MEDICAL UNIVERSITY – PLEVEN
FACULTY OF MEDICINE

DIVISION OF PHYSICS AND BIOPHYSICS

LECTURE 4

KINETIC THEORY AND MEMBRANE TRANSPORT PHENOMENA

The kinetic energy of molecules. Diffusion. Osmosis. Dialysis. Transport across living membranes. Cohesion and adhesion. Surface tension and respiration. Surfactants and breathing

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THE KINETIC ENERGY OF MOLECULES

At ordinary room temperatures, the molecules of solids, liquids, and gases move continuously and at very high speeds.

NATURE OF THE MOTION OF GAS MOLECULES - Free of the attractive forces which hold liquids and solids together, gas molecules travel randomly and at very high speeds.

Consider nitrogen, the major constituent of the air.

A nitrogen molecule is extremely small, $d=1.8 \times 10^{-10}$ m and $m=4.7 \times 10^{-26}$ kg. But with its diminutive size it has an excessive amount of activity.

At 0°C it has an average speed $v \approx 490 m/s$, which is about the speed of a bullet from a high-powered rifle and it will collide with about 5 billion other molecules each second.

If a gas is confined in a container, the gas molecules will make billions of collisions with the walls each second. The average effect of these collisions causes the pressure of a gas on the walls of its container.

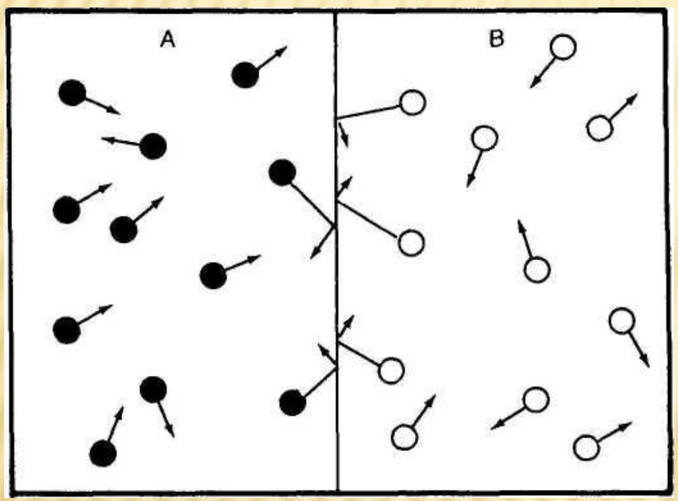
In the solid and liquid states, the motion of molecules is limited

- by their mutual attractive forces
- by the fact that there is less empty space in which to move.

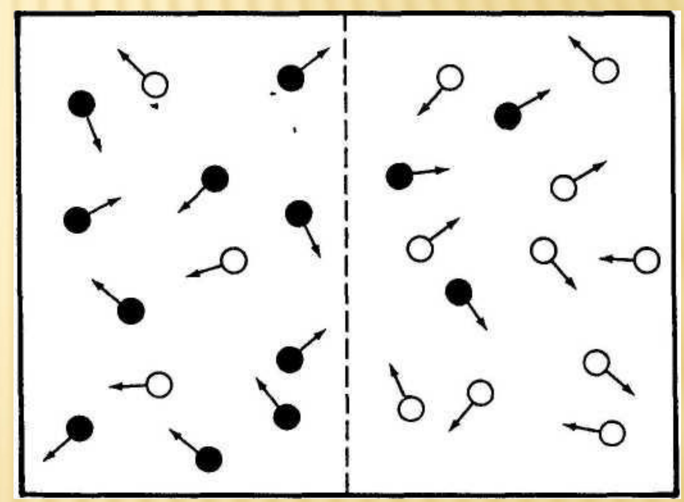
Within the confines of their limited space molecules vibrate back and forth very rapidly (solids) or move about each other like sticky spheres with a mutual attraction but no preferred order (liquids).

Despite the attractive forces, the molecules in solids and liquids are extremely agitated and have a large amount of kinetic energy.

Diffusion refers to the process by which molecules intermingle as a result of their random motion.



gases separated by a partition



diffusion of gases across an interface

If the partition is removed , the gases will mix because of the random velocities of their molecules.

The tendency toward a uniform distribution is due to the nature of the random statistical process.

If only the *A* type molecules were placed in the container and the other side were a perfect vacuum, the *A* type molecules would diffuse toward the right side when the partition was removed.

