MOVEMENT IN AND OUT OF CELLS

The plasma membrane isolates the inside of the cell protoplasm from its extracellular environment. Materials are exchanged between the protoplasm and the extracellular environment across the plasma membrane. The plasma membrane is selectively permeable and allows transport of materials across it.

Substances move in and out of cells by the following processes:

a. Simple diffusion
b. Facilitated diffusion
c. Osmosis
d. Active transport
e. Endocytosis
   i. Phagocytosis
   ii. Pinocytosis
   iii. Receptor mediated endocytosis
f. Exocytosis

The transport of substances is important to;

a) Supply cells with oxygen for respiration and raw materials for anabolism (synthesis of biological molecules)
b) Regulate the pH and solute concentration for maintaining a stable internal environment for enzymes to function optimally
c) Excrete toxic waste substances
d) Secrete useful substances for cell activities

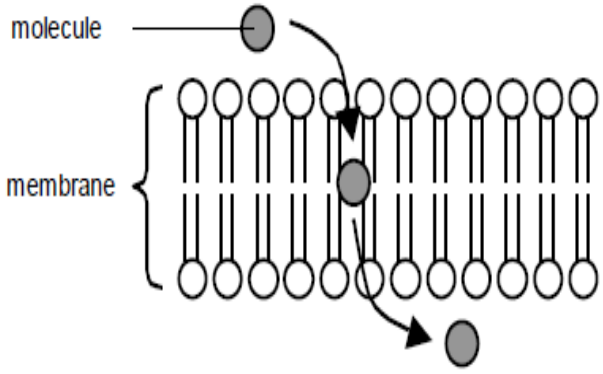
Note: the transport of substances across the cell membrane takes place by two major fundamental processes.

SIMPLE DIFFUSION

Diffusion is the random movement of ions or molecules from a region where they are at higher concentration to a region of lower concentration. That is, to move down a concentration gradient until equilibrium is reached.

The phospholipid bilayer is permeable to **very small** and **uncharged molecules** like oxygen and carbon dioxide. These molecules diffuse freely in an out of the cell through the phospholipid bilayer. **Hydrophobic substances** (lipid-soluble) e.g. steroids, can also diffuse through. These non-polar molecules do not require the aid of membrane proteins (channel or carrier) to move across the cell membrane.

Even though water is an extremely small, its **polar** therefore it does not move across the cell membrane by simple diffusion.



A charged molecule or atom and its surrounding shell of water, find the hydrophobic layer (non-polar) of the membrane more difficult to penetrate thus the lipid bilayer partly accounts for the membrane's selective permeability by preventing very large molecules and small polar molecules of ions to move across it.

The rate of diffusion depends upon;

The concentration gradient
This refers to the relative concentration on either side of the membrane or between two points. The greater the difference between the points, the faster the rate of diffusion and if the difference is less, the slower the diffusion rate. Therefore a reduced concentration gradient causes a reduced rate of diffusion and vice versa.

Temperature
When increased, temperature causes an increased rate of diffusion because the particles acquire increased kinetic energy which causes increased speed of movement hence increased rate of diffusion.
At low temperatures, the kinetic energy is very low and the speed of movement by particles is equally very low.

Surface area
The larger the surface area over which the molecules are exposed, the faster the rate of diffusion.

Distance over which diffusion takes place

This is the distance over which the molecules are to travel i.e. the surface thickness across which the molecules move. The greater the distance the lower the rate of diffusion

Size and nature of diffusing molecules

The smaller the size of the diffusing particles, the faster they diffuse i.e. smaller particles move very fats while the large ones will move slowly.

Permeability

The more porous a surface is, the greater the number of particles that diffuse through it hence the greater the rate of diffusion

Significance of diffusion

a) It's a means by gaseous exchange occurs in plants and animals e.g. in plants diffusion of gases occur through the stomata and in animals, in gills of fish, , the skin and buccal cavity of amphibians alveoli of reptiles, mammals and birds.
b) Absorption of certain digested food materials e.g. glucose in the ileum.
c) A means of exchange of materials between blood in capillaries and the tissues
d) During formation of the nerve impulse, sodium ions diffuse into the nerve cells facilitating generation of nerve impulses and ensures transmission of nerve impulses from one neurone to another i.e. diffusion facilitates synaptic transmission
e) It ensures excretion of waste products e.g. ammonia in fresh water fishes
f) It's the main means of transportation of materials within the cell's cytoplasm e.g. in unicellular organisms
g) Absorption of mineral salts by plants from the soil is effected by diffusion as one of the mechanisms

In order maximize the rate of diffusion, tissues where diffusion occurs attained special adaptations. These include;

1. The lungs are ventilated by the respiratory tract (trachea, bronchus, bronchioles) which maintain a steep concentration gradient between the lung alveoli and blood in the capillaries.
2. Respiratory surfaces like the lung alveoli and intestine epithelial lining possess a rich supply of blood vessels which transport away the diffusing materials hence maintaining a steep gradient which sustains the fast diffusion
3. Diffusion surfaces e.g. lung alveoli and intestines (ileum) are covered by a thin epithelium lining which reduces the distance over which diffusion takes place.
4. The epithelial lining covering the alveoli and rumen of the ileum is very permeable to allow molecules to travel across them
5. In lungs there are numerous alveoli and in the ileum infoldings known as villi and microvilli which is coupled with a very long ileum also increases the surface area along which particles move into cells hence increase the rate of diffusion.
6. Flattened body e.g. platyhelminthes (flatworms) which increases the surface area for movement of materials by diffusion
7. Some organisms are of small size e.g. unicellular organisms which increases the surface area to volume ratio of the surface that permits increased rate of diffusion

FACILITATED DIFFUSION

This refers to the transport of molecules and ions across a membrane by specific transport proteins, carrier and channel proteins, found within the membrane in the direction of lower concentration of the ions or molecules i.e. in favour of the concentration gradient (difference) of ions.

Facilitated diffusion is a faster form of movement than simple diffusion and it involves transport of **large polar molecules** and **ions** that cannot be transported by simple diffusion.

Trans-membrane proteins form channels or act as transport proteins to facilitate and increase the rate of diffusion across the semi permeable membrane. The transport protein molecules involved in facilitated diffusion include channel and carrier proteins.

Facilitated diffusion by carrier proteins

Some small hydrophobic organic molecules e.g. amino acids and glucose pass through the cell membrane by facilitated diffusion using carrier proteins. These proteins are specific for one molecule, so substances can only cross a membrane if it contains the appropriate proteins.

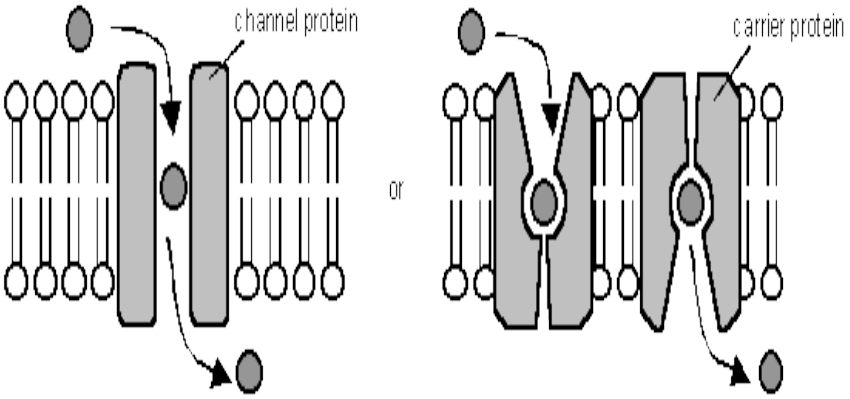
The transport of glucose across the plasma membrane of fat cells, skeletal muscle fibres, the microvilli of the ileum mucosa and across proximal convoluted tubule cells of vertebrate kidneys is brought about by a change in the shape of the carrier protein once the glucose molecule bonds to it.

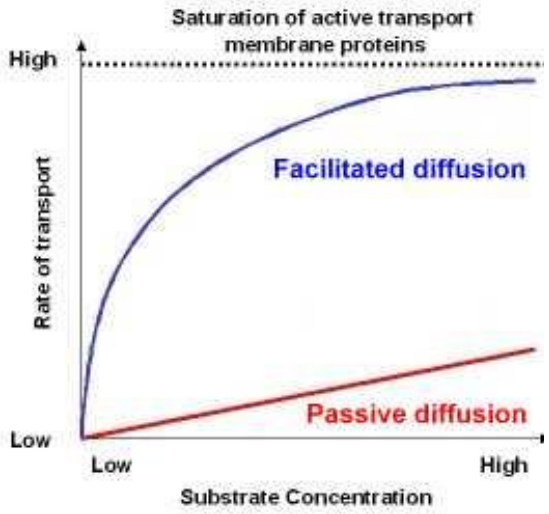
Carrier proteins alter the conformation of the carriers moving the solute across the membrane as the shape of the carrier changes. The solute molecule is released on the other side of the membrane, down its concentration gradient.

Facilitated diffusion by protein channels:

These trans-membrane proteins form water-filled functional pores in the membrane. This allows charged substances, usually ions, and polar molecules to diffuse across the cell membrane. Most channels can be gated (opened or closed), allowing the cell to control the entry and exit of the ions, these include the ligand-gated and voltage gated channels. The proteins form specific water filled hydrophilic channels that permit the diffusion of various ions such as K^+, Na^+, Ca^{2+},Cl^-,HCO^-_3.

There are also specialized channels for water known as **aquaporins** found in both plant and animal cells. The aquaporins speed up the rate of diffusion of water molecules down its water potential gradient.





Comparison between simple and facilitated diffusion

Differences

Simple	Facilitated
The rate of diffusion depends on the concentration gradient	The rate of diffusion does not depend on the concentration gradient
Diffusion can occur in either direction	Diffusion occurs in only one direction
Similar molecules diffuse at the same rate	Specific molecules diffuse faster than others
does not require special transport proteins	Occurs via special channels or carrier proteins

Similarities

Both move molecules from a region of high concentration to a region of low concentration through a partially permeable membrane.

ACTIVE TRANSPORT

It is the movement of molecules or ions across a cell membrane against their concentration gradient aided by the protein pump with specific binding sites, involving the expenditure of energy.
Cells which carry out active transport have a high respiratory rate and a large number of mitochondria to generate a high concentration of Adenosine Tri Phosphate (ATP). The energy from ATP can be directly or indirectly used in active transport.

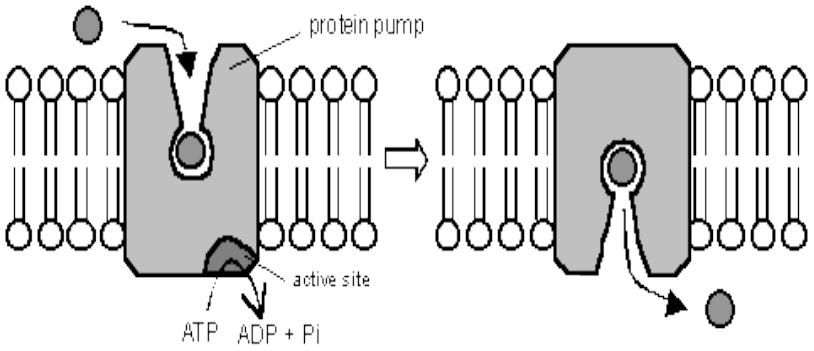
Active transport can be slowed or inhibited by respiratory poisons (inhibitors) e.g. cyanide or lack of oxygen.

Mechanism of active transport

This can be direct active transport if the energy from ATP is used directly to transport the substances, ions or molecules, or it can be indirect active transport if the energy is not directly used to transport a substance across a membrane.

a) Direct active transport (e.g. Na^+- K^+ pump)

ATP is hydrolysed and the binding of the phosphate group to the protein pump changes the protein conformation. The protein pump actively transports three sodium ions (3 Na^+) out of the cell for every two potassium ions ($2K^+$) pumped against their concentration gradient into the cell. This generates a difference in ionic charge on the two sides of the membrane which is important for the transmission of nerve impulses. The Na+ gradient is also used in the coupled uptake of solutes such as glucose into the cells against its concentration gradient.

