MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 3

PRESSURE AND THE CIRCULATORY SYSTEM

Types of pumps. The heart as a force pump. The circulatory system. The energy supplied by the heart. The variations of the blood pressure. The measurement of blood pressure

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PRESSURE AND THE CIRCULATORY SYSTEM

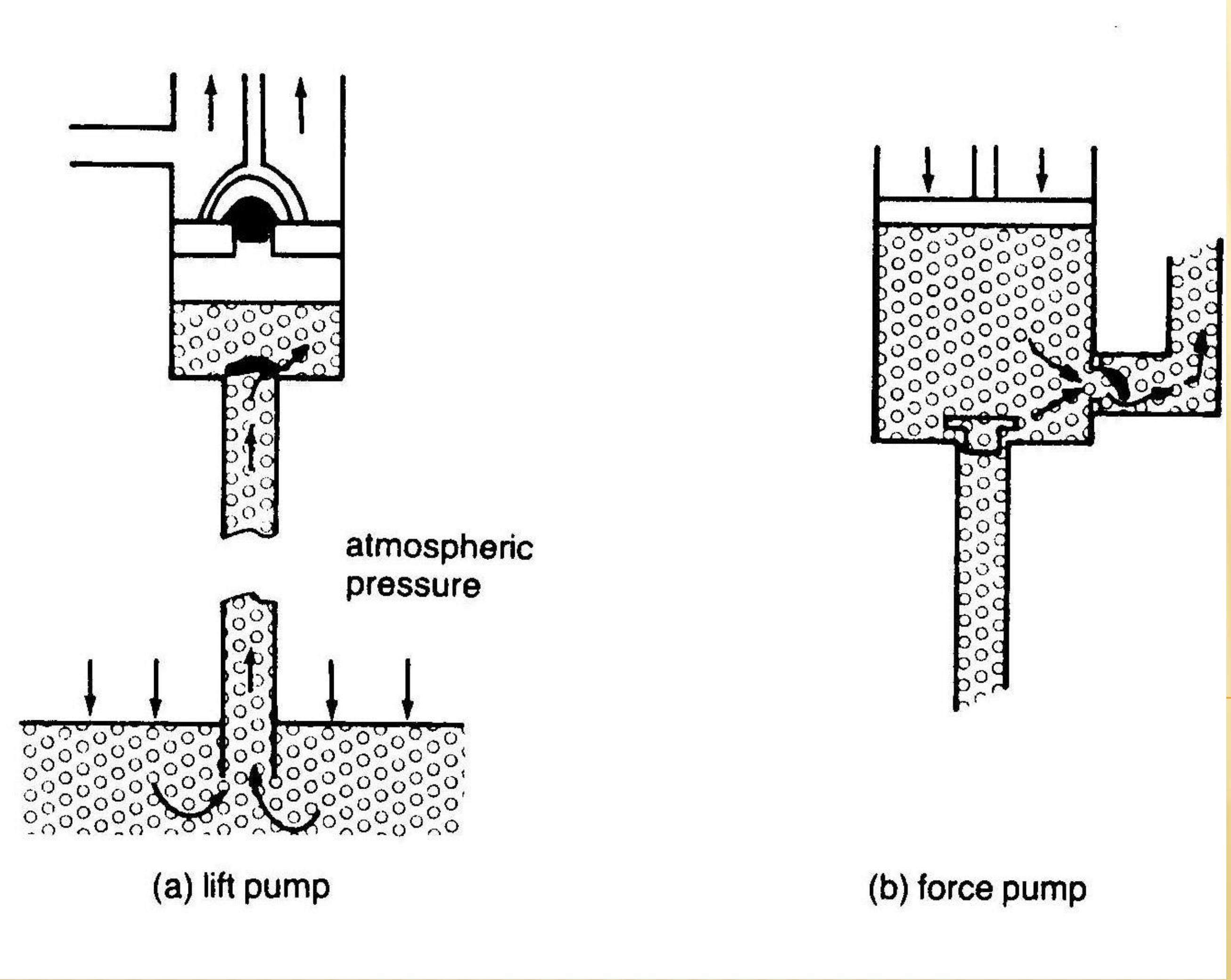
The circulatory system basically consists of the heart plus the network of arteries, veins, and capillaries.

It is an oversimplification to view the system as a pump circulating fluid through a closed network of pipes, but such a model can be expanded to more closely approximated the actual circulatory system.

The function of a pump is to increase the pressure in a fluid to enable the fluid to move in the desired manner.

TYPES OF PUMPS

Simple pumps might be classified as either lift pumps or force pumps.