Assume that there are 20 of the *A* molecules. Now at the time when there are 15 molecules on the left side and 5 on the right side, the diffusion will still be proceeding toward the right side. Although one of the five molecules might cross the boundary to the left, it is three times as likely that one of the left-hand molecules will cross over to the right.

Once there are 10 molecules on each side, the diffusion will stop because there will be no further net transfer of *A* type molecules across the interface.

!!! This does not imply that none are crossing; it just means that as many are crossing to the left as to the right. Therefore an equilibrium condition exists.

The energy which accomplishes this net transfer of molecules is the random kinetic energy of the molecules.

Although the process occurs most rapidly in gases, it also occurs in liquids and even solids. When any two dissimilar substances are in contact with each other, diffusion is taking place.

The basic equation for diffusion is Fick's law.

$$\frac{\Delta m}{\Delta t} = -DA\frac{\Delta C}{\Delta X}$$

D is the coefficient of diffusion and has units of m^2/s.

The rate of diffusion is proportional to the cross-sectional area A and to the change in concentration per unit distance, which is called the concentration gradient.

Since diffusion is the result of molecular motion, anything which increases the motion will speed the diffusion. Heating and mechanical stirring will hasten the diffusion process.

OSMOSIS

Osmosis describes the diffusion of a solvent across a membrane while the dissolved matter, or solute, is left behind. In biological processes, the solvent is usually water.

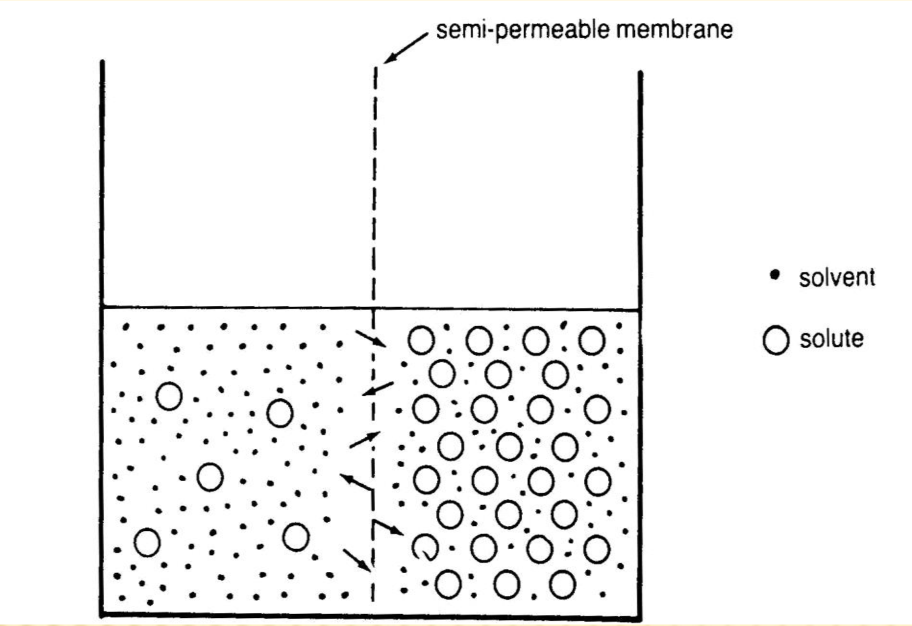
Suppose two solutions of differing C are separated by a membrane. Both the solvent and the solute molecules possess a large amount of E_k.

