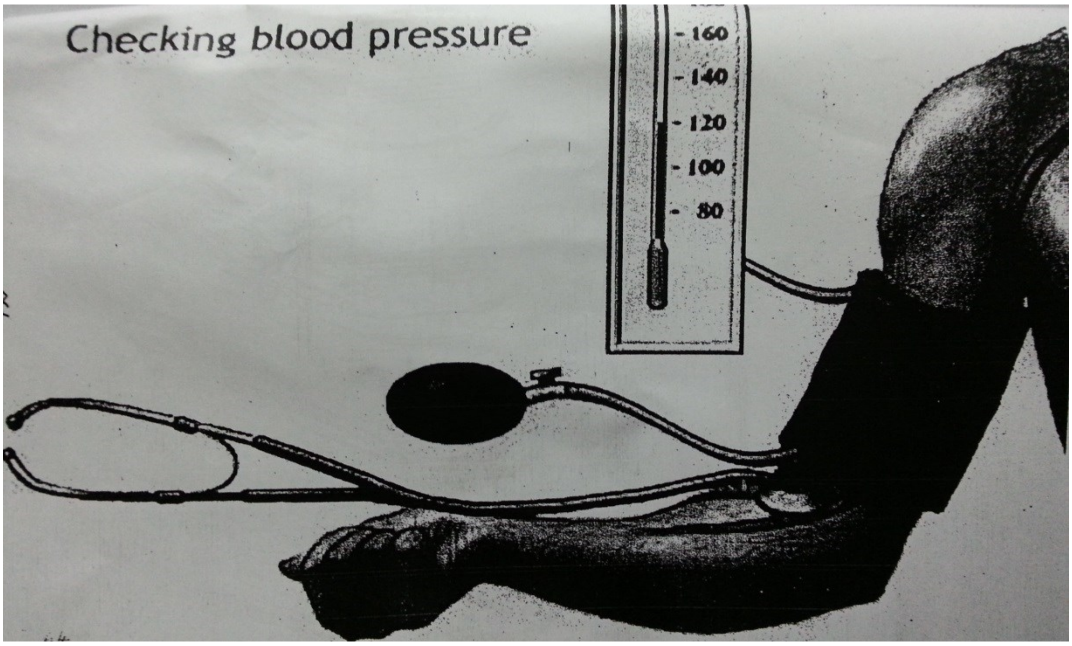
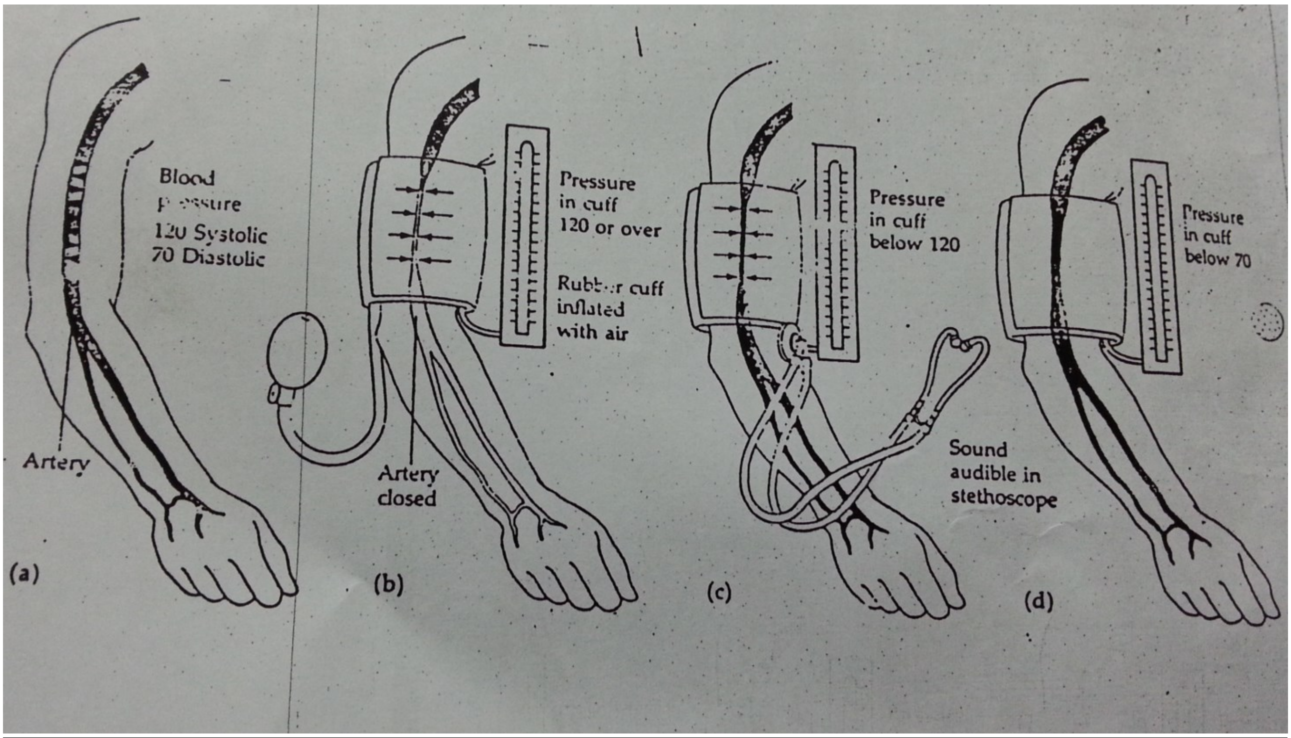