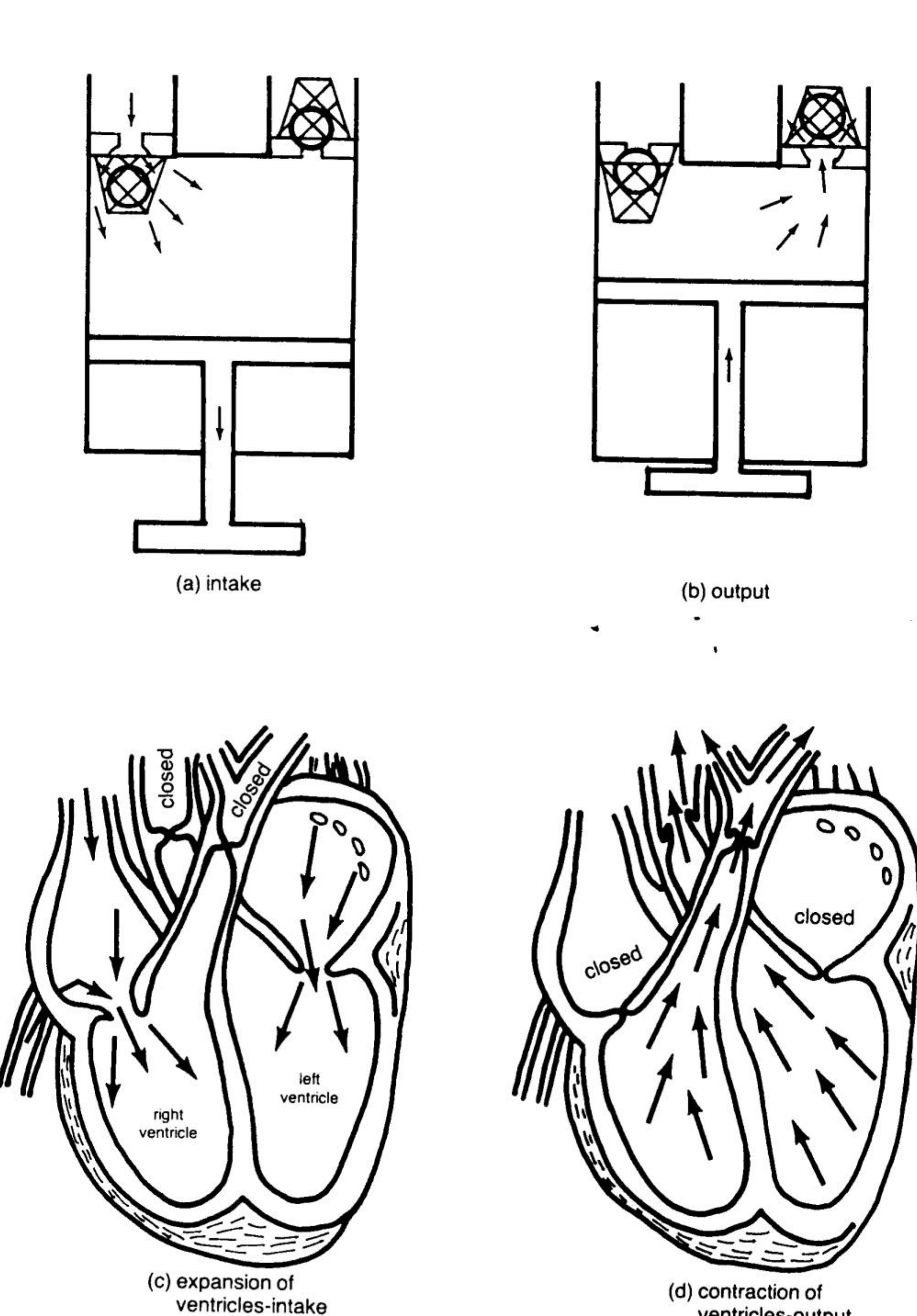
The *force pump* does not rely on atmospheric pressure directly and can be used to circulate liquids in a sealed, closed liquid circuit.

THE HEART AS A FORCE PUMP

The heart receives the blood from the venous system and raises its pressure to push it out into the arterial system.