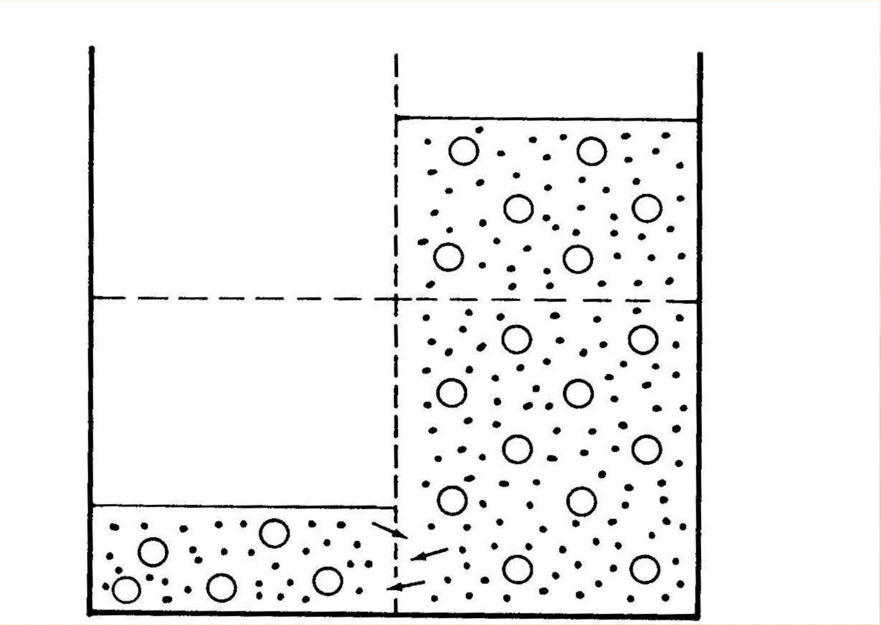
If the membrane were permeable to both types of molecules, diffusion would occur in both directions and the solutions would approach equal concentrations.

If the membrane is permeable to the solvent molecules but blocks the passage of the solute molecules, it is said to be *semipermeable.*

Since there are more solvent molecules per unit volume on the left, more of them will successfully penetrate the membrane, resulting in a decrease in volume on the left side and an increase on the right.

The transfer of a given type of molecule is always down the "concentration gradient."





The net migration of the solvent molecules to the right yields a difference in the height of the liquids, which is proportional to the osmotic pressure difference.

The osmotic pressure of solutions is a very important concept in physiology since it is related to the transfer of fluids in the body.

The osmotic pressure of a solution is defined with respect to the pure solvent. The *osmotic pressure* of the solution can be defined as the pressure required to prevent the diffusion from a pure solvent into that solution.

It is measured in mm Hg, cm H_2O, in atmospheres, Pa or any other convenient pressure scale.

A solution with more dissolved matter has a higher osmotic pressure.

Solutions are said to be *isoosmotic* or *isotonic* if their osmotic pressures are balanced.

If solution *A* is more concentrated than *B,* then it has a higher osmotic pressure and is said to be *hyperosmotic* or *hypertonic* with respect to *B.* Solution *B* is *hypoosmotic* or *hypotonic* in reference to *A.*

The terms isotonic, hypotonic, and hypertonic are relative terms and must be used with respect to some reference solution or solvent.

When these terms are used for fluids in the body, the plasma is usually the reference fluid. A solution of 0.9% sodium chloride is isotonic with the plasma.

If a red blood cell were placed in such a solution, there would be no net transfer of water across the membrane. If a red blood cell were placed in pure water, the water would rapidly cross the membrane into the cell and it would quickly burst.

If RBC were placed in a 1.5% NaCl solution (hypertonic), water would pass out of the cell and it would shrivel up.

DIALYSIS

The term osmosis is usually limited to those processes in which only one material, the solvent, is transported across the membrane.

In living organisms there are membranes which are permeable to several types of molecules (water, salts, glucose, urea, and other small organic molecules).

However, membranes normally block the passage of larger molecules such as hemoglobin, globulin, albumin, and other large protein molecules. Such membranes might be said to be "selectively permeable."