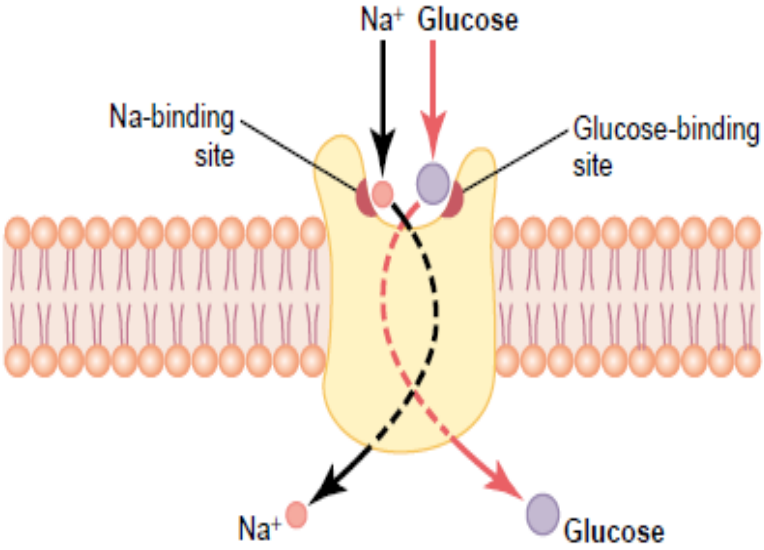


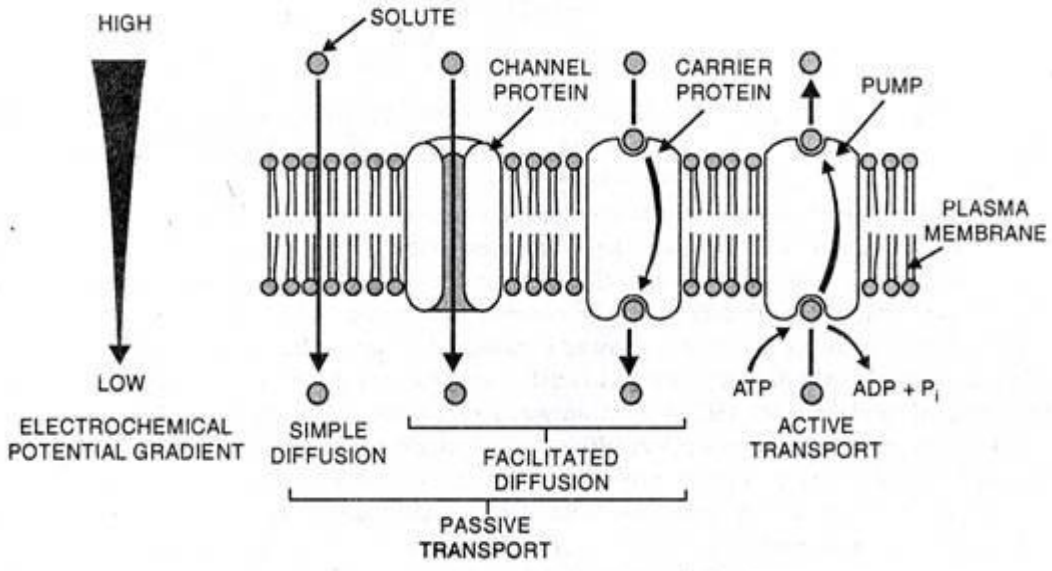
Indirect active transport mechanism (secondary active transport)

This is also known as co-transport e.g. the coupled uptake of glucose into cells lining the ileum in mammals where glucose and Na+ ions are absorbed into the cells. Sodium ions down a concentration gradient while the glucose molecules against the concentration gradient.

In co-transport of Na^+ and glucose, ATP is used by the protein pump to pump Na^+ out of the cell creating a Na^+ concentration gradient.

The Na^+ and glucose molecules then bind to trans-membrane protein (carrier protein), also called co-transport proteins/coupled transport proteins. They are then moved by the proteins inside the cells i.e. the Na^+ moves down its concentration gradient while the glucose molecules moves down against its concentration gradient.

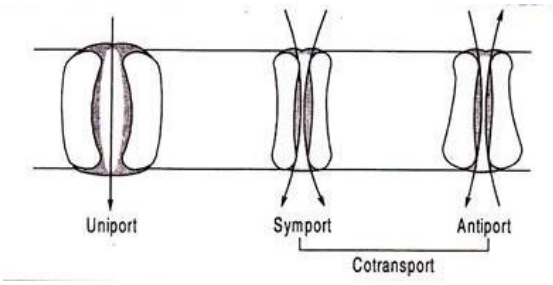




Types of membrane proteins involved in active transport

Three main types of membrane proteins exist;

a) **Uniport carriers**. They carry (transport) a single ion or molecule in a single direction.
b) **Simport carriers**. They carry two substances in the same direction.
c) **Antiport carriers**. They carry two substances in opposite directions.



The factors required for active transport to take place;

i. **Temperature**
Increase in temperature increases the rate of transport of substances by active transport, so long as the increase in not above the optimum. The increase in temperature makes respiratory enzymes more active, having their speeds of movement increased (kinetic energy) with that of substrate molecules which results into collisions of molecules at a faster rate thus forming enzyme substrate complexes that form products. In this case, ATP is required to power active transport.
At very high temperatures, above the optimum, respiratory enzymes are denatured in the carrier proteins in the membrane. This reduces the rate of active transport.
At very low temperatures, below the optimum, the respiratory enzymes together with the carrier proteins are inactive and this reduces the rate of active transport.

ii. **Availability of oxygen**
Oxygen is required for aerobic respiration to generate ATP. Increase in oxygen concentration results into increased rates of active transport as more ATP molecules are available for the process. In circumstances of very little or no oxygen, the rate of active transport is reduced since in the case of anaerobic respiration, there's very little or no ATP molecules available for active transport

iii. **Concentration of respiratory substrates e.g. glucose**
If the concentration of respiratory substrate is increased, the rate of active transport also increases and if it is lowered, the rate of active transport lowers. This is because increase in the amount of the substrate increases the rate of ATP generation during respiration. If the amount of substrate is reduced, the rate of ATP generation is also lowered.

Importance of active transport

a) It is a means of absorption of food materials in the mammalian gut
b) It is the means of absorption of mineral salts by plant root hairs and the root epidermal cells of the peliferous layer
c) It facilitates the excretion of waste materials from the cells to the extracellular fluids against a concentration gradient e.g. excretion of urea
d) It is important in muscle contractions and relaxations where there's active pumping in and out of calcium ions inside the cytoplasm (sarcoplasm) of the muscle.
e) It is used in the loading and unloading of materials in the plants phloem tissue which creates pressure differences in the phloem tissue that maintain mass flow of materials.
f) Active transport is vital in transmission of nerve impulses along nerve cells where it creates a membrane action potential using the potassium-sodium pumps.
g) It plays a part in the opening and closure of stomata where differential pumping of potassium ions between the guard cells and neighboring subsidiary cells lead to turgidity changes hence causing stomatal movements (opening/closure).

Note: metabolic poisons (inhibitors), inhibit the enzymes and carrier proteins required to bring about active transport by either changing the active sites/binding sites for the enzymes/carrier proteins for the molecules to be transported. The poisons also inhibit ATP synthesis hence cutting off the source of energy needed to affect the active transport.

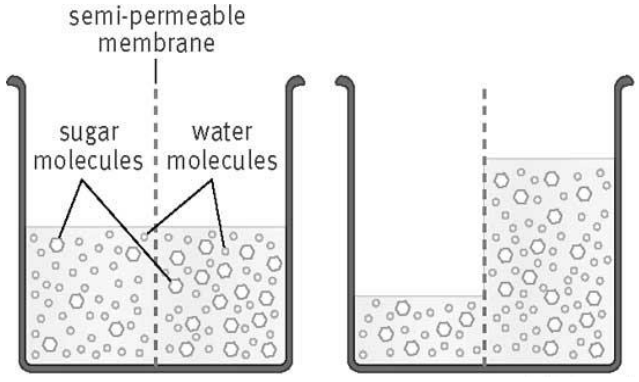
OSMOSIS

This is the passive movement of water molecules, across a partially permeable membrane, from a region of lower solute concentration to a region of higher solute concentration. It may also be defined as the passive movement of water molecules from a region of higher water potential to a region of lower water potential through a partially permeable membrane.

A selectively permeable membrane is one that allows unrestricted passage of water molecules but no passage of solute molecules.

Different concentrations of solute molecules lead to different concentrations of free water molecules on either side of the membrane. On the side of the membrane with a high concentration of free water molecules (low solute concentration), more water molecules will strike the pores in the membrane in a given interval of time, water molecules pass through the pores resulting in net diffusion of water molecules from the region of high concentration of free water molecules to the region of low concentration of free water molecules.

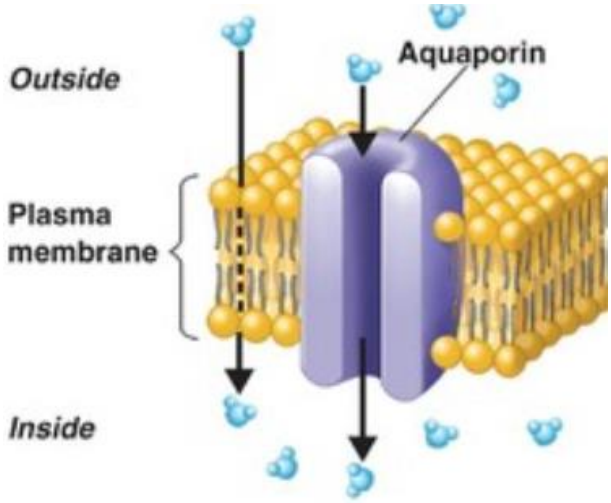
A net flow of free water molecules is maintained because in the side with more solute molecules, water forms hydrogen bonds with solutes which are charged or polar forming a hydration shell around them in solution, making water molecules unfree and therefore cannot flow back across the membrane.



Osmosis and aquaporins

In living cells, transport of water across the cell membrane is facilitated by channel proteins called aquaporins which have specialised channels for water.

Water molecules are small but they are polar and therefore cannot interact with hydrophobic phospholipid layers easily and therefore diffusion through the lipid bilayer is extremely rare or not there at all, and water molecules can quickly enter with ease through aquaporins in the cell membrane.



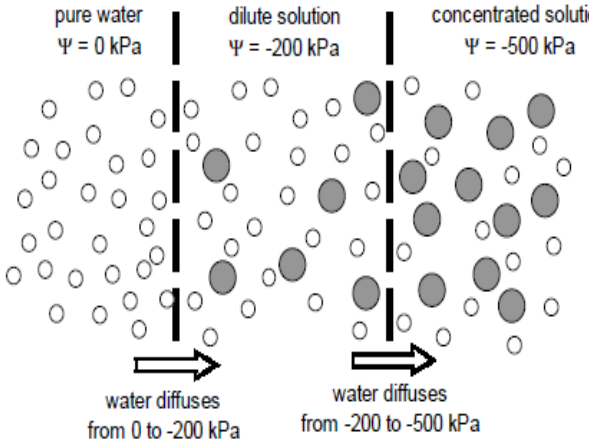
(d) Osmosis through the lipid bilayer (left) and an aquaporin (right)

WATER POTENTIAL

This is the net tendency of any system to donate water to its surroundings. The symbol for the water potential is Ψ, the Greek l psi, and is usually measured in kilopascals (Kpa).

The water potential of pure water is zero pressure units and any addition of solute to pure water reduces its water potential and makes its value negative i.e. pure water has the highest water potential.

In pure water or dilute solution with very few solute molecules, the water molecules have a *high free kinetic energy* and can move very freely. A dilute solution therefore has a higher water potential than a concentrated solution. This is because the movement of the water molecules is restricted by the attraction between solute and water molecules i.e. there are fewer water molecules with a *high kinetic energy* to move across the membrane. The greater the concentration of solutes, the more negative is the water potential.



Water potential of a plant cell ψ_{ω} is the algebraic sum of its wall pressure (pressure potential) ψ_{p} and its osmotic (solute) potential

A concentrated solution has a low water potential and water therefore moves down a water potential gradient. The water potential of pure water Ψ_W at atmospheric pressure is arbitrarily given the value of 0 Kpa.

$\Psi_W = 0$ Kpa.

The water potential of solutions is therefore less than 0 i.e $\Psi_{solution} < 0$ Kpa.

SOLUTE POTENTIAL (Ψ_S)

This is the potential or force of attraction towards water molecules caused by dissolved substances (solutes) inside the solution. That is to say, a change in water potential of a system in the presence of solute molecules.

The attraction between solute molecules and water molecules reduces the random movement of water molecules. The addition of more solute molecules lowers the water potential of a solution.

Solute potential/osmotic potential is denoted by (Ψ_S) and its equal to 0 for pure water and it is always negative solutes because the forces of attraction between the solute molecules and water molecules reduces the movement of water molecules.

PRESSURE POTENTIAL (Ψ_P)

This is the pressure exerted on a fluid by its surrounding. At any one time, the water potential of a plant is the sum of the solute potential and pressure potential. Pressure potential is usually, though not always, positive.

Ψ_W	=	Ψ_s	+	Ψ_p
Water potential of plant cell		Solute / osmotic potential		Pressure potential

When water enters the cell by osmosis, the pressure of the cytosol builds up, pushing out against the cell membrane. This pressure is called hydrostatic pressure. In blood cells, this pressure builds up pushing the cell membrane against the cell wall. The cell wall begins to resist the swelling caused by the influx of water. The pressure that the cell wall develops is the **pressure potential**. For plants therefore, pressure potential is the pressure exerted on the cell contents by the cell wall and cell membrane.