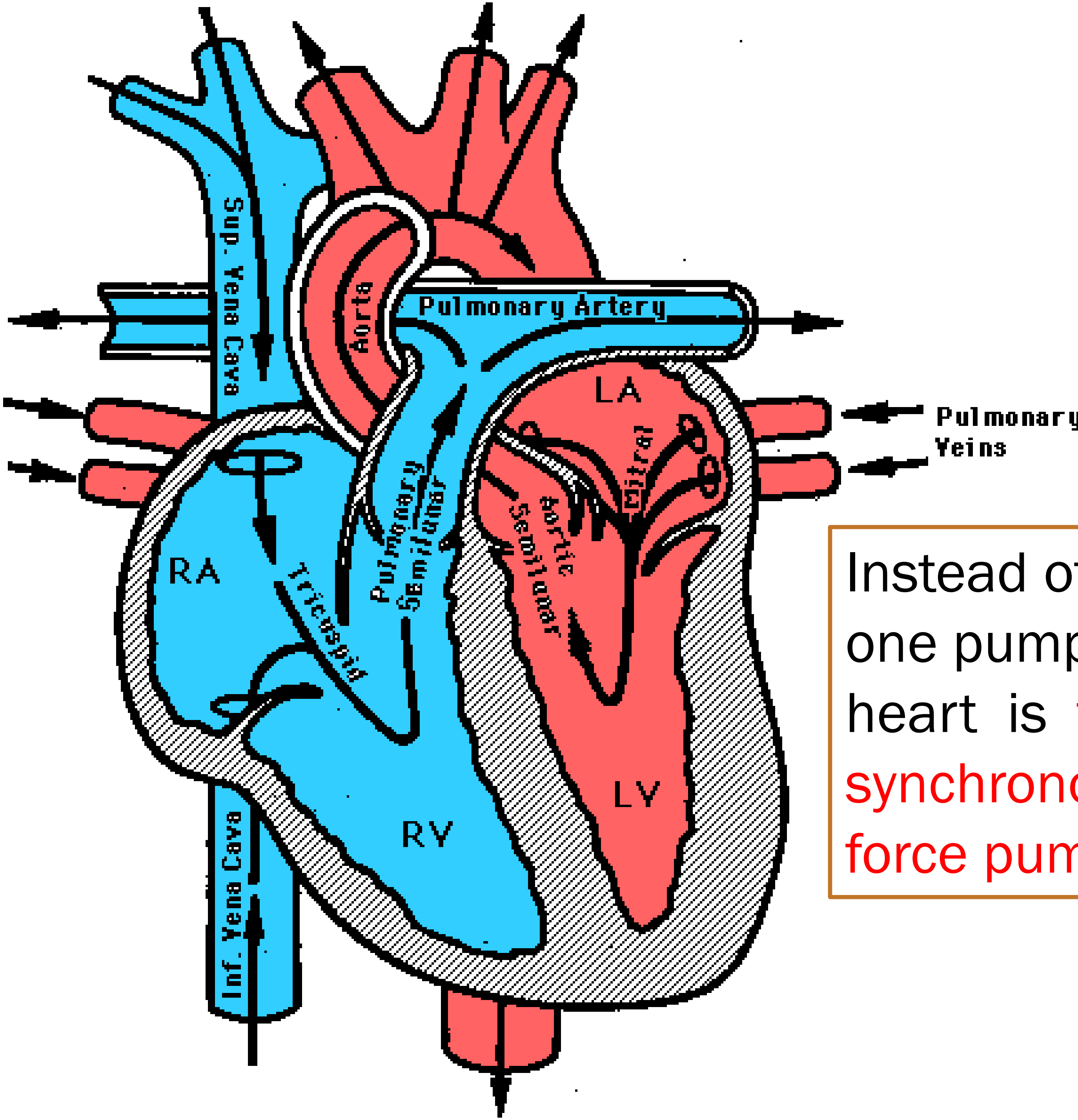
The action of the ventricles is that of a force pump which achieves the excess pressure by contraction.

A rough analogy can be drawn to the simple force pump .



When the right ventricle expands, the atrioventricular valve opens to let the venous blood flow into the ventricle, while the output valve (the semilunar valve) remains closed to prevent backflow of previously pumped blood. Upon contraction of the ventricle, the valves reverse and blood is pumped through the pulmonary artery to the lungs.

The blood returning from the lungs undergoes a similar pumping process when the left ventricle expands and contracts, pumping the oxygenated blood out through the aorta.



Instead of being one pump, the heart is two synchronous force pumps.

Many common faults involve valves which either have holes in them or do not close completely.

If the right atrioventricular valve does not close completely, then the contraction of the right ventricle will pump blood back out into the venous system. A central venous pressure measurement would indicate this by a periodic high pressure in the vein.

If a semilunar valve did not close properly, then the blood would backflow from the arterial system during the expansion of the ventricle.

Either type of faulty valve obviously represents a great impairment of the heart's pumping action.

THE CIRCULATORY SYSTEM

When a pump circulates a fluid in a closed system, it raises the pressure of the fluid to enable it to overcome the system resistance.