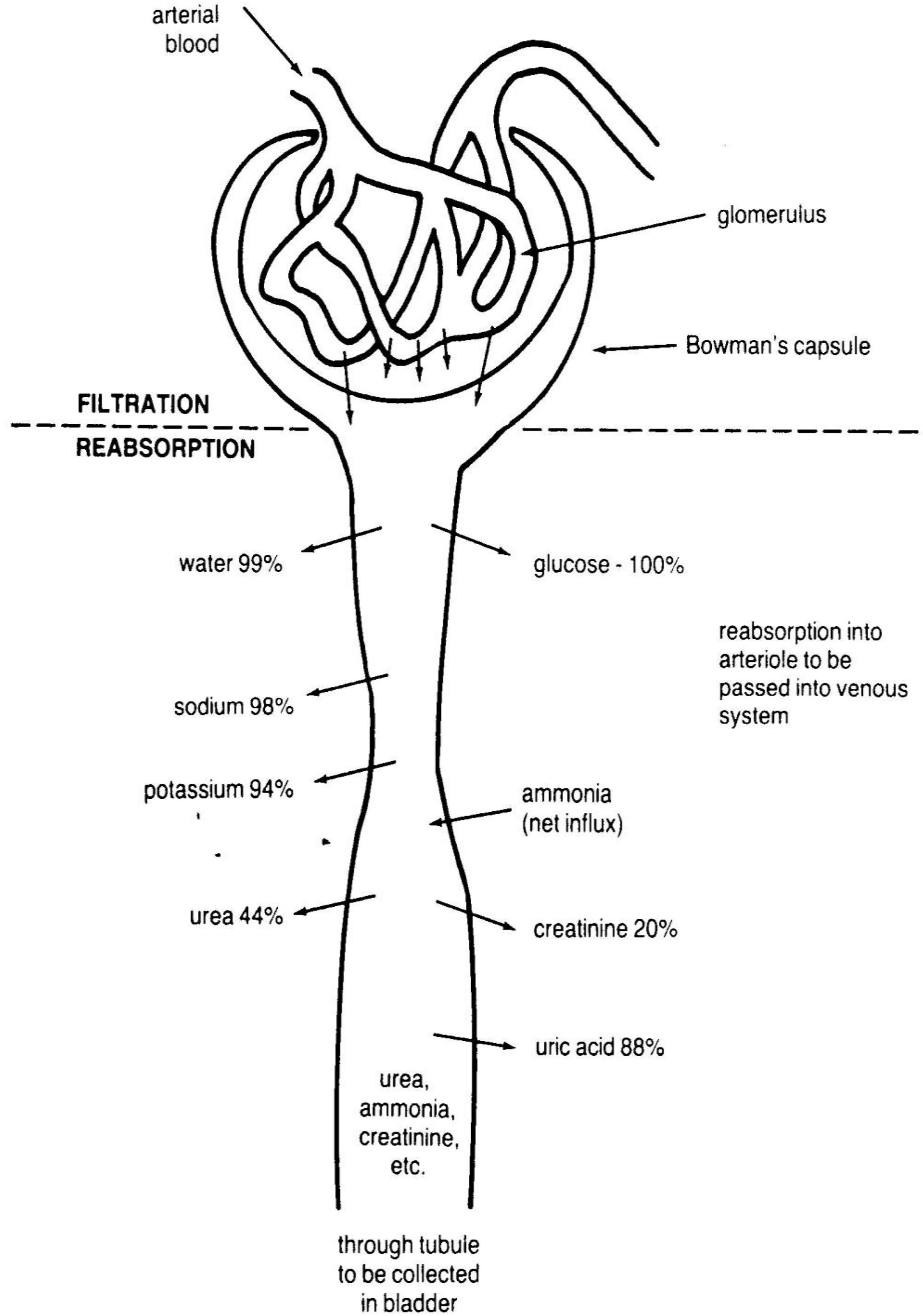
<u>Def.</u> The process, involving the diffusion of several types of molecules through a selectively permeable membrane, is referred to as "dialysis."

The most common use of the term "dialysis" is with reference to the kidney function. The removal of waste materials from the blood takes place in small bodies called nephrons in the human kidney.

There are about a million nephrons in each kidney. A nephron can be considered to have two main parts, the glomerulus and the tubule.

The glomerulus is a coiled ball of thin-walled capillaries which is enclosed by a section of the tubule called Bowman's capsule.

Most of the constituents of the blood diffuse into the tubule from the glomerulus, crossing two membranes. Only the very large molecules such as proteins are left behind in the capillaries.



This process might be thought to be dialysis in the sense that selectively permeable membranes are involved, but it does not proceed by diffusion. It is more properly termed "glomerular filtration”.

Once in the tubules, about 99% of this solution is reabsorbed through the tubule walls into the bloodstream. Most of the water and almost 100% of the glucose are reabsorbed, along with a large % of the salts.

This process of reabsorption of the vital body fluids, with the resultant concentration of the urine, proceeds largely by diffusion and could be referred to as dialysis.

▶! Diffusion alone does not seem to be sufficient to explain fully the reabsorption percentages, particularly for sodium and potassium. Apparently some active transport mechanisms are also operating.

The term dialysis is most appropriately used with respect to the function of the artificial kidney, which is commonly referred to as a "dialysis machine."

The artificial kidney operates by removing blood from the body and passing it along one side of a selectively permeable membrane. Large volumes of a fluid called the "dialysate" flow on the other side of the membrane.