OSMOTIC PRESSURE AND CELL RELATIONSHIP

Osmotic pressure is the pressure needed to stop osmotic flow. If the membrane is strong enough, the cell reaches an equilibrium, a point at which the osmotic pressure drives water into the cell exactly counterbalanced by the hydrostatic pressure which tends to drive water back out of the cell. However, the plasma membrane itself cannot withstand the large internal pressures and an isolated cell under such conditions would just burst. In contrast, cells of prokaryotes, fungi, plants and many protocists are surrounded by a strong cell wall which can withstand high internal pressure without bursting.

If a cell is surrounded by pure water or solution whose concentration is lower than that of the cell contents, water will osmotically flow into the cell; such a solution with a lower osmotic pressure than that of the cell's cytoplasm is said to be **hypotonic**. If the cell is surrounded by a solution whose solute concentration exceeds that of the cell cytoplasm, water flows out of the cell. In this case the outer solution is said to be **hypertonic** to the cell cytoplasm.If the cell concentration of the cell cytoplasm and the surrounding medium are the same and there would be no net flow of water in other directions and the external solution is said to be **isotonic**.

The osmotic flow of water into the cell is **endosmosis** and the osmotic flow of water out of the cell is **exosmosis**.

OSMOSIS AND PLANT CELLS

Fig 4.5 pg 52 Roberts

A. TURGIDITY

When the external solution is hypotonic, the cell's cytosol have a lower water potential, causing an influx of water into the cells. The water enters into the cells vacuole causing an internal hydrostatic pressure developed by the cell by **osmosis**.

The pressure potential reaches its maximum when the cell wall is stretched to its maximum. At this point, the cell is described as a fully turgid or it has full turgor reached and the water potential at this point equals to 0 i.e. Ψ=0 and no more water can enter the cell.
Turgor pressure plays part in supporting plants and maintains their shape and form of herbaceous plants by being filled with fully turgid cells tightly packed together. It is also responsible for holding leaves in flat and horizontal position.

B. PLASMOLYSIS

When a plant cell is immersed in a hypertonic solution, then its cytosol, the cell decreases in volume as water moves out osmotically from its vacuole. The protoplast shrinks, pulling away from the cell wall and leaving gaps between the cell wall and plasma membrane. A cell in this condition is said to be plasmolysed and the cell is flaccid.
Plasmolysis is the shrinking of a plant cell's protoplast away from the cell wall leaving gaps between the cell wall and the plasma membrane.
When a plant cell is placed in hypertonic solution, it loses water by exosmosis. The protoplast shrinks and pulls away from the cell wall. Also on a dry and hot day, the plant cells lose their way evaporation and the turgor pressure of the plant cells is reduced with the result that the plant drops. The phenomenon is called wilting. This is the dropping of leaves and stems as a result of plant cells losing water exosmotically and becoming flaccid.

PLANT-WATER RELATION

This takes into account of three forces which include;

i. Water potential of the cell sap
ii. Solute potential
iii. Pressure potential

Considering a fully plasmolysed cell which is immersed in pure water, water enters the sap osmotically and the protoplasm begins to expand. As the osmotic influx of water continues, the protoplast goes on expanding until it comes into contact with the cell wall. When this point is reached the osmotic influx of water into the cell starts to be opposed by the inward pressure of the cell wall i.e. pressure potential. In a plasmolysed cell, the water potential of the cell now becomes less negative than the solute potential of the sap equal to/by the amount of the pressure potential.

As the cell continues to expand, the pressure potential of the cell gets steadily greater and the water potential becomes less and less negative. Eventually full turgor is reached, when the cell cannot expand anymore and at this point Ψs (osmotic potential) is exactly outbalanced by the pressure potential (Ψp).

If the solution produces no change within the volume of the cell, it has a solute concentration similar to that of the cell sap or tissue and therefore water potential of the solution equals to the water potential of the cell or tissue. When the strength of the external solution causes the cell just to plasmolyse so that the protoplast just contact the cell wall, this is called **incipient plasmolysis**.

Graphical illustration of a relationship between Ψs (osmotic potential), Ψcell and pressure potential (Ψp) of a plant cell at different stages of turgor and plasmolysis is shown below

Fig 4.6 pg 54 Roberts

In general Ψcell = Ψs (always negative) + Ψ p (always positive)

At total plasmolysis; the vacuole almost disappears, minimum hydrostatic pressure, cell membrane completely not attached to the cell wall. Cell generally small and described as **flaccid**.

At incipient plasmolysis; cell membrane begins to leave cell wall and water is lost from the cell.

At full turgidity; the cell vacuole with maximum volume and no more water can enter.

OSMOSIS AND ANIMAL CELLS

If a human red blood cell is placed in an isotonic solution i.e. 0.9% sodium chloride solution, the cell neither shrinks nor swells. If they are placed in a hypertonic solution i.e. 1.2% sodium chloride, it will shrink and appear crinkled and this is called **crenation**.

If it is placed in a hypotonic solution i.e. 0.5% sodium chloride, it will swell and even burst and this is called **haemolysis**. Haemolysis is due to red blood cells lacking cellulose cell walls which would prevent red blood cells expansion and therefore stops bursting.

ROLE OF OSMOSIS IN LIVING ORGANISMS

1. It is the main form by which root hairs and piliferous layer cells on roots absorb water from the soil
2. Kidney nephrons (tubules) re-absorb water back into the blood stream via the blood capillaries osmotically leading to water conservation in the body hence bringing about osmoregulation
3. In herbaceous plants, osmosis brings about turgidity in plant cells due to presence of cell wall leading to provision of support and shape in a whole plant body.
4. Osmosis causes plant structures (organs) like leaves and flowers to determine their form for example holding the leaf in flat and horizontal position enabling it to trap maximum sunlight.
5. Osmosis bring about opening and closure of petals of flowers and osmosis bring about the opening and closure of stomata in plant leaves when the guard cells become turgid facilitating gaseous exchange in plants.

CYTOSIS

This is a form of active transport involving infoldings or folding of secretions into vesicles or vacuoles which can be moved.

Cytosis involves the contractile proteins in cellular microfilaments and microtubules. Cytosis results in bulk transport of materials into the cell or outside the cell, thus cytosis is divided into two main types i.e.

i. Endocytosis
ii. Exocytosis

Fig 4.22 pg 70 Toole OR Fig 5.23 pg 147 Soper

ENDOCYTOSIS

This is bulk transport of materials inside the cell. It involves a small area of plasma membrane folding inwards to surround a material to be taken in and moves deeper inside the cell. There are three types of endocytosis;

i. Phagocytosis
ii. Pinocytosis
iii. Receptor-mediated endocytosis

PHAGOCYTOSIS (cellular eating)

This is called cellular eating and it involves the cell taking in large solid substances. Phagocytosis involves invagination of cell membrane surrounding of the organism or particle forming a phagocytotic vesicle or vacuole which pinches off the cell membrane and moves into the cytoplasm.

Lysosomes fuse with vacuoles and release hydrolytic enzymes into the vacuole which break down the substances in the vacuole. The protein substances are absorbed into the surrounding cytoplasm across the lining of the vacuole.

Any undigested material may be got rid of by the vesicles of vacuoles moving into the cell surface membrane and fusing with it.

Mechanism of phagocytotic killing by white blood cells

White blood cells form cytoplasmic extensions to form pseudopodia which surround and engulf micro-organisms. Micro-organisms are completely surrounded by pseudopodia to form phagocytotic vesicles or phagosomes which pinch off the cell membrane into the cytoplasm. The phagosome fuses with the lysosome to form a phagolysosome. Inside the phagolysosome are microbes which are broken down by hydrolytic enzymes.

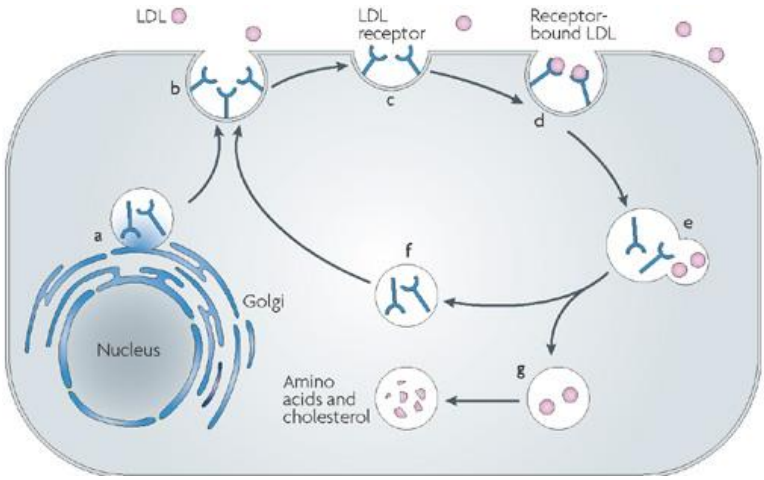
PINOCYTOSIS (cellular drinking)

This is cellular drinking, it is similar to phagocytosis only that the infoldings forming the vesicles are much smaller. Liquid and large macro molecules such as proteins are taken in via small pinocytotic vesicles. The process is highly specific involving the binding of the molecules with corresponding receptor molecules in the plasma membrane.

RECEPTOR MEDIATED ENDOCYTOSIS

This involves receptor molecules on a cell membrane which binds with specific substance from extracellular fluid as the receptor sites are filled, the surface falls inwards until the coated vesicles finally separates from the cell surface membrane.

Illustration



EXOCYTOSIS

This involves the vesicles or vacuoles moving to the cell membrane fusing with the releasing their contents to the outside of the cell.

Exocytosis provides a means by which enzymes, hormones, antibodies and cell wall precursors are released from the cell.

The vesicles are often derived from the Golgi apparatus which move along microtubules of the cytoskeleton of the plasma membrane. When the vesicles get into contact with the plasma membrane, the lipid molecules of the two bilayers rearrange and diffuse. The content of the vesicles spill to the outside of the cell and the vesicle membrane becomes part of the plasma membrane.

Importance of cytosis

1. Many secretory cells use exocytosis to release their excretory products outside themselves e.g. pancreatic cells manufacture insulin and secrete it into blood by exocytosis and many other hormones are secreted in this form by the gland cells
2. Exocytosis facilitates synaptic transmission during which neuro-transmitter substances like acetylcholine in synaptic vesicles of synaptic knobs fuse with the pre-synaptic membrane to release neuro transmitter substances into the synaptic cleft of the synapse.
3. Exocytosis delivers cell wall materials to the outside of the cell from the Golgi apparatus/body through vesicles which contain proteins and certain carbohydrates
4. Exocytosis leads to replenishment of the plasma membrane as the vesicle membrane become part of the plasma membrane become part of the plasma membrane after spilling/discharging their contents to the outside.

Summary			
Features	**Simple diffusion**	**Facilitated diffusion**	**Active transport**
Concentration gradient	Down the concentration gradient from high to low	Down the concentration gradient from high to low	Against a concentration gradient from low to high
Energy expenditure	None	None	Energy expenditure is in the form of ATP
Carrier protein/ transporter	Not required	Required	Required
Speed	Slowest mode	Fast	Fastest

UPTAKE AND TRANSPORT IN PLANTS

Water and mineral salts are necessary for photosynthetic reactions and other metabolic processes; hence they must be absorbed in sufficient quantities by using the root system and transporting them through the xylem to the mesophyll cells of leaves where photosynthesis takes place.

Water however can be lost from the mesophyll cells into sub-stomatal air chambers and then eventually lost into the atmosphere of water vapour through tiny pores called “stomata” by a process known as **transpiration.**

TRANSPIRATION

This is the process of water loss inform of water vapour to the atmosphere from the plant mainly through the stomata pores.

Types of transpiration

There are three types of transpiration which include the following;

i. Stomatal transpiration
ii. Cuticular transpiration
iii. Lenticular transpiration

Stomatal transpiration

This is the loss of water vapour to the atmosphere through the stomatal pores of the leaves. This contributes 90% of the total water loss from a leafy shoot. This is because leaves contain a large number of stomata for gaseous exchange where this water vapour can pass and also there’s little resistance to the movement of water vapour through the stomatal pores. In addition, leaves also have a large surface area over which water vapour can evaporate rapidly to the atmosphere.

Cuticular transpiration

This is the loss of water vapour to the atmosphere directly through the epidermis coated with a cuticle layer. It contributes 5% to the total water loss from the leafy shoot. This is because the cuticle is hard, waxy and less permeable to most diffusing molecules including water vapour molecules.

Lenticular transpiration

This is the loss of water vapour through a mass of loosely packed cells known as lenticels found scattered on the stems. It also contributes 5% of the total water loss to the atmosphere in a leafy shoot. It is because the lenticels are usually few in number and not directly exposed to environmental conditions. Lenticular transpiration is the main source of water loss from deciduous plants after shading off their leaves. Because there are more stomata on the leaves than elsewhere in the shoot system, it is evidence that most of the water vapour is lost from the leaves.

