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L4 Physics of the cardiovascular system

Exchange of O2 and CO2 in the capillary system

Oxygen and carbon dioxide also diffuse through tissue. The most probable distance D that a molecule will travel after N collisions with other molecules with an average distance λ between collisions is: -

$$D = \lambda\sqrt{N}$$

In tissue the density of the molecules is about 1000 times greater than in air; therefore, λ is much longer in air than in tissue.

A typical value for λ in water, which can serve as a model for tissue, is about 10^{-11}m, and a molecule makes about 10^{12} collisions/sec. Thus after 1sec in water the most probable diffusion distance is about 10^{-5}m or about a factor of 10^{3} less than in air.

$$D = \lambda\sqrt{N}$$

$$D=10^{-11}\sqrt{10^{12}}$$

$$D= 10^{-5}m$$

This very short diffusion distance is the primary reason that the capillaries in tissue must be very close together. Not all capillaries are carrying blood at any one time. In resting muscle only 2 to 5% of the capillaries are functional.

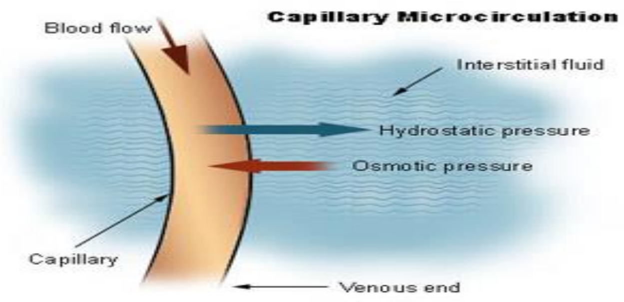
Starling's law of capillary describes the flow of fluids into and out of the capillaries. Fluid movement through the capillary wall is the result of two pressures:

1. The hydrostatic pressure P across the capillary wall forcing fluids out of the capillary.(hydrostatic pressure is the force exerted by a fluid due to gravitational pull, usually against the wall of the container in which it is located)

2. The osmotic pressure π bringing fluids in.

Starling law:

Fluid movement through capillary wall= the hydrostatic pressure (p) across the capillary wall+ osmotic pressure bringing fluid in.



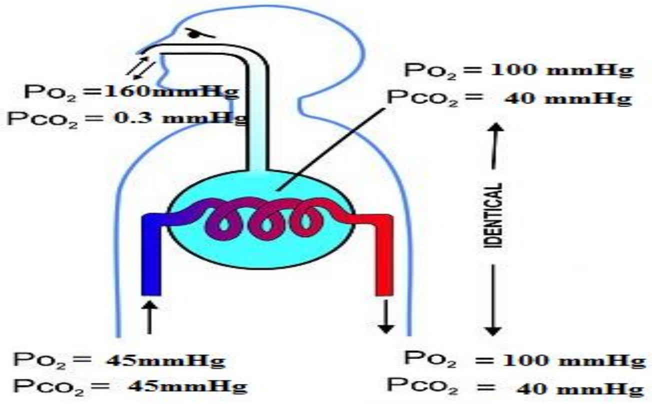
In respiration, oxygen (O_2) is required to enter cells, while waste carbon dioxide (CO_2) must be excreted.

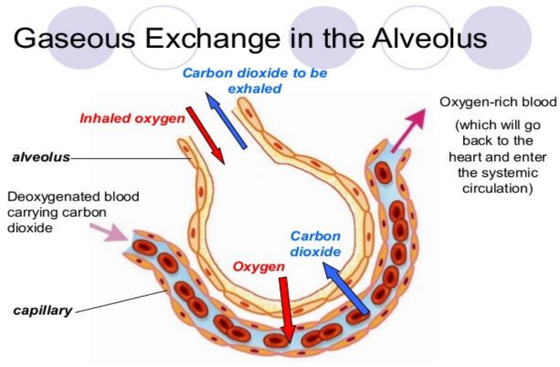
- **Oxygen and carbon dioxide move independently of each other; they diffuse down their own pressure gradients.**
- **During each inhalation, at rest, approximately 500 ml of fresh air flows in through the nose.**
- **The alveolar partial pressure of oxygen remains very close to (100 mmHg), and the partial pressure of carbon dioxide varies minimally around (40 mmHg) throughout the breathing cycle (of inhalation and exhalation).**
- **As blood leaves the lungs through the pulmonary veins, the venous PO_2=100mmHg, whereas the venous PCO_2=40mmHg.**
- **As blood enters the systemic capillaries, the blood will lose oxygen and gain carbon dioxide because of the pressure difference between the tissues and blood.**
- **In systemic capillaries, PO_2=100mmHg, but in the tissue cells, PO_2=40mmHg. This pressure gradient drives the diffusion of oxygen out of the capillaries and into the tissue cells. At the same time, in systemic PCO_2=40mmHg and in tissue PCO_2=45mmHg.**
- **The pressure gradient drives CO_2 out of tissue cells and into the capillaries. The blood returning to the lungs through the pulmonary arteries has a venous PO_2=40mmHg and a PCO_2=45mmHg. The blood enters the lung capillaries where the process of exchanging gases between the capillaries and alveoli begins again .**

The factors that influence tissue gas exchange are similar to the factors of alveolar gas exchange, and include:

1. **Partial pressure gradients between the blood and the tissues,**
2. **The blood perfusion of those tissues,**
3. **The surface areas of those tissues.**

Each of those factors generally increase gas exchange as those factors are increased (i.e., more oxygen diffusion in tissues with more blood perfusion).