The dialysate is a carefully controlled solution of electrolytes (sodium, potassium, etc.) which approximate the normal blood in concentration.

Urea, creatinine and other waste molecules diffuse across the membrane and are carried away, while the blood cells and molecules in the blood are retained.

If the ion concentration in the blood is abnormally high, there will be a net diffusion of these ions out of the blood so that the electrolyte concentration can be adjusted during dialysis.

The dialysate is often subjected to a negative pressure to speed the removal of excess water from the blood.

The dialysate is carefully regulated so that the osmotic pressure difference across the membrane does not become too large.

E.g. If pure water were substituted for the dialysate, the water would diffuse into the blood extremely rapidly. The blood would become hypotonic with respect to RBC and enough water would enter them to cause them to burst.

! The dialysis procedure has proven to be quite successful when proper care is taken to maintain the balance of the concentrations.

TRANSPORT ACROSS LIVING MEMBRANES

Osmosis and dialysis refer to processes in which the energy for transport is obtained from the inherent kinetic energy of the molecules. They are diffusion processes in which the membrane plays a completely passive role.

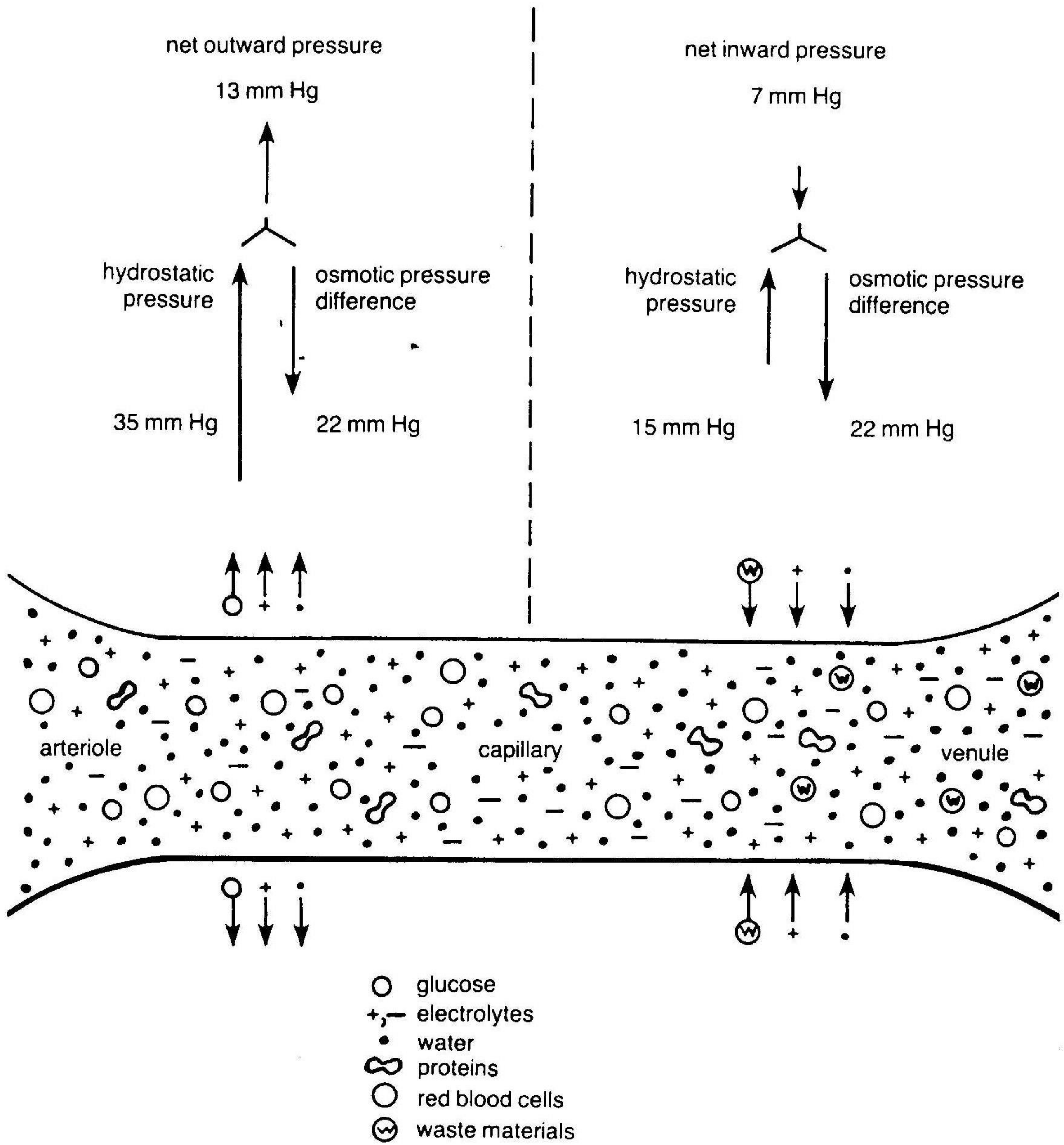
Often molecules are transported uphill across membranes. Such transport is referred to as "**active transport**" and can be accomplished only by living membranes which have a source of energy.