In order to establish that transpiration occurs mostly in the leaves, an experiment using absorptive paper, dipped Cobalt II Chloride solution or Cobalt II thiocynate solution is carried out. The paper is covered on the surface of both sides of the leaves and then clamped with glass slides. After some time, the blue cobalt thiocynate paper changes to pink, indicating the evaporation of water molecules from the leaf by transpiration. The rate of change from blue to pink is higher at the lower epidermis than the upper epidermis. This is because structurally there are more stomata on the lower epidermis to prevent excessive loss of water by transpiration due to direct solar radiation

Measuring the rate of transpiration

The rate of transpiration can be measured by either determining the rate of transpiration at which the plant loses mass due to water loss or the rate at which the plant takes in water (water uptake), using an instrument called a **potometer.**

Determining the rate of transpiration using

a) the weighing method

The rate of mass loss by the plant can be determined by using the potted plant placed on an automatic weighing balance whereby the change in mass is noted over a given period of time. Using this method, it is assumed that the mass loss is only due to water loss by transpiration. However, the whole pot must be enclosed in a polythene bag to prevent water from evaporating from the soil. In addition, the soil must be well watered before the beginning of the experiment so that the plant has enough water throughout the experiment. The rate of transpiration is then expressed in terms of mass lost per unit time

b) the potometer

The potometer is used to measure the rate of water uptake by the shoot of the leafy plant.

However, since most of the water taken up is lost by transpiration, it is assumed that water uptake ≈ water loss. The leafy shoot is cut under water to prevent the air bubbles from entering and blocking the xylem vessels. The cut leafy shoot is immediately fixed in the sealed vessel of connected to the capillary tube. The rate of water uptake is then measured by introducing an air bubble at the end of the graduated capillary tube and the distance moved by the air bubble per unit time is noted.

To drive the air bubble back to the original position, water is introduced into the capillary tube from the reservoir by opening the tap on the reservoir.

The leafy area is also established by tracing the outline of the leaves on a squared graph paper and then counting the number of complete and incomplete squares enclosed in the outline

P 530 Total area of leaves = Number of complete squares + Number of incomplete squares x $\frac{1}{2}$

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The rate of transpiration is therefore expressed in terms of the volume of water taken up by the leafy shoot per unit time per unit leaf area. The structure of a potometer is shown in the diagram below.

(Kent Fig 2 pg 276, Soper Fig 13.10 pg 439, Toole fig 22.12 pg 457)

Precautions taken when using a potometer

1. The leafy shoot used should have a significant water loss by having very many leaves
2. The stem of the leaf shoot must be cut under water to prevent air from entering and blocking the xylem vessels
3. The setup must have plenty of water
4. Ensure that only one bubble is present in the capillary tube
5. A well graduated scale must be used e.g. a ruler, so that clear readings are taken
6. The air bubble should always be reset to zero mark before the potometer is used again under different conditions
7. The water reservoir should be filled with water when setting the air bubble at the zero mark
8. The cut leafy shoot must be in contact with water in the sealed vessel

How to use a potometer

The leafy shoot is cut under water to prevent air bubbles from entering and blocking the xylem vessels. The cut leafy shoot is immediately fixed in the sealed vessel of water connected to a capillary tube. Allow time (5 minutes) for the apparatus to equilibrate. The rate of water uptake is measured by introducing the air bubble at the end of the graduated capillary tube and the distance moved by the air bubble per unit time is noted.

To drive the air bubble back to the original point, water is introduced into the capillary tube from the reservoir by opening the tap.

The leafy area is then established by tracing the outline of the leaves on squared papers and then counting the number of complete and incomplete squares in the outline of the leaves.

The rate of transpiration is therefore expressed in terms of the volume of water taken up by the leafy shoot per unit time per leafy area.

NOTE; since most of the water taken up by the potometer is lost by transpiration, it is assumed that water uptake = water loss.

Advantages of transpiration

i. It allows the uptake of water from the roots to leaves in form of a transpiration stream. This is due to a transpiration pull created in the leaves. This ensures proper distribution of water throughout the plant to keep it alive.
ii. It facilitates the uptake of the absorbed mineral salts within the xylem vessels from roots to leaves
iii. It brings about the cooling of the plant since as water evaporates to the atmosphere, excessive heat is also lost as heat of vaporization, which results into the cooling of the plant
iv. It brings about mechanical support in non-woody or herbaceous plants, due to water uptake which provides turgidity to the parenchyma cells of the stem and leaves
v. It is important for cloud formation via evapotranspiration hence resulting into rainfall

Disadvantages of transpiration

i. It causes wilting of plants in case of excessive transpiration
ii. It may eventually cause death of the plant, when the plant looses water excessively due to excessive transpiration

NOTE: wilting is the loss of water from the plant cells. Evaporation occurs at rate greater than that at which it is absorbed, resulting into reduction in turgor pressure and dropping of the plant. It always takes place in hot and dry areas. Wilting also results into the closure of the stomata which cuts off gaseous exchange and therefore may cause death if it persists.

FACTORS AFFECTING TRANSPIRATION

The potometer may be used to investigate the effect of environmental factors on the rate of transpiration i.e. it can be moved to a windy place or a place which is dark. Transpiration is affected by both environmental and non-environmental factors.

ENVIRONMENTAL FACTORS

1. Humidity

The humidity of the atmosphere affects the gradient of water vapour between the sub-stomatal air chamber and the atmosphere around the leaf i.e. it affects the rate of diffusion of water vapour.

Low humidity (low water vapour pressure) outside the leaf increases the rate of transpiration because it makes the diffusion gradient of water vapour from the moist sub-stomatal air chamber to external atmosphere steeper.

When humidity is high in the atmosphere, the diffusion gradient or the water vapour pressure gradient is greatly reduced between the sub-stomatal air chamber and the atmosphere which results into reduction in the rate of transpiration.

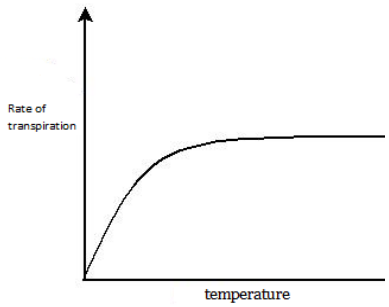
In areas where humidity is too high, plants loose liquid water from their leaves via structures/glands on their leaf margins known as **hydathodes**, a process known as **guttation.** Guttation is the loss of liquid water from plant leaves through hydathodes due to excessive humidity in the atmosphere.

2. Temperature

Increase in temperature increases the rate of water loss by the leaves via transpiration. A decrease in temperature lowers the rate of water loss by the plant leaves via transpiration.

This is because increase in temperature increases the kinetic energy and movement of water molecules hence the water molecules evaporate rapidly to the sub-stomatal chambers and eventually to the atmosphere via the stomata.

Increase in temperature also lowers humidity outside the leaf which further increases the rate of transpiration. In extremely hot conditions, the stomata of some plants close, an adaptation to prevent water loss by transpiration.



3. Air movements

In still air (no wind), layers of highly saturated vapour build up around the stomatal pores of the leaf and reduces diffusion gradient between the stomatal air chamber and the external atmosphere, thereby reducing the rate of diffusion of water vapour from the leaf. The layers of highly saturated water vapour which build up around the stomatal pores of the leaf are called **diffusion shells.**

Windy conditions result in increased transpiration rates because the wind sweeps away the diffusion shells around the leaf, thereby maintaining a steep diffusion gradient which keeps the rate of transpiration high.

(Soper fig 13.9 pg 439)

4. Atmospheric pressure

Water vapour and the atmospheric pressure decreases with increasing altitude.

The lower the atmospheric pressure the greater the rate of evaporation of water from the sub-stomatal air chamber. This implies that plants growing on a mountain have a higher rate of transpiration than those growing in low land areas.

However, when the atmospheric pressure is high e.g. in the lowland areas, the evaporation of water vapour from the sub-stomatal air chamber to the atmosphere decreases, thereby increasing the rate of transpiration.

5. Water availability

For water vapour to diffuse out of the sub-stomatal air chamber to the atmosphere, the mesophyll cells must be thoroughly wet. Shortage of water in the soil or any mechanism which hinders the uptake of water by the plant leads to wilting of the plant hence the closure of the stomata.

When water is supplied in large amounts, too much water evaporates to the atmosphere and therefore a high rate of transpiration. However, when the water supply to the mesophyll cells is low, less water evaporates from the sub-stomatal to the atmosphere, hence a low rate of evaporation.

6. Light intensity

It affects transpiration indirectly by affecting the closure and opening of the stomata, which usually opens in bright sunlight to allow evaporation of water to the atmosphere. Therefore sunlight increases the rate of transpiration.

At night and in darkness, the stomata close and therefore there is no evaporation of water from the sub-stomatal air spaces to the atmosphere. This greatly lowers the rate of transpiration in the plant.

(Soper fig 13.13 pg 443)

NON-ENVIRONMENTAL FACTORS

1. Leaf area

The larger the leaf surface area on the plant, the higher the rate of water loss by transpiration. In addition, broad leaves provide a large surface area over which water vapour diffuses to the atmosphere as compared to the narrow leaves.

2. Cuticle

The thinner the cuticle, the higher the rate of water loss by transpiration and the thicker the cuticle, the lower the rate of water loss from the plant to the atmosphere by transpiration. This is because this offers a significant resistance towards the diffusion of water vapour from the plant to the atmosphere.

3. Number of stomata

The larger the number of stomata on the plant, the higher rate of water loss by transpiration and the lower the number of stomata, the lower the rate of transpiration.

However, a very large number of stomata so close to each other may instead reduce the rate of transpiration especially in still air due to the accumulation of water vapour around the whole stomata pore.

STOMATA

In terrestrial plants, gaseous exchange takes place predominantly in the leaves. The epidermis of the leaves contains small pores called stomata (singular. stoma). Through stomata, gaseous exchange between the inside of the leaf and the outside air takes place by diffusion.

The broad leafed shape of the leaf offers a large surface for diffusion of gases, its thinness reduces the distances over which diffusion of gases from the atmosphere to the inner most cells.

In most terrestrial plants, stomata are more abundant on the lower side than the upper surface of the leaf. This reduces water loss through transpiration since the upper surface is exposed to direct sunlight.

The number of stomata in leaves vary from one plant species to another. They are normally absent in submerged leaves of water plants.

Structure of the stoma

Each stoma consists of a stomatal pore bordered by a pair of crescent or bean-shaped cells called **guard cells.** Unlike epidermal cells, guard cells contain chlorophyll. The inner cell wall of guard cells is thicker and less elastic than the outer wall. Microfibrils are radially orientated in the cell wall and the guard cells are joined at the ends. The epidermal cells surrounding the guard cells are subsidiary cells.

(Toole fig 22.7a pg 452)	(Toole fig 22.7b pg 452)

(Soper fig 13.15 pg 444)

Ventilation (opening and closing of stomata)

The opening and closing of stomata occurs as a result of changes in the shape of the guard cells. When guard cells take in water by osmosis, they expand and become turgid. However, they do not expand uniformly in all directions. The thick inelastic inner wall makes the guard cells to curve away from each other, opening the stoma. When the guard cells lose water, they become flaccid and collapse, closing the stomata.

The closing and opening is controlled mainly by the intensity of light. They are normally open during daylight and closed during the night.

Several theories have been put forward to explain how the light intensity influences the opening and closing of stomata.

1. Photosynthetic product theory

Guard cells have chloroplast. During day light, they carry out photosynthesis producing sugar. The sugar increases the osmotic pressure of the cell sap. This causes water to move into the guard cells from nighbouring epidermal cells by osmosis. The result is an expansion and increase in turgidity of the guard cells containing the stomata to open.

In darkness, photosynthesis stops and the sugar in the guard cells is converted to starch. This lowers the osmotic pressure of guard cells causing them to lose water to neighboring cells by osmosis. The guard cells become flaccid and the stomata close.

Note; this theory does not explain how the low rate of glucose formation can account for the rapid opening of stomata

2. Potassium ion (K^+) mechanism (mineral ion concentration)

When guard cells are exposed to light, the light energy activates the ATPase enzyme, hence their chloroplasts manufacture ATP. The ATP drives a K^+ - pump on the cell membrane of the guard cells. This causes an active uptake of K^+ ions in the guard cells from the surrounding epidermal cells. Accumulation of K^+ in the guard cells increases the osmotic pressure of their cell sap. This causes water to move into the guard cells from neighboring epidermal cells by osmosis. The result is an expansion and increase in turgidity of the guard cells causing the stomata to open because when they become turgid, they expend but not uniformly since the inner wall is inelastic, making the guard cells curve away from each other.

At the onset of darkness, ATP concentration in guard cells falls rapidly stopping the K^+ pump. K^+ migrates from the guard cells to neighboring epidermal cells by diffusion. This lowers the osmotic pressure of guard cells causing them to lose water to neighboring cells by osmosis. The guard cells become flaccid and the stomata close.

Note; the above theory is the most widely accepted theory today. It is supported by the fact that the opening of stomata is prevented by metabolic poisons which inhibit active transport.