Figure (1): Checking blood pressure.



Figure(2): Blood pressure measurements

The pressure in the circulatory system varies throughout the body. Even in major arteries the pressure varies from one point to another because of gravitational forces. Figure(3) shows schematically of blood pressure measurements made on standing person. Open glass tube manometers are shown connected to arteries in the head, upper arm and foot. In this situation the blood rises to essentially to essentially the same level in all three manometers. The greater pressure P in the foot is due to the gravitational force (ρgh) produced by the column of blood (of high h) between the heart and the foot added to the pressure at the heart. Similarly, the decreased pressure in the head is due to the elevation of the head over the heart.

If the gravity on earth became three times greater, blood pressure would rise only about 43cm above the heart and it would not reach the brain of a standing person.

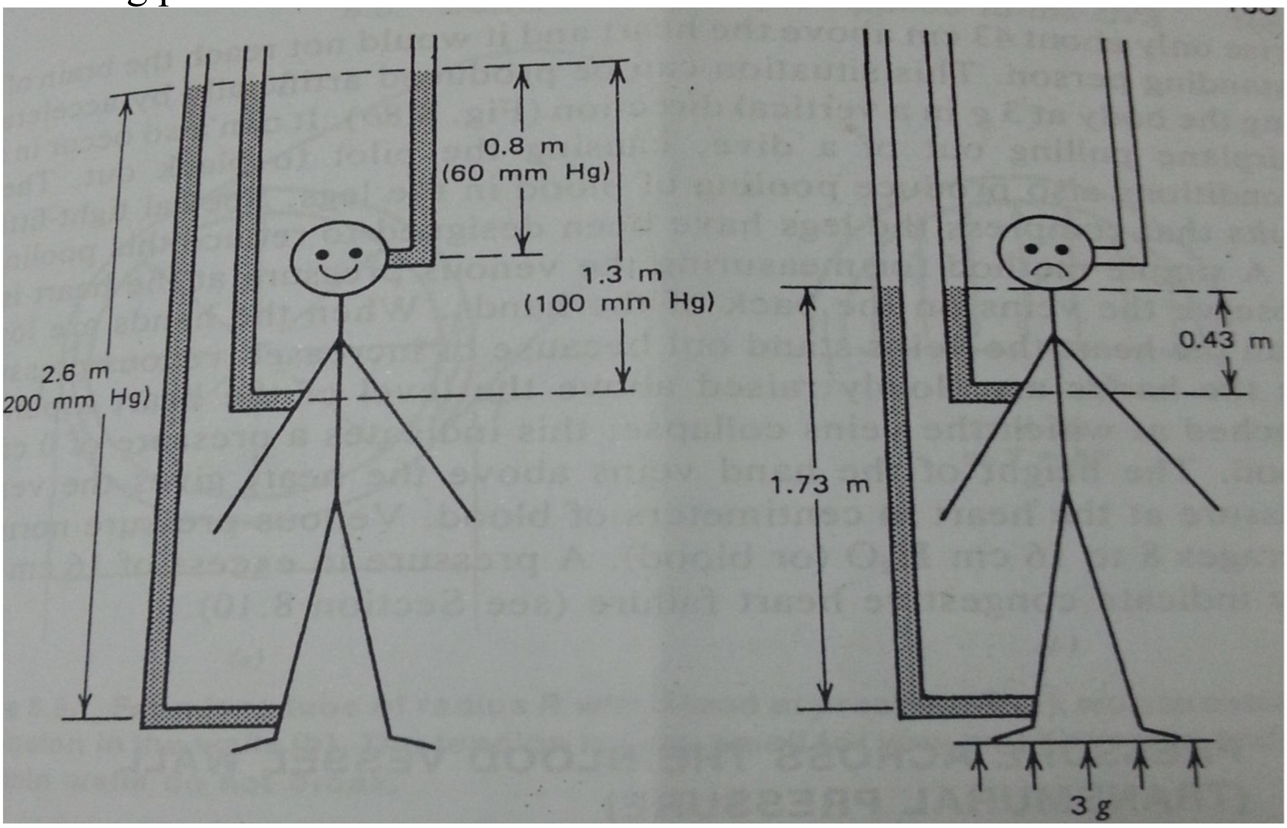
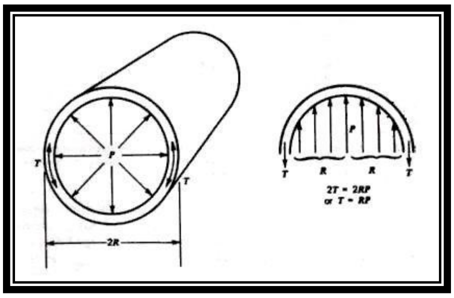