Some insight into the various transport mechanisms may be obtained by examining the transport of fluids from the capillaries into the interstitial fluid and then into the cells.

The plasma, with the exception of the very large protein molecules, is capable of moving through the capillary walls into the tissue spaces.

The selectively permeable capillary walls are subjected to the positive blood pressure which tends to force the plasma out.

Opposing this hydrostatic pressure is the tendency for water and small solute molecules to diffuse into the capillaries because of the "osmotic pressure" of the proteins in the capillaries.


net outward pressure
13 mm Hg
hydrostatic pressure
osmotic pressure difference
35 mm Hg
22 mm Hg
net inward pressure
7 mm Hg
hydrostatic pressure
osmotic pressure difference
15 mm Hg
22 mm Hg
arteriole
capillary
venule
glucose
+,– electrolytes
water
proteins
red blood cells
waste materials

Normally, the outflow from the capillary on the arteriole end is almost balanced by the return on the venule end, maintaining an almost constant volume of circulating blood.

This normal case of near-equilibrium between the capillary blood and the interstitial fluid is called the **Starling equilibrium for capillary exchange**.

The equilibrium is not exact, there being a slight outward excess, which is balanced by fluid return via the lymphatic circulation. The blood albumin constitutes a **considerable fraction of the "large molecules" which stay in the capillaries** and which contribute to the osmotic pressure difference.

E.g. If a person loses albumin from the blood, then the balance is upset. The fluid balance is shifted toward the tissue, since more fluid leaves the capillaries on the arteriolar end and less returns to the capillaries. The resulting collection of fluid in the tissues is referred to as edema.

E.g. The fluid balance can also be upset by a loss of salt from the blood. The blood and the interstitial fluid become hypotonic with respect to the cells. Water molecules tend to diffuse into the cells at a greater than normal rate, depleting the interstitial fluid.

COHESION AND ADHESION

Many aspects of the behavior of liquids can be attributed to the strong attractive forces between individual molecules.

When the forces are between like molecules, they are referred to as *cohesive* forces and when they are between unlike molecules, they are said to be *adhesive* forces.

One of the common examples of adhesion and cohesion is the formation of the curved surface or meniscus observed when a liquid is placed in a tube.

The meniscus of water turns up because the water molecules at the edge adhere to the glass wall more strongly than they cohere to each other.

By contrast, the meniscus of mercury turns down because the cohesion of mercury atoms is much stronger than their adhesion to the container wall.

SURFACE TENSION

The molecules at the surface of a liquid do not have other like molecules on all sides of them and consequently they cohere more strongly to those directly associated with them on the surface.

This forms a surface "film" which makes it more difficult to move an object through the surface than to move it when it is completely immersed.

Small insects can walk on water because their weight is not enough to penetrate the surface.

The surface tension is responsible for the shape of liquid droplets. Droplets of water tend to be pulled into a spherical shape by the cohesion forces of the surface layer.

The relatively high surface tension of water accounts for the ease with which it can be nebulized, or placed in an aerosol form.

The cleaning properties of a liquid are strongly dependent upon its surface tension.

A liquid with a low surface tension will be a good cleansing agent because it will spread out and "wet" the surface readily.

Why is hot water a better cleaning agent than cold water?

Ans: An increase in T of a liquid will agitate the molecules at the surface and reduce their cohesive forces, it will lower the surface tension.

There is a strong correlation between the surface tension of a liquid and its effectiveness as an antiseptic or disinfectant. Other things being equal, the antiseptic with the lowest surface tension will be the most effective.

SURFACE TENSION AND RESPIRATION

Surface tension and Laplace's law play a crucial role in the respiratory process, since the oxygen exchange from air to the blood stream occurs in the small, bubble-like alveoli in the lungs.