(Toole fig 22.8 pg 452 OR Kent fig 3 pg 281)

The two above theories can be summarised into a single mechanism of stomata opening and closing as described below;

Stomata opening

1. Stomata opening is promoted by high light intensity and low mesophyll carbon dioxide levels. Guard cells generate ATP by photophosphorylation during photosynthesis. .
2. Blue light is absorbed by blue-light photoreceptors which activate a proton-pump (H^+-ATPase) in the cell membrane of the guard cell
3. ATPs generated by the light-dependent reaction of photosynthesis are hydrolysed to provide energy to drive the proton-pump. As protons (H^+) are pumped out of the guard cells, the cells become increasingly negatively charged. Potassium channels are activated and K^+ ions diffuse from subsidiary cells through the channels down this electrochemical gradient into guard cells. Chloride ions (Cl^-) then enter to balance the charge.
4. In some plants the starch is converted to malate.
5. The accumulation of K^+ (and malate ions) causes the water potential in the guard cells to become more negative. Water enters by osmosis from the neighbouring subsidiary cells into the guard cells. The guard cells become turgid.
6. The outer wall of the guard cells is t hinner and more elastic than the thicker inner wall. There are cellulose micro fibrils which are radially arranged around the cell wall and the ends of the two guard cells are joined
7. The increased turgor pressure therefore causes the guard cells to curve outward and the stoma opens

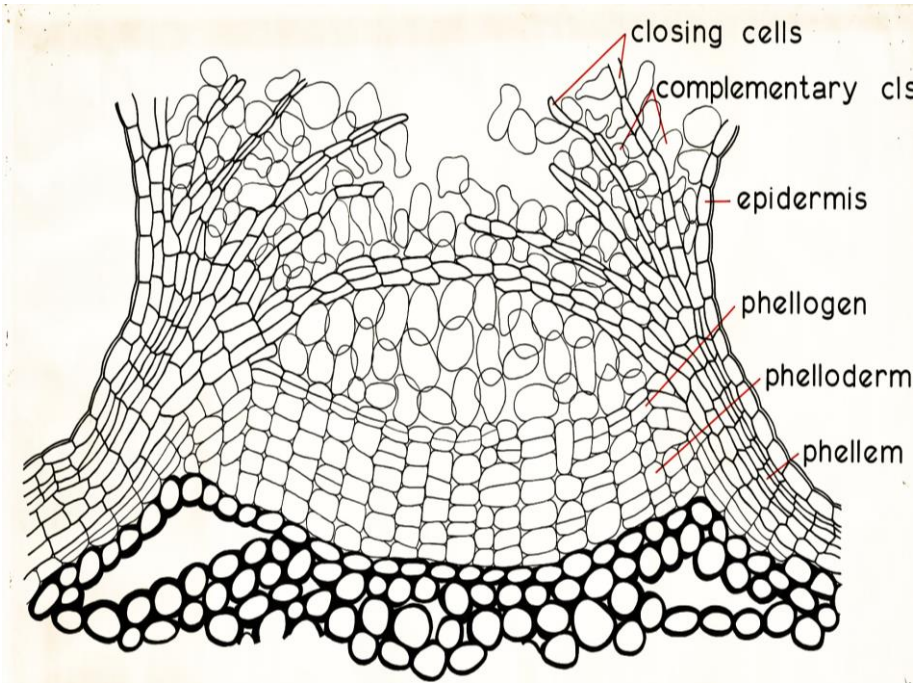
Stomata closure

1. Stomata closure can be triggered by water stress, high temperature, increasing carbon dioxide levels in the leaf mesophyll and low light intensity (night time)
2. The hormone abscisic acid (ABA) is secreted by plant cells when transpiration rate is high and soil water is low.
3. ABA binds to receptors at the cell membrane of the guard cells. This increase the permeability of calcium channels in the cell membrane. Calcium ions (Ca^+) enter into the guard cell. The influx of calcium ions also triggers the release of Ca^+ from the cell vacuole into the cytosol.
4. Potassium ions (K^+) move out of the guard cells into the subsidiary cells
5. In some plants (Cl^-)and certain organic ions e.g. malate ions also move out of the guard cells
6. The water potential in the guard cells increase. Water diffuses out to neighbouring subsidiary cells by osmosis. The turgor pressure in the guard cells decreases, the cells become flaccid and the stoma closes.
7. At night the chloroplasts in the guard cells do not photosynthesise, less ATP is produced and there's no active uptake of K^+ ions. Instead, the K^+ ions diffuse out of the guard cells. The cells become flaccid and the stoma closes.

LENTICELS

A small amount of gaseous exchange takes place in the stem through structures called lenticels. The small gaps in the stem, usually circular or oval slightly raised on the bark surface. The cells in this area are thin walled and loosely parked, leaving air spaces which communicate with air spaces in the cortex. Here oxygen for respiration is taken up and carbon dioxide is given out.

Structure of the lenticel



ROOT EPIDERMAL CELLS

Root cells can also take in oxygen for respiration and give out carbon dioxide. Gaseous exchange takes place by diffusion between the epidermal cells of roots and the air spaces in the soil. Most of the exchange takes place at the root hairs which provide a large surface area.

Water logged soils have their air spaces occupied by water, thereby reducing respiration in the roots which may subsequently die. This would obviously kill the whole plant.

Some aquatic plants, like pond weeks and multi cellular algae are completely submerged in water. These obtain their gaseous requirements by diffusion from the surrounding water. Epidermal cells of such plants have no cuticle and gasses diffuse directly across it.

Others like rice and water lilies are partially submerged in water. Their aerial parts obtain carbon dioxide and oxygen in the same manner as terrestrial plants. The submerged parts may face the problems of obtaining adequate oxygen for their respiratory requirement. However such plants have large air spaces in their stems and roots which store oxygen obtained from the aerial parts and that formed during photosynthesis. Floating leaves of such plants have stomata on the upper surfaces only.

In swampy environments, root systems give rise to breathing roots or pneumatophores. These grow out of the water and op into the air. Oxygen diffuses into them and aerates the submerged parts of the root system.

EXPERIMENT TO OBSERVE STOMATA

Obtain a leaf a leaf of comelina. Hold it in such a way that the lower surface is facing you. Slowly tear the leaf as you would tear a piece of paper by moving the right hand towards the body. This produces a thin, transparent membrane-like tissue along the edge of the tear on the part of the leaf in the left hand. This is the lower epidermis. Using forceps, remove a small section of the epidermis and mount it in a drop of water on a slide and cover it with a cover slip. Observe under low power and then under the high power of a microscope. Identify the guard cells and the normal epidermal cells. Observe a closed stoma and an open stoma under low and high power. Draw each of these.

WATER UPTAKE BY THE ROOTS

Internal structure of the root

The root consists of various tissues which occur in concentric layers. The cells at the surface of the young root forming the peliferous layer are so called because it is by the root hairs. As the roots get older, they increase in girth (thickness or diameter) and the peliferous layer (breaks) raptures and peels off leaving the outer most layer of cells known as epiblem, to become the functional outer layer.

Next to the epiblem is the thicker layer of loosely packed parenchyma cells, known as cortex. Adjacent to the cortex is a layer of cells known as endodermis.

The endodermal cells have their radial and horizontal walls coated with a corky band called **casparian strip.** This strip is made up of a substance called **suberin**. The Casparian strip is impermeable to water and solutes due to the suberin that it contains and therefore prevents water and solutes to pass through the cell walls to the endodermis. The endodermis also contains starch grains.

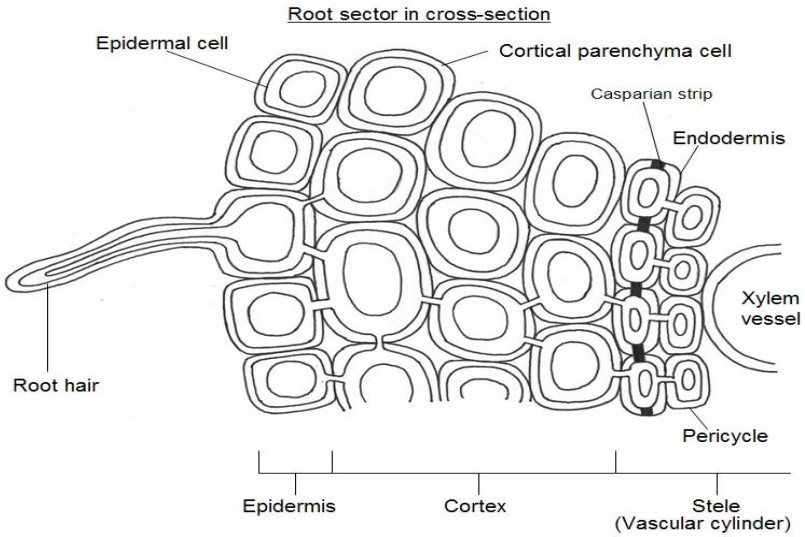
Next to the endodermis is another layer of cells known as **pericycle** from which lateral roots develop. The pericycle, that is made up of parenchyma cells which encloses the vascular bundles (xylem and phloem) in the centre of the root.

Diagram showing the internal structure of the root

(Toole fig 22.13a pg 462)

(Toole fig 22.13b pg 462)

Longitudinal section through a root



Mechanism of water uptake by the roots

For water to be transported up to the leaves through the stem, it must be absorbed from the soil by the tiny root hairs. Water absorption into the root hairs occurs by **osmosis**. This is due to the water potential of the cell sap of the root hairs being lower than that of the soil solution (water content).

When the root hair absorbs water, its water potential increases and becomes higher than that of the adjacent cells of the root. This facilitates the flow of water from the root hairs to the endodermal cells across a water potential gradient.

The water flow is also due to the root pressure developed by the cell cortex and endodermis which ensures that water flows from the root hairs to the xylem vessels and upwards to the leaves.

Water flows by osmosis form the root hairs to the endodermal cells using three pathways, namely;

a) Apoplast (cell wall) pathway
b) Symplast (cytoplasm) pathway
c) Vacuolar pathway

Apoplast pathway

This is the pathway in which water moves through the spaces between the cellulose fibres in the cell wall of one cell to the cell wall of the adjacent cells.

However, this movement does not occur within the endodermal cells because they possess the impermeable **casparian strip** which prevents water and solutes flow through the cell walls of the endodermal cells. This means that water and solutes flow through the cell walls of the endodermal cells via the Symplast and the vacuolar pathways only.

The significance of this casparian strip is to actively pump salts (ions) from the cytoplasm to the endodermal cells into the xylem vessels which creates a high solute concentration in the xylem, thereby greatly lowering the water potential in the xylem than in the endodermis. This makes the water potential of the xylem vessels more negative (very low) and results into

rapid osmotic flow of water from the endodermal cells to the xylem vessels, due to the steep water potential gradient between the endodermal cells and the xylem vessels.

The casparian strip facilitates the pushing of water upwards through the xylem vessels by root pressure up to the leaves due to its active pumping of the salts. In addition, this active pumping of the salts into the xylem vessels prevents leakage of slats (ions) out of the xylem vessels so as to maintain a low water potential in this vessel.

Symplast pathway

This is the movement of water through the cytoplasm of one cell to the cytoplasm of the adjacent cell via plasmodesmata.

Water leaving the pericycle cells to enter the xylem causes the water potential of these cells to become more negative (more dilute). This facilitates the flow of water by osmosis from the adjacent cells into these cells. In this way the water potential gradient from the root hairs to the xylem is established and maintained across the root. This pathway offers a significant resistance to the flow of water unlike the apoplast pathway.

Vacuolar pathway

This is the movement of water from the sap vacuole of one cell to the sap vacuole of the adjacent cell following a water potential gradient.

This is achieved by maintaining a steep water potential gradient. However, this also offers a reasonable level of resistance towards water flow in comparison to the Symplast pathway.

Note; the apoplast is the most appropriate pathway in plants because it provides less resistance to water flow in the plant.

Diagram showing the three pathways of water in the root

(Soper fig 13.18a pg 448)

To ensure maximum absorption of water, the root hairs have the following **adaptations**

a. They are numerous in number so as to provide a large surface area for the maximum absorption of water by osmosis.
b. They are slender and flexible for easy penetration between the soil particles so as to absorb water.
c. The lack a cuticle and this enhances the passive osmotic absorption of water without any resistance
d. They have a thin and permeable membrane which allows the absorption of water by osmosis.
e. They have a water potential lower than that of the soil solution which facilitates a net osmotic flow of water from the soil

ROOT PRESSURE

Root pressure is the force developed by cells of the roots which forces water from the endodermal cells into the xylem vessels of the root and constantly forces water upwards through the stem to leaves. This process is active and involves utilization of many ATP molecules. Root pressure occurs as a result of endodermal cells actively secreting salts into the xylem sap from their cytoplasm, which greatly lowers the water potential in the xylem.

In some plants, root pressure maybe large enough to force liquid water through pores called hydathodes of the leaves in a process called guttation

The following is the **evidence to support the mechanism of water uptake from the endodermis into the xylem vessel as an active process**

a. There are numerous starch grains in endodermal cells which could act as an energy source for active transport.

b. Lowering the temperature reduces the rate of water exudation (given out) from the cut stem as it prevents root pressure, an active process.