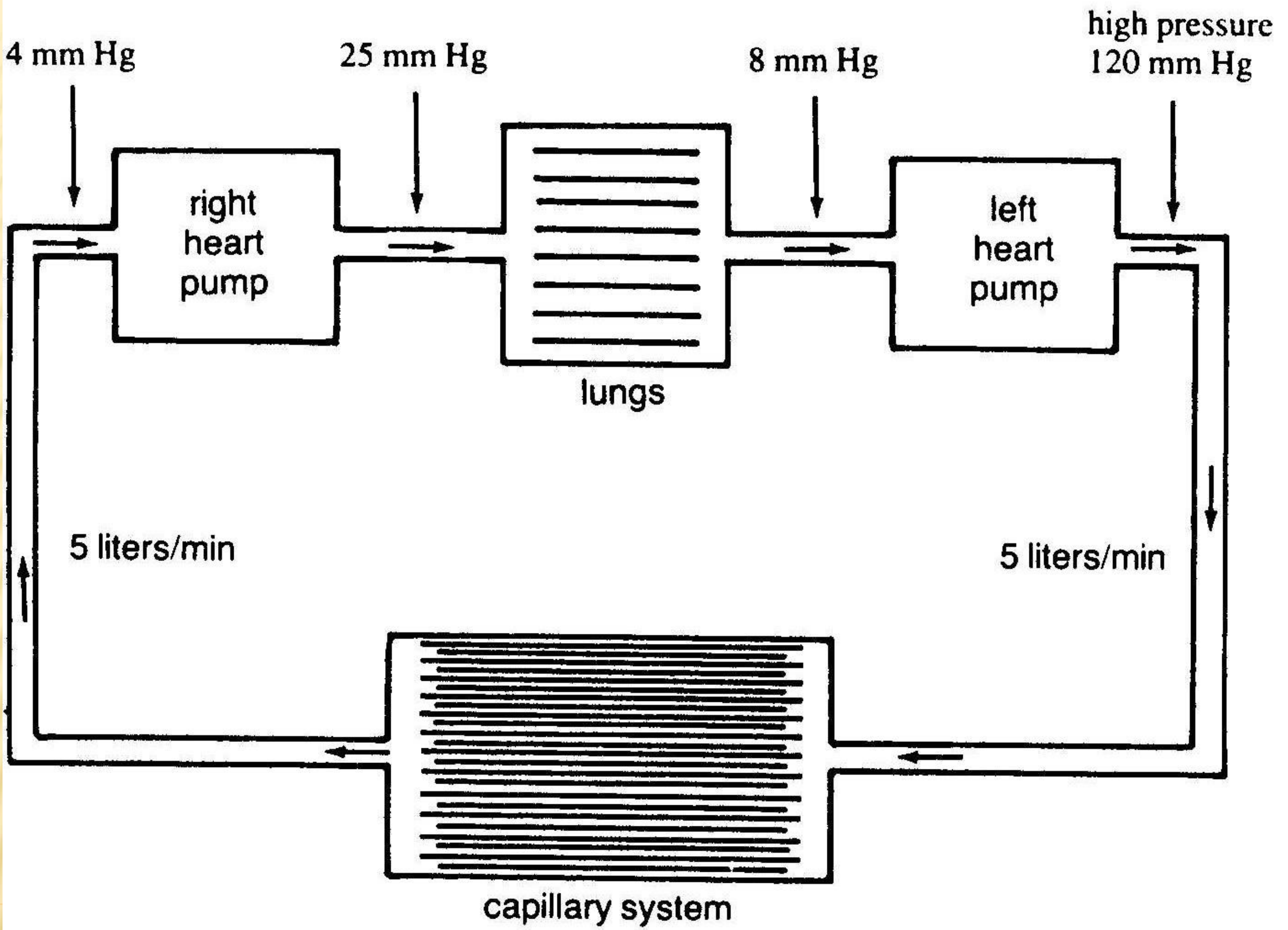
Pressure variations - As the fluid flows through the system and back to the pump, the pressure drops back to the original pressure if the flow has reached a stable uniform rate.

Under an equilibrium flow situation, there will be some base pressure at which the fluid enters the pump and a peak pressure at which the fluid leaves the pump.

In the circulatory system, the pressure is highest as it leaves the left ventricle and lowest as it enters the right atrium. Then the pressure is raised again by the right ventricle and drops to enter the left atrium at a low residual pressure.

The **left ventricle** is the **main pump** and supplies the pressure for the systemic circulation through the body.

The amount of pressure drop which occurs in any segment of the circulatory system depends upon the flow rate and the resistance of that segment, according to Poiseuille's law.



Block diagram of circulatory system showing typical systolic pressure values

The pressure drop across the arterioles is greater than that across the capillaries.

That fact is somewhat surprising, since the radius of a typical arteriole may be three times that of a capillary. Recalling Poiseuille's law, pressure drop equals flow rate times resistance. The resistance is proportional to the tube length divided by the radius to the fourth power.

Eg. If an individual capillary had a diameter of 8 μm and a length of 1 mm compared to a diameter of 20μm and a length of 2 mm for an arteriole, the capillary would have a resistance to flow almost 20 times as great as that of the arteriole.

!!! The pressure drop depends upon the volume flow rate as well as the resistance, and since there are many times more capillaries than arterioles, the flow rate through each capillary is much smaller.

The Control of Volume Flow Rate

The heart pumps blood to supply oxygen and nutrients for the cells. If the demands of the cells are not being met, signals are generated which provide "feedback" to the heart and circulatory system.

The supply is increased by increasing the volume flow rate of the blood.

The volume flow rate is the primary variable to be controlled, and the circulatory system uses all means at its disposal to generate the proper volume flow rate.

From Poiseuille's law we know that the physical factors which influence the volume flow rate through a tube are the pressure drop, radius, length, and the viscosity of the liquid.

Of these variables, the circulatory system must use the blood pressure and the internal radii of the vessels for the short-term control of volume flow rate.