Surface tension provides the necessary membrane strength to maintain the bubbles.

$$T = \frac{p_L \ x \ r}{2}$$

(1) If the membrane tension is increased, more pressure in the bubble is required to keep the bubble radius the same. If that pressure cannot be produced, the bubble will collapse.

$$T = \frac{p_L \ x \ r}{2}$$

(2) If p=const in the bubble and the radius decreases, the bubble becomes unstable and will collapse.

(3) If a bubble begins to expand because its membrane strength is insufficient to stabilize it at that radius, it will continue to expand toward rupture, since the required membrane tension becomes greater with expansion.

All of these implications are important in the gas exchange process in respiration.

The lining of the lung is covered with the alveoli – they must be inflated to accomplish the respiratory gas exchange.

Given that the pressure is always close to P_{atm}, the primary determinant of the radii of the alveoli is T. This membrane tension is mainly the surface tension of the fluid that coats them (water containing a *surfactant* produced by the body that lowers the T of the membrane to obtain an optimal radius for the alveoli.

Pure water has a surface tension that is much too high. Replacing the surfactant with pure water would cause the alveoli to collapse.

On the other hand, a surface tension that is too small will cause the alveoli to expand and rupture.

Laplace's law is involved in the challenge of the first breath of air taken by an infant at birth.

The alveoli are in a partially collapsed state and must be inflated. This is a considerable challenge since the pressure required to inflate them from a small radius is considerably greater than that required to keep them inflated.

As in the case of the balloon, a small radius implies a small wall tension for a given pressure, so it takes a much greater pressure to create enough wall tension to stretch the membrane.

This initial inflation is a major problem for some premature infants who have not yet developed a sufficient amount of the needed surfactant. Respiratory assistance is necessary for such infants for initial inflation until the surfactant is produced.

The surfactant and fluid coating of the alveoli is able to accomplish some regulation. As the radius gets smaller, the surfactant becomes more concentrated on the surface of the fluid, lowering its surface tension and halting the collapse.

As the alveolar radius increases and the surfactant layer gets thinner, the higher surface tension of the underlying fluid halts the expansion.

Exhalation is accomplished by the elastic recoil of the chest wall after inhalation is complete and the chest muscles are relaxed. A significant amount of this elasticity is provided by the surface tension.

As the alveoli begin to deflate, their smaller radii lead to increased T, helping the chest recoil process, which pushes air out of the lungs. If chronic obstructive pulmonary disease has caused combining and enlarging of alveoli, the force of exhalation may be greatly reduced.

REVIEW QUESTIONS

1. How can you account for the fact that liquids which are apparently at rest can move freely across certain membranes?
2. What can be done to speed the dissolving of a solid material in water?
3. What is the difference between osmosis and dialysis?
4. Why are osmosis and dialysis said to be diffusion processes?

5. Define osmotic pressure. Does a solvent migrate toward a higher osmotic pressure or toward a lower osmotic pressure?

6. What is meant by the terms isotonic, hypotonic, and hypertonic?

7. What would happen to the red blood cells if a hypotonic solution were injected into the bloodstream? If a hypertonic solution were injected?

8. How does surface tension affect the properties of an antiseptic ?

9. Why do falling liquid drops tend to take on spherical shapes ?

10. Which of the following contribute to capillary action: cohesion, adhesion, surface tension, adsorption, viscosity? Explain.

11. What factors affect the height to which a liquid will rise in a capillary tube?

Numerical problems

1. Assume that the osmotic pressure of the blood is 7 atm, and that it has an excess of 22 mm Hg osmotic pressure compared to the interstitial fluid. Express both osmotic pressures in mm Hg.

2. Evaluate the effect of an albumin loss from the blood that dropped the blood osmotic pressure from 5320 mm Hg to 5313 mm Hg while the interstitial fluid outside the capillary remained unchanged. Assume the blood pressure drop in the capillary is from 35 mm Hg to 15 mm Hg as the blood travels from the arterial to the venous end of the capillary.

3. A patient receives a blood transfusion through a needle of radius 0.2 mm and length 2 cm. The density of blood is 1050 kg/m^3. The bottle supplying the blood is 0.5 m above the patient's arm. What is the rate flow through the needle? ($\eta = 2.7 \times 10^3$ Pa.s)