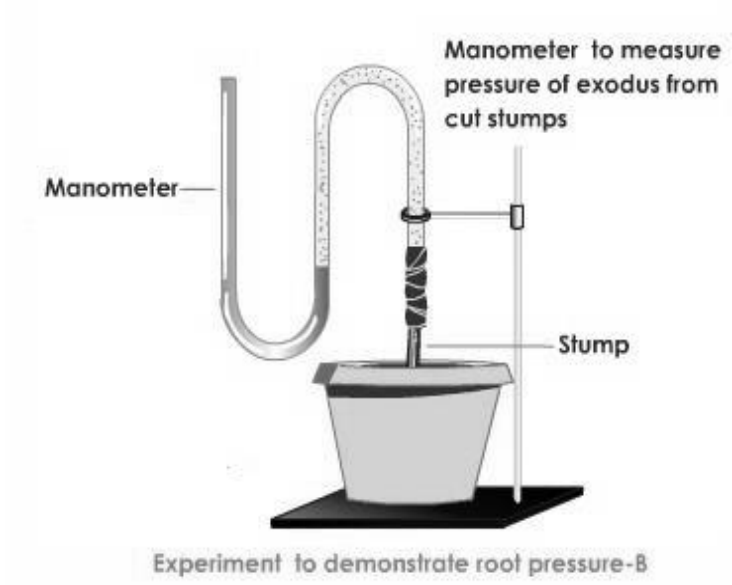
c. Treating the roots with metabolic poisons e.g. potassium cyanide also prevents water from being exuded from the cut stems. This is because the poisons kill the cells thereby preventing aerobic respiration, a source of ATP molecules.

d. Depriving roots of oxygen prevents water from being exuded from the cut stems. This shows that water was being pushed upwards in the cut stem by root pressure, an active pressure.

The following is **the evidence to show that water moves by pressure in a plant.**

When the stem of a plant is cut water continues to exude from the xylem vessels of the plant stem. The continuous exudation of water from the xylem vessels of the cut stem is due to root pressure because the leafy shoot is cut off, meaning that water not only moves upwards by transpiration pull, but also due to pressure and other forces.

Root pressure can be measured using a mercury manometer whose diagram is shown below



Experiment to demonstrate root pressure-B

Though it is true that water moves from the roots through the stem to the leaves by transpiration pull, root pressure partly contributes towards the movement of water from the **parenchyma cells** to the xylem of the root, to the stem and eventually up to the leaves.

THE UPTAKE OF WATER FROM THE ROOTS TO THE LEAVES

The movement of water from the roots to the leaves is by combination of different forces which include the following;

A. Root pressure
B. Transpiration pull(cohesion force)
C. Capillarity

Root pressure

This enables movement of water from the parenchyma cells of the main root into the xylem tissue due to the active pumping of cells from endodermal cells into the xylem tissue.

Root pressure also ensures upward movement of water through the xylem tissues to the leaves.

Transpiration pull (cohesive force/cohesion-tension theory of water uptake)

This offers an explanation for the continuous flow of water upwards through the xylem of the plant i.e. from the root xylem to the stem xylem and finally to the leaf xylem. Water is removed from the plant leaves by transpiration which creates a tension within the leaf xylem vessels that pulls water in the xylem tubes upwards in a single unbroken column or string held together by the cohesive forces of attraction between water molecules.

According to the cohesion-tension theory, evaporation of water from the mesophyll cells of the leaf to the sub-stomatal air chamber and eventually to the atmosphere via the stomata by transpiration, is responsible for the rising of water from the roots to the leaves. This is because the evaporated water molecules get replaced by neighbouring water molecules which in turn attract their other neighbours and this attraction continues until the root is reached.

Evaporation of water results in a reduced water potential in the cells next to the leaf xylem. Water therefore enters these mesophyll cells by osmosis from the xylem sap which has the higher water potential. Once in the mesophyll cells water moves using the three pathways namely; apoplast, Symplast and vacuolar pathways from one cell to another by osmosis across a water gradient.

When water leaves the leaf xylem to the mesophyll cells by osmosis, a tension is developed within the xylem tubes of water which is transmitted to the roots by cohesive forces of water molecules. The tension develops in the xylem vessels and builds up to a force capable of pulling the whole column of water molecules upwards by means of mass flow and water enters the base of these columns from neighbouring root cells. Because such a force is due to water loss by osmosis by transpiration, it is referred to as **transpiration pull.**

The upward movement of water through the xylem tissue from the roots to leaves is also facilitated by the **cohesive forces** of attraction which holds the water molecules firmly together, due to the hydrogen bonds which exist between them. This enables water to have a high tensile strength which enables it to move upwards in a continuous stream without breaking. In addition, the upward movement of water from roots to leaves is also facilitated by cohesive forces which hold the water molecules on the xylem walls so that it continues moving upwards.

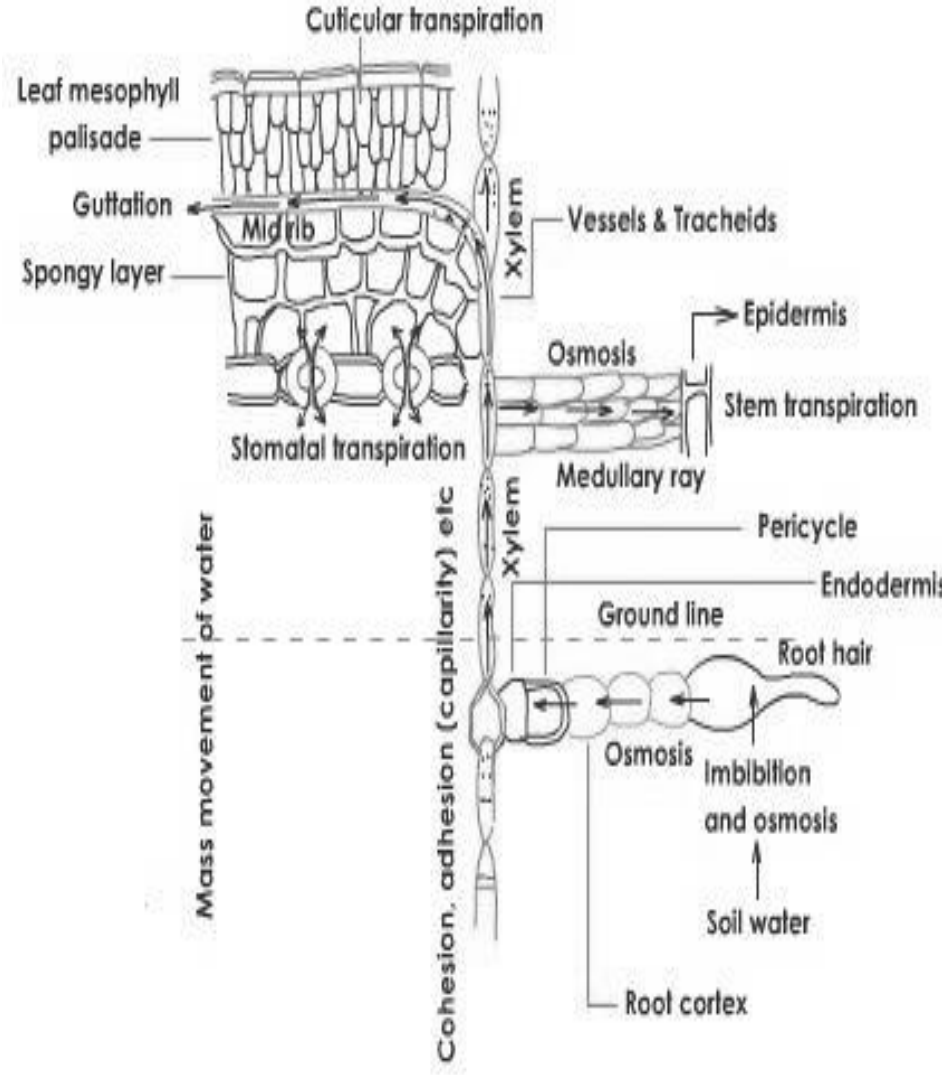
Capillarity

Since the water rises upwards through narrow leaves, it is also facilitated by capillarity through the stem. This is because the xylem vessels are too narrow and the flow of water is maintained without breaking by both the cohesive and adhesive forces.

NOTE

1. The continuous mass flow of water through the xylem vessels from the roots to the leaves in a stream without breaking, due to the transpiration pull is called the **transpiration string**
2. Adhesion is the force of attraction between molecules of different substances while cohesion is the force of attraction between molecules of the same substance

The diagram below shows the upward movement of water from the soil up to the leaves.



UPTAKE AND TRANSLOCATION OF MINERAL IONS

Translocation is the movement of mineral salts and chemical compounds within a plant.

There are two main processes of translocation which include;

a. The uptake of soluble minerals from the soil and their passage upwards from the roots to the various organs via the xylem tubes.
b. The transfer of organic compounds synthesized by the leaves both upwards and downwards to various organs via the phloem tubes

Mechanism of mineral ion uptake

Minerals such as nitrates, phosphates, sulphates e.t.c. may be absorbed either actively or passively.

1. Active absorption of minerals

Most minerals are absorbed from the soil solution having the less mineral concentration into the root hairs with the higher mineral concentration, selectively by using active transport which uses a lot of energy.

The rate of active absorption of minerals into the root hairs depends on the rate of root respiration. Factors such as oxygen supply and temperature will affect the rate of ion uptake. The addition of respiratory poison has shown to inhibit uptake of mineral ions.

(Soper Fig 13.19 pg 449)	(Soper Fig 13.20 pg 450)

2. Passive absorption

If the concentration of a mineral in a soil solution is greater than its concentration in the root hair cell, the mineral may enter the root hair cell by diffusion.

Mass flow or diffusion occurs once the minerals are absorbed by the root hairs so that they move along cell walls (apoplast pathway). In mass flow, the mineral ions are carried along in solution by water being pulled upwards in the plant in the transpiration stream, due to the transpiration pull i.e. the mineral ions dissolve in water and move within the water columns being pulled upwards.

The mineral ions can also move from one cell of the root to another against the concentration gradient by using energy inform of ATP.

The mineral ions can also move through the **Symplast pathway** i.e. from one cell cytoplasm to another. When the minerals reach the endodermis of the root, the Casparian strip prevents their further movement along the cell walls (**apoplast pathway).** Instead the mineral ions enter the cytoplasm of the cell (Symplast pathway) where they are mainly pumped by active transport into the xylem tissues and also by diffusion to the xylem tissues.

Once in the xylem, the minerals are carried up the plant by means of mass flow of the transpiration stream. From the xylem tissues, minerals reach the places where they are utilised called **sinks** by diffusion and active transport i.e. the minerals move laterally (sideways) through pits in the xylem tissue to the sinks by diffusion and active transport.

NOTE;

1. The following is the evidence to show that most mineral ions are absorbed actively by the root hairs

a. Increase in temperature around the plant increases the rate of mineral ion uptake from the soil as it increases respiration that can provide energy for active transport
b. Treating the root with respiratory inhibitors such as potassium cyanide prevents active mineral ion uptake leaving only absorption by diffusion. This is because the rate of mineral ion uptake greatly reduces when potassium cyanide is applied to the plant.
c. Depriving the root hairs of oxygen prevents active uptake of minerals by the roots and as a result very few ions enter the plant by diffusion.

2. The following is the evidence for supporting the role of the xylem in transporting minerals

a. The presence of mineral ions in the xylem sap i.e. many mineral ions have been found to be present in the xylem sap.
b. There's a similarity between the rate of mineral ion transport and the rate of transpiration i.e. if there's no transpiration, then there's no mineral ion transport and if transpiration increases, the rate of mineral ion transport also increases.
c. There's evidence that other solutes e.g. the dye, eosin, when applied to the plant roots, it is carried in the xylem vessels
d. By using radioactive tracers e.g. phosphorous-32. When a plant is grown into a culture solution containing radioactive phosphorous-32, phosphorous -32 is found to have reached all the xylem vessels but not the phloem tubes.
(The interpretation of these elements is that where lateral transfer of minerals can take place minerals pass from the xylem to the phloem and where lateral transfer is prevented, the transport of minerals takes place in the xylem)

NOTE; Some plants absorb mineral salts by using mutualistic associations between their roots and other organisms e.g. the association between the fungus and the higher plant roots called **mycorrrhiza**.

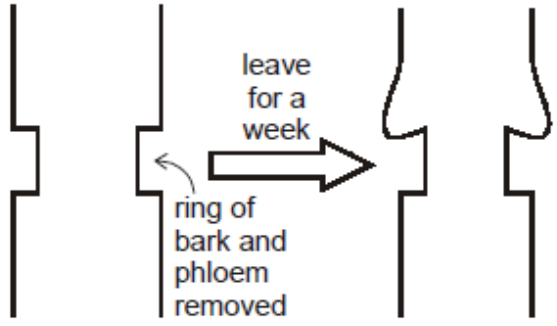
TRASLOCATION OF ORGANIC MOLECULES

(Food molecules in the phloem)

The organic materials produced as a result of photosynthesis; need to be transported to other regions of the plant where they are used for growth or storage. This movement takes place in the phloem tissue particularly in the sieve tubes.