Figure (3); (a)Glass capillaries were connected to the arteries at different locations the blood would rise to about the same level.(b) if the body were accelerated 3g.

<u>Pressure across the blood vessel wall (The law of Laplace)</u>

The greatest pressure drop in the cardiovascular system occurs in the region of the arterioles and capillaries.

In order to understand why they do not burst we must discuss the **law of Laplace**, which tells us how the tension in the wall of a tube is related to the radius of the tube and the pressure inside the tube.



Consider a long tube of radius ***R*** carrying blood at pressure ***P***. We can calculate the tension ***T*** in the wall (***T=RP***).

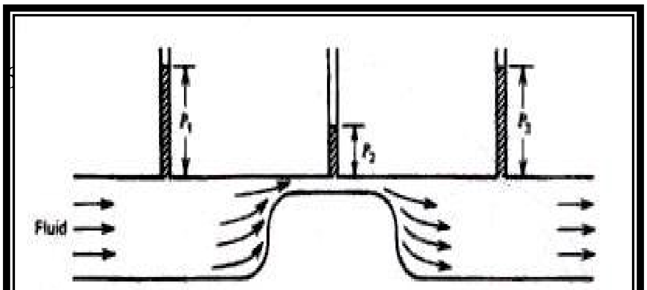
Bernoulli's principle applied to the cardiovascular system

Whenever there is a rapid flow of a fluid such as air or water, the pressure is reduced at the edge of the rapidly moving fluid.

Bernoulli's principle is based on the law of **conservation of energy**. Pressure in a fluid is a form of potential energy **PE** since it has the ability to perform useful work. In a moving fluid there is kinetic energy **KE** due to the motion. This kinetic energy can be expressed as energy per unit volume such as ergs per cubic centimeter.

If fluid is flowing through the frictionless tube, the velocity increases in the narrow section and the increased kinetic energy **KE** of the fluid is obtained by a reduction of the potential energy **PE** of the pressure in the tube.

As the velocity reduces again on



the far side of the restriction the kinetic energy is converted back into potential energy and the pressure increases again as indicated on the manometers.

*Notice that the blood velocity is related in an inverse way to the total cross-sectional area of the vessels carrying the blood.