The arterioles are often called the "resistance vessels" of the circulatory system and play an important part in controlling blood flow. They are surrounded by muscle cells which can produce large changes in the vessel diameters.

Since the resistance to flow is so strongly dependent upon the diameter, such changes can control local blood flow to the tissues.

Eg. Given a constant pressure, doubling the diameter of the arteriole increases the flow by a factor of 16, and only a 19% increase in the diameter will double the flow rate.

This ability to reduce the resistance of the circulatory system enables the body to respond to the greater demands for blood during exercise without overburdening the heart pump.

Eg. During moderate exercise the blood flow rate may increase by a factor of three while the blood pressure increases only a small percentage, indicating that the total resistance of the circulatory system has dropped to less than half its previous value.

During vigorous exercise, a larger fraction of the blood flows to the muscles because of vasodilation in the muscle tissue.

Vessels to the kidneys and digestive tract may actually constrict during this time of high demand for blood for the muscles, so that the body is not only controlling total volume flow rate
but also the distribution of the blood.

The Applicability of Poiseuille's Law

1. Within the normal range of blood pressures and speeds, $\eta \approx$ const.

2. Departures from Poiseuille's law might be expected in the microcirculation of the capillaries. RBC have $d \approx$ *8 μm* and must move through vessels which may be *4 μm* or smaller in diameter. They must then be distorted to get through.

3. The law applies only for laminar flow, and it has been shown experimentally that for a given size tube there is a critical speed above which turbulence occurs.

This turbulence increases the resistance dramatically, and a large increase in pressure is required to further increase the flow rate.

$$V_c = \frac{R\eta}{\rho r}$$

R is an experimental constant called the Reynolds number. For the blood $R=10^3$.

Eg. Find V_c for the aorta, with a radius of about 0.9cm ($\eta=4x10^{-3}$ Pas; $\rho=10^3$ kg/m^3). Ans. V_c=44cm/s

The normal average blood speed in the aorta is about 33 cm/s but since it increases considerably during exercise, it could be expected that turbulence occurs in the aorta near the heart during exercise.

!!! The presence of obstructions or partial occlusions of the vessels can produce turbulence.

Changes in Blood Speed During Circulation

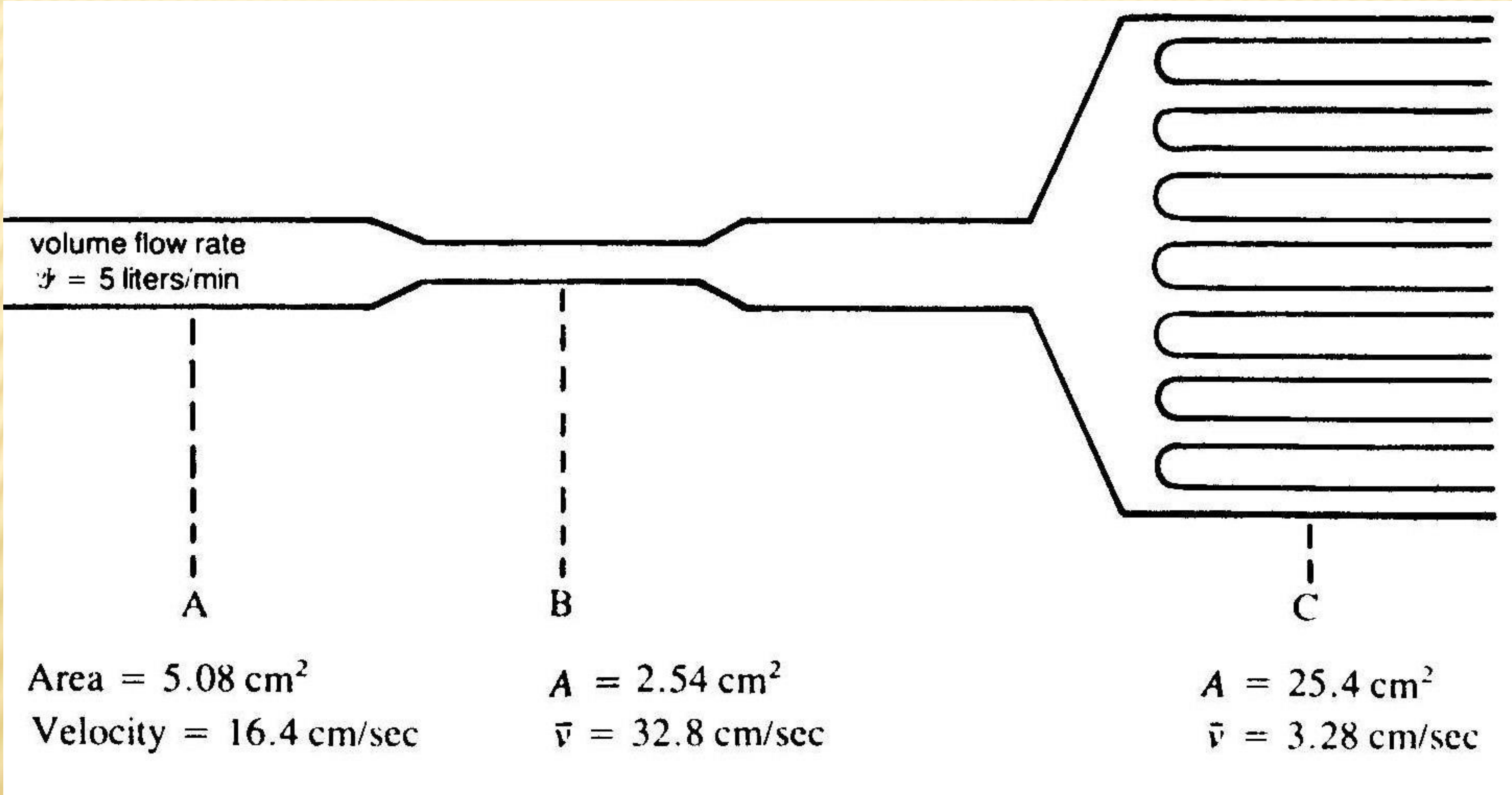
The speed is max in the aorta, drops to min in the capillaries, and accelerates to a fairly high speed in the major veins leading to the heart.