Evidence to support that organic molecules of photosynthesis are transported in the phloem

a. When the phloem is cut, the sap which exudes out of it is rich in organic food materials especially sucrose and amino acids.
b. The sugar content of the phloem varies in relation to environmental conditions. When the conditions favor photosynthesis, the concentration of the sugar in the phloem increases and when they not favor photosynthesis and concentration of the sugar in the phloem reduces.



c. Removal of a complete ring of phloem around the phloem causes an accumulation of sugar around the ring, which results into the swelling of the stem above the ring. This indicates that the downward movement of the sugars has been interrupted and results into the part below the ring failing to grow and may dry out. This is called the **ringing experiment.**

d. The use of **radioactive tracers.** If radioactive carbon dioxide-14 is given to plants as a photosynthetic substrate, the sugars later found in the phloem contain carbon-14. When the phloem and the xylem are separated by waxed paper, the carbon-14 is found to be almost entirely in the phloem.
e. Aphids have needle like proboscis with which they penetrate the phloem so as to suck the sugars. If a feeding aphid is anaesthetized using carbon dioxide or any other chemical e.g. chloroform and then its mouth parts cut from the main body, some tiny tubes called the proboscis remain fixed within the phloem sieve tubes from which samples of the phloem content exudes.

When the contents of the phloem are analyzed, they are confirmed to be containing carbohydrates, amino acids, vitamins e.t.c. which further confirms that the phloem transports manufactured foods.
When small sections of the pierced stems are cut following the proboscis penetration, the tips of the proboscis are found within the phloem sieve tubes.

MECHANISM OF TRANSLOCATION IN THE PHLOEM

It was found out that organic materials do not move through the phloem sieve tubes by diffusion because the rate of flow of these materials is too fast for diffusion to be the cause. The mechanism of translocation of food in the phloem is explained by the following theories or hypothesis.

1. The mass flow or pressure flow hypothesis (i.e. Much's hypothesis)
2. Electro-osmosis
3. Cytoplasmic streaming

Mass flow or pressure flow hypothesis

Mass flow is the movement of large quantities of water and solutes in the same directions.

According to this theory, photosynthesis forms soluble carbohydrates like sucrose in the leaves. The photosynthesizing cells in the leaf therefore have their water potential lowered due to the accumulation of this sucrose. Sucrose is actively pumped into the phloem sieve cells of the leaf. As a result, water which has been transported up to the stem xylem enters these mesophyll cells by osmosis due to the accumulation of sucrose. This causes an increase in the pressure potential of the leaf cells including the leaf sieve tube elements more than that in the cells in **the sink** i.e. the mesophyll cells where the sugars are manufactured are referred to as **the source** while the other parts of the plant such as the roots where food is utilized are referred to as the sink.

The food solution in the sieve tubes then moves from a region of higher pressure potential in the leaves to that of lower pressure potential in the sink such as roots following a hydrostatic pressure gradient. At the other parts of the plant which form the sink e.g. the roots, sucrose is either being utilized as a respiratory substrate or it is being converted into insoluble starch for storage, after being actively removed from the sieve tubes and channeled into the tissues where they are required. The soluble content of the sink cells therefore is low and this gives them a higher water potential and consequently lower pressure potential exists between the source (leaves) and the sink such as roots and other tissues

The sink and the source are linked by the phloem sieve tubes and as a result the solution flows from the leaves to other tissues (sinks) along the sieve tube elements

A diagram showing movement of the products of photosynthesis by mass flow

(Toole fig 22.23 pg 470, Kent fig 2 pg 286)

Evidence supporting the mass flow theory

1. When the phloem is cut, the sap exudes out of it by mass flow
2. There's rapid and confirmed exudation of the phloem's sap from the cut mouth parts of the aphids which shows that the content of the sieve tubes move out at high pressure.
3. Most researchers have observed mass flow in microscopic sections of the sieve tube elements.
4. There's some evidence of concentration gradient of sucrose and other materials with high concentration in the leaves and lower concentration in the roots.
5. Any process that can reduce the rate of photosynthesis indirectly reduces the rate of translocation of food.
6. Certain viruses are removed from the phloem in the phloem translocation stream indicating that mass flow rather than diffusion, since the virus is incapable of locomotion.

Criticism of mass flow

1. By this method all organic solutes would be expected to move in the same direction and at the same speed. It was however observed that the organic solutes move in different directions and at different speeds.
2. The phloem has a relatively high rate of oxygen consumption which this theory does not explain.
3. When a metabolic poison such as potassium cyanide enters the phloem, the rate of translocation is greatly reduced, implying that translocation is not a passive process, but an active one.
4. The mass flow hypothesis does not mention any translocation of solutes with influence of transfer cells and Indole Acetic Acid (IAA) hormone that loads the sugars or solutes into the sieve tubes and also unload it into the cells of the sink.
5. The sieve plates offer a resistance which is greater than what could be overcome by the pressure potential of the phloem sap. This implies that the pressure would sweep away the sieve plates during this transport.
6. Higher pressure potential is required to squeeze the sap through the partially blocked pores in the sieve plates than the pressure which has been found in the sieve tubes

NOTE: the mass flow theory is considered to be the most probable theory in conjunction with electro-osmosis

Electro-Osmosis

This is the passage of water across a charged membrane.

(Clegg fig 16.39b pg341)

This membrane is charged because positively charged ions e.g. K^+ ,actively pumped by the companion cells across the sieve plate into the sieve tube element using energy from ATP of the companion cells.

Potassium ions accumulate on the upper side of the sieve plate thereby making it positively charged. Negatively charged ions accumulate on the lower sides of the sieve plate thereby making it negatively charged. The positive potential above the sieve plate is further increased by hydrogen ions, actively pumped from the wall to the upper sieve tube element into its cytoplasm.

Organic solutes such as sucrose are transported across the sieve plates due to an electrical potential difference between the upper and the lower side of the sieve plate whereby the lower side is more negative than the upper side i.e. solutes move from the upper sieve tube element which is positively charged to the lower sieve element which is negatively charged.

The electrical potential difference is maintained across the plate by active pumping of positive ions, mainly potassium ions, in an upward direction. The energy used is produced by the companion cells.

The movement of K^+ ions through the pores of the sieve plates rapidly draws molecules of water and dissolved solutes through the sieve pores, to enter the lower cell.

Evidence to support the electro-osmosis theory

1. K^+ ions stimulate the loading of the phloem in the leaves with sugars during photosynthesis.
2. Numerous mitochondria produce a lot of energy for translocation, an indicator that translocation is an active process. If however, the phloem tissues are treated with a metabolic poison, the rate of translocation reduces.

Cytoplasmic streaming theory

This suggests that the protoplasm circulates using energy from sieve tubes elements or companion cells through the sieve tube elements from cell to cell via the sieve pores of the sieve plates.

As the protoplasm circulates, it carries the whole range of the transported organic materials with it. The solutes are moved in both directions along the trans-cellular strands by peristaltic waves of contraction, such that they move from one sieve tube element to another using energy in from of ATP. The proteins in the strands contract in a wave form, pushing the solutes from one sieve tube element to another, using energy in form of ATP.

Diagram showing Cytoplasmic streaming

(Kent fig 3 pg 287)

Evidence supporting the cytoplasmic streaming theory

1. It has been found that the solute materials move in both directions in the phloem tissue
2. The theory explains the existence of the trans-cellular strands in the phloem tissue as well as many mitochondria in the companion cells
3. Presence of a sieve plate where a potential difference can be developed across the plate

Criticism of the Cytoplasmic Streaming Theory

1. Cytoplasmic streaming has not been reported in mature sieve tube elements but only in young sieve tubes.
   The rate at which the protoplasm streams is far slower than the rate of translocation

TRANSPORT IN ANIMALS

Many materials including oxygen, carbon dioxide, soluble food substances, hormones, urea e.t.c. need to be transported from one point to another using a transport network and medium.

The transport system in animals is mainly made up of blood vessels consisting of blood as the medium circulating through them to the various body tissues. The transport system is also made up of the pump i.e. the heart which brings about circulation of blood throughout the body, by pumping it. The transport system is also composed of the lymph vessels containing the lymph fluid.

The larger, compact and more active an organism is, the more the need for a transport system due to a small surface area to volume ratio which reduces the rate of diffusion of materials from the body surface to the cells in the middle of the organism. There are however some organisms which lack the transport system e.g. protozoa and platyhelmithes e.t.c. This is because,

being small in size and being flattened in shape gives these animals a large surface area to volume ratio, this enables free and rapid diffusion of materials from one part of the body to another. Consequently large multi-cellular organisms have an elaborate transport system that carries useful substances such as oxygen and glucose to the cells and carries away the waste products of metabolism. An elaborate transport system has two major features;

i. An increased surface area of the sites of exchange of materials. Such sites include the lungs and the gills where oxygen is absorbed and the villi of the ileum where food nutrients are absorbed along the alimentary canal.
ii. A system whereby the circulating medium carries the absorbed substances at a faster rate than diffusion. In some organisms with a blood circulating system, blood flow is not confined to blood vessels but instead it flows within a blood filled cavity called ***Haemocoel*** e.g. in arthropods and molluscs. In other organisms with the blood circulatory system, blood flow is confined to blood vessels only e.g. in vertebrates and some invertebrates such as the earth worm.

IMPORTANCES OF A BLOOD CIRCULATORY SYSTEM (FUNCTIONS OF BLOOD)

1. **Tissue respiration.** It enhances the formation of energy in the tissues by transporting oxygen and soluble food substances to the tissues to be used as raw materials for respiration. Carbon dioxide is also transported away from the tissues mainly in the form of bicarbonate ions (HCO_3^-) as a by-product of respiration and then taken to the lungs for its removal from the body. Oxygen is transported in the form of oxyhaemoglobin from the respiratory surfaces to the tissues.
2. **Hydration.** Blood transports water from the gut to all tissues.
3. **Nutrition.** Blood transports the soluble well digested food materials from the gut to the body tissues.
4. **Excretion.** Blood transports metabolic waste products from the tissues to the excretory organs for their removal from the body e.g. blood transports urea from the liver to the kidney in order for it to be removed from the body.
5. **Temperature regulation.** Blood distributes heat from the organs where it is mainly generated e.g. the liver and the muscles, uniformly throughout the body.
6. **Maintenance of constant pH.**Blood maintains a constant pH through the maintenance of circulation of the plasma proteins manufactured by the liver which act as buffers to maintain the pH of the body fluids constant. This enables enzymes to function efficiently as charges will denature the enzyme.
7. **Growth, development and co-ordination.** Blood transport different metabolites such as glucose, amino acids and hormones needed for the growth and development of the body.
8. **Defence.** Blood defends the body against diseases through the following ways;
   a. By using some white blood cells (leucocytes) which phagocytotically ingest and destroy pathogens that cause diseases.
   b. By formation of a blood clot around the wound so as to prevent entry of microbes or pathogens into the body.
   c. By use of the immune response mechanism towards infection e.g. by use of the different types of antibodies to destroy the microbes.

BLOOD

This is a highly specialized fluid tissue which consists of different types of cells suspended in a pale yellow fluid known as the **blood plasma**

BLOOD PLASMA

This is a pale yellow fluid component of blood composed of the plasma proteins and blood serum where the blood cells are suspended. Blood plasma carries the biggest percentage of blood and consists of a colourless fluid known as **serum** and also plasma proteins. It is the blood serum that all the different soluble materials are dissolved e.g. urea, hormones, soluble food substances, bicarbonate ions e.t.c.

The plasma proteins are manufactured by the liver and include the following;

a. Fibrinogen. This protein is important for normal blood clotting by changing into fibrin in the presence of thrombin enzyme.

Fibrinogen (soluble) ⟶ Fibrin (insoluble)

b. Prothrombin. This is the inactive form of the proteoltyic enzyme, thrombin, used in converting fibrinogen to fibrin during the clotting of blood.

c. Globulin. Both Prothrombin and globulin play important roles in the homeostasis. All the plasma proteins maintain pH of the body fluids constant by acting as buffers.

d. Blood cells. There are three main types of blood cells which include;

- Erythrocytes (Red blood cells)
- Leucocytes (White blood cells)
- Platelets

ERYTHROCYTES (Red blood cells)

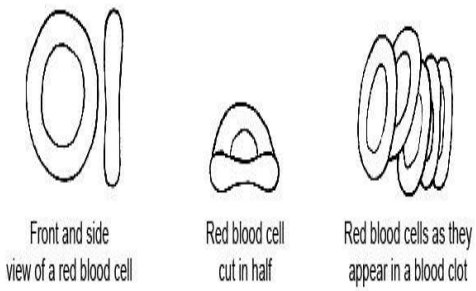
These are small numerous bi-concave disc shaped cells mainly important in transportation of oxygen as oxyhaemoglobin from the respiratory surfaces e.g. lungs and gives it to the tissues. Erythrocytes are manufactured by the bone marrow in adult and by the liver in the foetus.