The SI unit of viscosity is Pascal second (Pas). The viscosity of water is about $\mathbf{10^{-3}}$**Pas** at $\mathbf{20^{o}}$**C**. The viscosity of blood is typically $\mathbf{3\times10^{-3}}$ to $\mathbf{4\times10^{-3}}$ **Pas depends** on the percentage of red blood cells in the blood (the hematocrit). As the hematocrit increases ,the viscosity increases, decreasing the flow rate.

Poiseuille's law states that the flow through a given tube **depends** on the pressure difference from one end to the other ($\mathbf{P_A}$-$\mathbf{P_B}$), the length **L** of the tube, the radius **R** of the tube, and the viscosity **η** of the fluid.
When all of these variables are put together with a constant to keep the units working correctly we get **Poiseuille's equation**: -

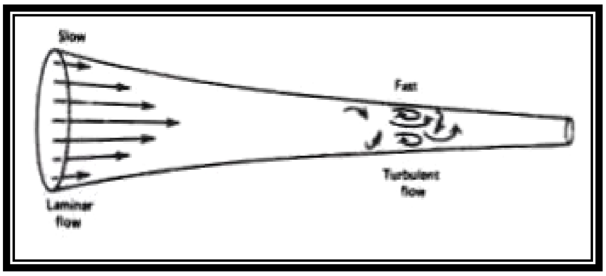
$$Flow\ rate = (P_A - P_B)\left(\frac{\pi}{8}\right)\left(\frac{1}{\eta}\right)\left(\frac{R^4}{L}\right)$$

In **SI units** the flow rate will be in *cubic meters per second* if P_A-P_B is in Newton's per square meter, η is in Pas, and R and L are in meters.

Blood flow-laminar and turbulent

The **first** type of river is analogous to the **laminar** or streamline flow that is present in most blood vessels.
The **second** is similar to the **turbulent** flow found at a few places in the circulatory system, ***for example***, where the blood is flowing rapidly past the heart valves.
An important characteristic of laminar flow is that it is silent. If all blood flow were laminar, information could not be obtained from the heart with a stethoscope. The heart sounds heard with a stethoscope are caused by turbulent flow.

If you increase the velocity of a fluid flow in a tube by reducing the radius of the tube, it will reach a **critical velocity** $\mathbf{V_c}$



when laminar flow changes into turbulent flow.

Osborne Reynolds determined that the critical velocity is proportional to the *viscosity **η** of the fluid and is inversely proportional to the density **ρ** of the fluid and* the radius R of the tube, $V_c = K\eta/\rho R$. The constant of proportionality K is called the Reynold's number, and it is approximately equal to 1000 for many fluids, including blood, flowing in long straight tubes of constant diameter. If there are bends or obstructions the Reynold's number becomes much smaller.

Example(3): Find the kinetic energy (KE) of 2gm of blood leaving aorta of radius 1.2cm.

$$KE = mv^2/2$$

$$KE = 1/2 \ mass \times (velocity)^2$$

$$V_c = \frac{K\,\eta_{blood}}{\rho R}$$

$$= \frac{1000 \times 3.5 \times 10^{-3}}{1.04 x 10^3 \times 1.2 \times 10^{-2}}$$

$$= 0.28 m/\sec$$

$$KE = 1/2 \times 0.002 \times (0.28)^2$$

$$= 8 x 10^{-5} \ joule$$

The physics of some cardiovascular diseases

Because of the many physical aspects of the cardiovascular system, heart diseases often have a physical component. Many of these diseases, *for example*, increase the work load of the heart or reduce its ability to work at a normal rate.

To reduce the work load of the heart, bed rest and O_2 therapy are prescribed. Giving O_2 increases the O_2 in the blood so that less blood must be pumped to the tissues. Man-made device that has helped heart patients is the artificial heart valve.

Heart valve defects are of two types: -

- **Stenosis**: - the valve does not open wide enough. In stenosis the work of the heart is increased because a large amount of work is done against the obstruction of the narrow opening, and the blood supply to the general circulation is reduced.
- **Insufficiency**: - the valve does not close well enough. In insufficiency some of the pumped blood flows back into the heart so that the volume of the circulated blood is reduced.