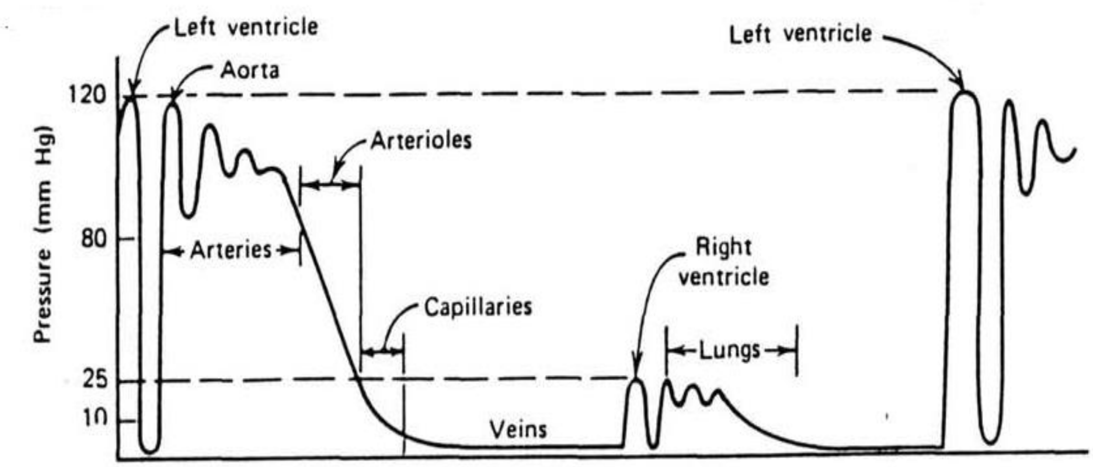
Work done by the heart

In a typical adult, each contraction of the heart muscles forces about 80ml of blood through the lungs from the right ventricle and a similar volume from the left ventricle. In the process the heart does work.

The pressure in two pumps of the heart is not the same.

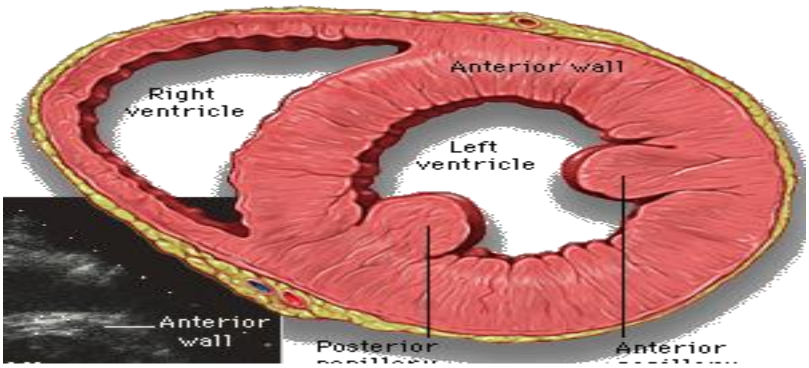
- **In the pulmonary system, the pressure is low because of low resistance of the blood vessels in the lungs.**
- **The maximum pressure (systole) about 25mmHg. It is about one-fifth of that in the systemic circulation.**

In order to circulate the blood through the much larger systemic net work the left side of the heart muscle produce pressure about 120mmHg at the peak(systole) of each cardiac cycle.



pressure conditions in the circulatory system.

The muscle driving the left ventricle is about three times thicker than that of the right ventricle. In addition, the circular shape of the left ventricle is more efficient for producing high pressure than the elliptical shape of the right ventricle.



The work W done by a pump working at a constant pressure P is equal to the product of pressure and volume pumped ΔV or

$$W = P\,\Delta V$$

We can estimate the physical work done by the heart by multiplying its average pressure(P average = (systolic+diastolic)/2) by the volume of blood that is pumped.

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:

The heart rate of a person is 120 pulse/min; calculate the action time and the resting time of heart muscle.

120pulse/1min = 120pulse/60sec =2pulse/1sec = 1pulse/0.5sec

1pulse = 1/3contraction + 2/3 relaxation

0.5x1/3 = 0.17sec (the time of contraction)

0.5x2/3 = 0.33sec (the time of relaxation)

Example:

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 = PΔV

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 = amount of blood in each beat/sec x number of beat/sec

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

ΔV = 120 cm^3

W = PΔV

Work = 166250 dyne/cm^2 x 120 cm^3

Work = 19950000 dyne.cm 1 erg = 1 dyne.cm

Work = 19950000 erg 1 erg = 10-7 Joule Work = 1.995 Joule

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

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