Since the normal volume flow rate of the blood is about 5 l/min, the average speed of the blood in the aorta can be calculated (r_a=0.9 cm). **F=A v** = const.

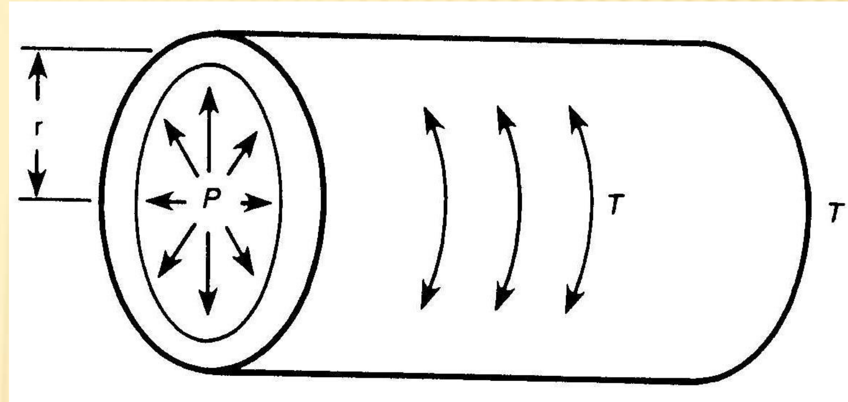
? This might be taken to imply that the speed of blood flow in the capillaries must be very large compared to the speed in the aorta, since they have diameters as small as 10 μm.

The total area of the capillary system is on the order of 1000 times as large as the aorta, so the flow in the capillaries can be assumed to be slower by a factor of about 1000.

The total volume of the circulating fluid is approximately constant.


volume flow rate
𝒱 = 5 liters/min
A
B
C
Area = 5.08 cm²
Velocity = 16.4 cm/sec
A = 2.54 cm²
v̄ = 32.8 cm/sec
A = 25.4 cm²
v̄ = 3.28 cm/sec

Wall Tension and Laplace's Law



Though the speed of the blood as it enters the capillaries is quite small compared to the aortic speed, the pressure is still a considerable fraction of that in the aorta.

"How can the tiny thin-walled capillary withstand a fluid pressure which is approximately 30% of that in the thick-walled aorta?"

Laplace was able to show that the wall tension required to withstand a given fluid pressure was proportional to the vessel radius.

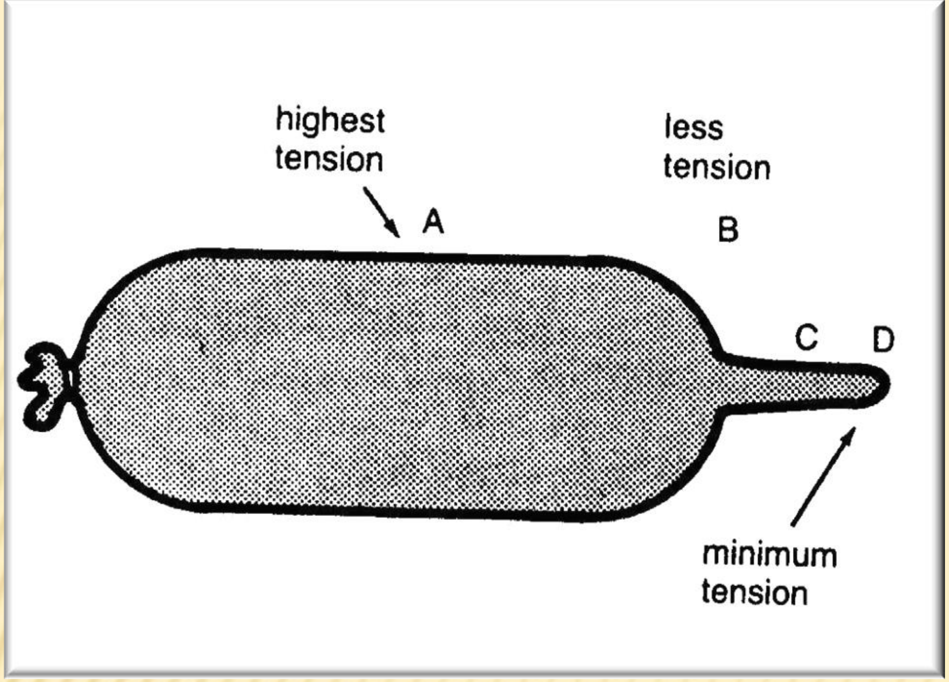
$$T = Pr \quad \text{cylindrical membrane}$$

$$T = \frac{Pr}{2} \quad \text{spherical membrane}$$

It is instructive to compare the wall tensions in the aorta and in the capillaries as calculated from Laplace's law.

A capillary with a radius of 4 μm may be subjected to a pressure of 30 mm Hg, giving a wall tension a factor of 7500 smaller than the wall tension in the aorta.

A smaller vessel can withstand more pressure with a given wall strength.



Changes in membrane tension in a balloon

If an artery wall expands because it is too weak to provide the required tension, the expansion places an even greater tension on the membrane — a classic "vicious circle."

The expansion of arterial walls is normally limited by collagen fibers which circle the artery and limit the expansion. If such limiting mechanisms fail, the membrane will continue to expand until it ruptures.

THE ENERGY SUPPLIED BY THE HEART

The heart does work on the blood flowing through it and in the process gives energy to it.

In a fluid, potential energy can take the form of gravitational potential energy (weight x height) and the potential energy due to pressure. The potential energy per unit volume of the blood is

$$\frac{E_p}{V} = \rho g h + P$$

The kinetic energy per unit volume of the blood is

$$\frac{E_k}{V} = \frac{1}{2}\rho v^2$$

The total energy per unit volume can then be written

$$\frac{E}{V} = \frac{1}{2}\rho v^2 + \rho g h + P$$

If it were not for the work done against fluid frictional resistance, this energy per unit volume would remain constant .

The heart, in pumping, increases the energy of the blood by increasing the pressure and the kinetic energy. When the blood flows down to the feet, the gravitational potential energy in the above equation is reduced and some of it is converted into pressure and kinetic energy, thus aiding the heart.

When the blood flows upward, some of the pressure and kinetic energy is used to overcome gravity, increasing the gravitational potential energy. Therefore, a person's blood pressure at the head when he or she is standing is lower than when in a horizontal position.

$$P = P \times F$$

Applied to the aorta upon exit from the heart, heart power = (average blood pressure) x (volume flow rate).

One direct implication of this is that if a person's blood pressure is elevated, the heart is having to work harder to supply a normal blood volume flow rate.

THE VARIATIONS OF THE BLOOD PRESSURE

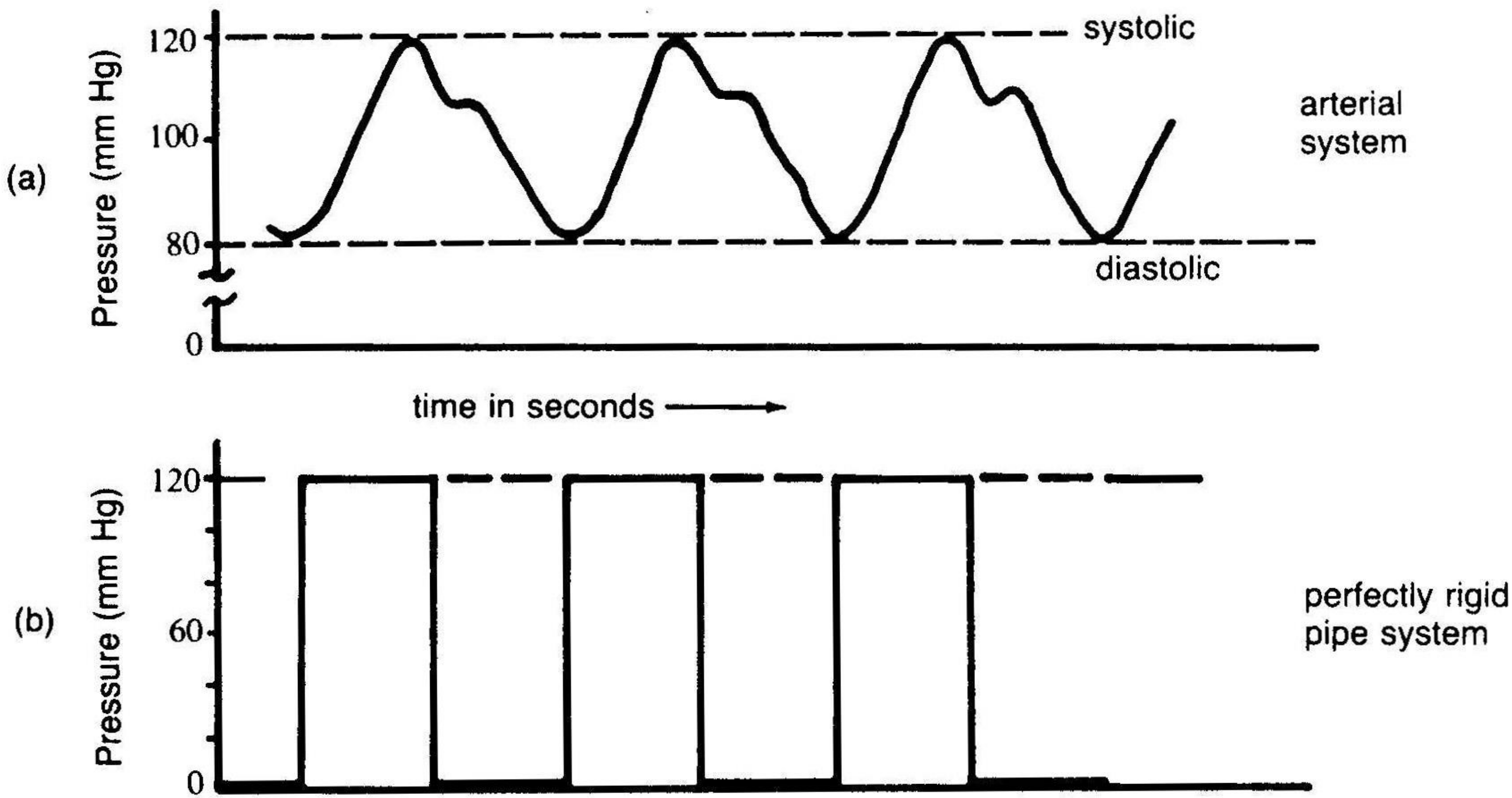
The heart supplies pressure to the blood in the systemic circulation only during the contraction of the left ventricle. If such a pulsating pressure were applied to a fluid in a rigid mechanical pipe system, the pressure would drop to zero between the pulses. (By Pascal's principle, if the applied pressure were zero, it would be zero throughout the system.)

The arteries, however, comprise an extremely elastic system of tubing. When blood leaves the heart, it bulges out the walls of the aorta, storing part of the energy in the form of elastic potential energy.

This elastic expansion of the wall travels along the arteries like a wave, causing the pulse.

The elastic contraction of the arterial walls maintains some pressure in the arterial system even during the expansion cycle of the left ventricle.

The peak pressure produced by the ventricular contraction is called the “systolic pressure” and the minimum pressure maintained by the elastic system is called the ”diastolic pressure”.



The pressure variation shown in (a) is typical of the arterial system only. The pressure variations diminish as the blood flows through the arterioles, and there is essentially no periodic variation of the blood pressure in the venous system.

If the elasticity of the blood vessels decreases, as in hardening of the arteries, the diastolic pressure drops lower since the elastic rebound is less effective in maintaining the pressure.

In this case the difference between the systolic and diastolic pressures becomes greater.

REVIEW QUESTIONS

1. Why doesn't the blood velocity increase as the blood enters the small capillaries? What is an approximate ratio of blood velocity in the capillaries to blood velocity in the aorta?

2. Why must the volume flow rate be the same at all stages in a closed liquid circulation system?

How does gravity affect the circulation of the blood?

3. If the blood flow rate doubles during exercise, why doesn't the blood pressure double?

REVIEW QUESTIONS

4. What physical variables affect the volume flow rate of the blood through a given section of artery? If each of these variables were doubled, which would produce the largest change in the volume flow rate?

5. Why doesn't the blood pressure drop to zero during the part of the cycle when the ventricles are not pumping?

6. Explain the terms systolic and diastolic pressure in terms of what is happening in the heart and circulatory system.

PROBLEMS

A person in a resting state has a systolic blood pressure of 120 mm Hg. He has a sudden demand for vigorous exercise (e.g., chased by a big dog), and the volume flow rate of his blood must increase to five times the resting value. If there were no vasodilation, how much would his blood pressure have to increase to provide the blood flow? If no blood pressure increase occurred but all the blood vessels dilated by the same percentage, what percentage dilation would be required to handle the demand?

PROBLEMS

Suppose a normal coronary artery has a volume flow rate of 100 cm^3/min when the person's average blood pressure is 100 mm Hg. Calculate the flow rates if the internal radius of that artery is reduced to 80%, 50%, and then 20% of its normal value. If all blood vessels were similarly affected, what blood pressure would be required to restore the normal volume flow rate of 100 cm^3/min in each case?

PROBLEMS

A certain highly trained athlete has a normal blood flow rate of 5 liters/min when at rest with an average blood pressure of 100 mm Hg. With maximum exertion he can increase the flow rate to 35 liters/min with an average blood pressure of 120 mm Hg. Calculate his pressure power in both cases.