Adaptations of erythrocytes

i. They have a bi-concave disc shape which provides a large surface area that enhances maximum diffusion of enough oxygen into them.
ii. They have a pliable membrane (flexible membrane) which can enable them change their original shape and squeeze themselves into the blood capillaries in order to allow the exchange of respiratory gases.
iii. They lack a nucleus so as to provide enough space for haemoglobin in order to carry a lot of oxygen in form of oxyhaemoglobin.
iv. They have a red pigment called haemoglobin in their cytoplasm which has a high affinity for oxygen and therefore rapidly transports oxygen.
v. They have a thin and permeable membrane which enables faster diffusion of oxygen and carbon dioxide into them.
vi. They have an enzyme known as carbonic anhydrase within their cytoplasm which enables most of the carbon dioxide to be transported in form of bicarbonate ions (HCO_3^-), by catalyzing the reactions between carbon dioxide and water to from carbonic acid.

$$CO_2 + H_2O \xrightarrow[\text{Carbonic anhydrase}]{} H_2CO_3$$

Diagram showing the shapes of erythrocytes



NOTE; Erythrocytes have a life span of 120 days.

LEUCOCYTES (white blood cells)

They are amoeboid cells having a nucleus and a colourless cytoplasm important for defense of the body against infections. They are fewer than erythrocytes i.e. they are about 7000/m^3 of blood. They are mainly manufactured by the bone marrow. They are classified into two main types which include;

Granulocytes (polymorphonuclear leucocytes)

These are leucocytes with granules in there cytoplasm and a lobed nucleus. They originate in bone marrow. There are three types of granular leucocytes which include;

i. Basophils (0.5%)
ii. Eosinophils (1.5%)
iii. Neutrophils (70%)

Basophils (0.5%) produce *heparin* and *histamine.* Heparin is an anti-coagulant which prevents blood clotting in blood vessels. Histamine is a substance that is released during allergic reactions e.g. hay fever. Histamine brings about allergic reactions by causing dilation (widening) and increased permeability of small blood vessels which results in such symptoms as itching,, localized swellings, sneezing, running nose, red eyes e.t.c.

Eosinophils (1.5%) possess anti-histamine properties and their number increases in people with allergic reactions such as high fever, asthma e.t.c. so as to combat the effects of histamine.

Neutrophils (phagocytes) (70%) engulf pathogens phagocytotically and digest them actively inside to defend the body against diseases.

Agranulocytes (mononuclear leucocytes)

These are leucocytes with no granules in there cytoplasm usually with a spherical or bean shaped nucleus. They originate in bone marrow and lymph nodes. They are divided into two types;

i. Monocytes (4%)
ii. Lymphocytes (24%)

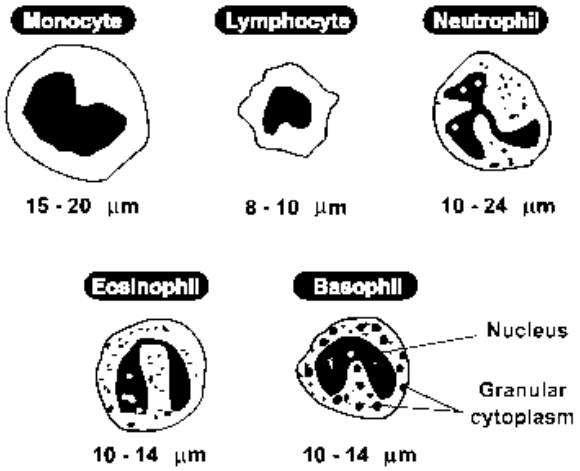
Monocytes (4%) are leucocytes which enter the tissues from which they develop into macrophages which carry out Phagocytosis to defend the body against pathogens.

They have a bean shaped nucleus.

Lymphocytes (24%) they are produced in the thymus gland and lymph nodes. The precursor cells of lymphocytes in the bone marrow form a tissue which is called the lymphoid tissue. Lymphocytes are usually round and they possess a small quantity of the cytoplasm. Lymphocytes produce antibodies, agglutins, lysins, opsonins and antitoxins.

Adaptations of white blood cells to their function

1. They do not have a fixed shape and hence the amoebic movements used to engulf pathogens.
2. They are larger than the pathogens
3. They are numerous
4. Some lymphocytes produce antibodies which attack pathogens
5. They have an irregular shaped nucleus which allows them to squeeze through the narrow capillaries
6. They have a sensitive cell surface membrane that detects micro organisms
7. They have enzymes in their cytoplasm to digest the engulfed micro organisms
8. They have a large nucleus which contains many genes for the control of antibody production.



- In adults they are produced and develop in the bone marrow and lymph glands while in embryos they are produced in the thymus gland, liver and spleen.
- They have a life span of 21 days

BLOOD PLATELETS (thrombocytes)

These are irregularly shaped, membrane bound cell fragments lacking the nuclei and are formed from the bone marrow cells. They are responsible for starting up the process of blood clotting. There are abound 250,000 blood platelets per mm^3 of blood.

TRANSPORT OF OXYGEN

The equation below shows how haemoglobin combines with oxygen.

$$Hb + 4O_2 \leftrightarrow HbO_8$$

As shown by the equation above, each haem group combines with one oxygen molecule and therefore 1 haemoglobin molecule carries four oxygen molecules.

HAEMOGLOBIN

Haemoglobin is a large and complex molecule that is composed of four polypeptide chains (therefore it has a quaternary structure) arranged around four haem groups. Two of the polypeptide chains are coiled to form α-helix, and this in turn is folded on itself into a roughly spherical shape, the other two chains are called β-chains due to unique primary structures in both types of chains. Various kinds of chemical bonds, together with electrostatic attraction, keep the folds of the chain together and maintain the shape of the molecule. Haemoglobin is an example of a conjugated protein: attached to the hydrophobic crevice of the polypeptide chain is a flat group of atoms, the prosthetic group, consisting of a central iron atom held by rings of nitrogen atoms, which are part of a large structure known as porphyrin rings. The prosthetic group is haem and it is to the iron atom in the middle of it that the oxygen molecule becomes attached. The presence of four haem groups means that a single molecule of haemoglobin can carry four molecules of oxygen. Haem belongs to a class of organic compounds known as the porphyrins.

Assignment;

a. Copy the extension on page 221 in Advanced biology by Michael Roberts and Monger

b. With the aid of a diagram, describe the structure of the haemoglobin molecule

c. How is haemoglobin adapted to its function

Oxygen tension and oxyhaemoglobin formation

The ability of erythrocytes to carry oxygen to the tissues is due to haemoglobin having a high affinity for oxygen i.e. it can readily combine with oxygen and becomes fully saturated with it at relatively low partial pressures of the gas. Partial pressure of a gas is the measure of the concentration of a gas expressed in Kilo Pascals (Kpa) or milimetres of mercury (mmHg)

The high affinity of haemoglobin for oxygen is measured experimentally by determining the percentage saturation of haemoglobin with oxygen. When the percentage saturation of blood with oxygen is plotted against the partial pressure of oxygen an ***S-shaped curve*** or ***sigmoid curve*** is obtained and this curve is called the **oxygen dissociation curve** which is shown below.

(Toole fig 21.3 pg 414 OR Kent fig 3 pg 129)

The curve indicates that a slight increase in the partial pressure of oxygen leads to a relatively sharp/steep increase in the percentage saturation of haemoglobin with oxygen. This indicates that haemoglobin has a high affinity for oxygen in that it readily combines with it and become saturated with it at low partial pressures of oxygen.

The S-shaped curve is due to the way in which haemoglobin binds to oxygen. The first molecule of oxygen combines with a haem group with difficulty and distorts the shape of the haemoglobin molecule during the process. The remaining three haem groups bind with three oxygen molecules more quickly than the first one which increases rapidly the percentage saturation of haemoglobin with oxygen.

When oxyhaemoglobin is exposed to regions where the partial pressure of oxygen is low, e.g. in the respiring tissues, the first oxygen molecule is released easily and faster but the last one is released less readily with a lot of difficulty and least readily.

The steep part of the curve corresponds to the range of oxygen partial pressures found in the tissues. Beyond this part of the curve, any small drop in oxygen partial pressure results into a relatively large decrease in the percentage saturation of blood due to the dissociation of oxyhaemoglobin to release oxygen to the tissues. Beyond this part of the curve any small drop in the oxygen partial pressure results into a relatively large decrease in the percentage saturation of blood with oxygen, due to the dissociation of oxyhaemoglobin to release oxygen to the tissues.

In conclusion, the curve indicates that haemoglobin has a high affinity for oxygen where the oxygen tension is high e.g. in the alveolar capillary of the lungs. However, the affinity of haemoglobin for oxygen is lower where the oxygen tension is low and instead it dissociates to release oxygen e.g. in the blood capillaries serving blood to respiring tissues.

Note; animals which burrow into oxygen-deficient mud have haemoglobin which has a high affinity for oxygen. The oxygen dissociation curve for the lugworm is therefore situated to the left of human blood.

The oxygen supply can be distributed according to the requirements of different times, with skeletal muscles getting more during exercise or the intestinal tract more during digestion. Of particular importance is the constant flow of blood to the brain. For example, falling during fainting actually prevents serious damage to the brain cells as a result of inadequate blood supply. (These responses are often thwarted by well-meaning bystanders anxious to get the affected individual 'back on his feet'. In fact, holding a fainting person upright can lead to severe shock and even death).

Effect of carbon dioxide on the oxygen dissociation curve (Bohr's effect)

Within tissues there is a high concentration of carbon dioxide produced during aerobic respiration

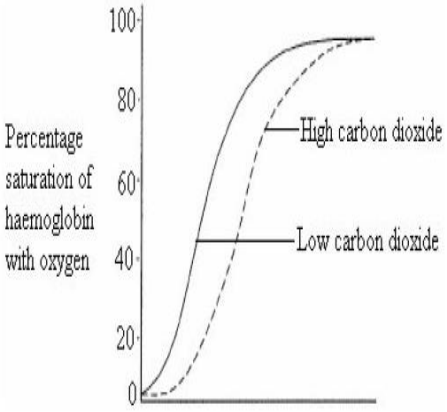
$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$$

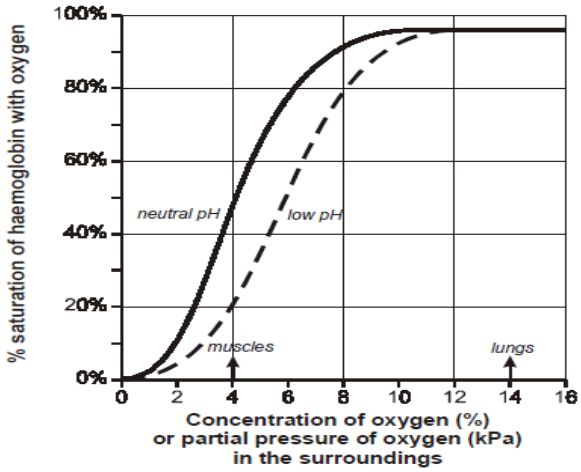
Increase in carbon dioxide concentration decreases the affinity of haemoglobin for oxygen, by making the pH of the surrounding medium more acidic (low), thereby shifting the oxygen dissociation curve to the right. This shifting of the curve to the right is known as **Bohr's effect** i.e. the shifting of the oxygen dissociation curve to the right due to the increase in partial pressures of carbon dioxide which results into haemoglobin having a low affinity for oxygen and a high affinity for carbon dioxide.

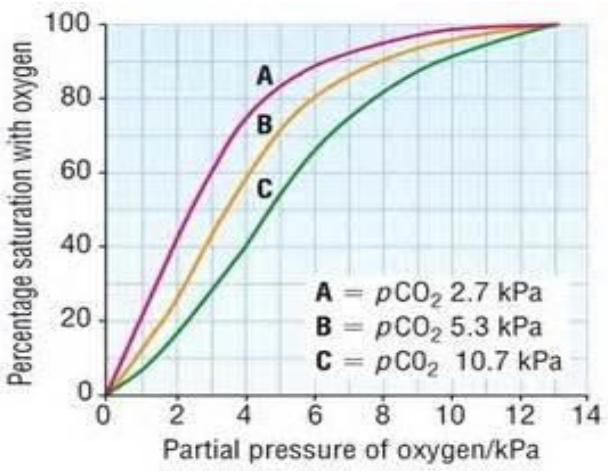
Bohr's effect may be defined as the lowering of the affinity of blood's haemoglobin for oxygen due to increased acidity caused by increase in carbon dioxide concentration.

From the dissociation curves below, shifting the oxygen dissociation curve to the left means that haemoglobin has a higher affinity for oxygen and therefore becomes fully saturated with oxygen it at very low partial pressures of oxygen. It also means that haemoglobin has a low rate of dissociation to release oxygen to the tissues but a high rate of combining with oxygen.

Shifting of the oxygen dissociation curve to the right means that haemoglobin has a lower affinity for oxygen and a higher rate of dissociation to release oxygen to the tissues rapidly to support tissue respiration







Effect of carbon monoxide on the affinity of haemoglobin for oxygen

There's a loose and reversible reaction between oxygen molecules and iron (II) atoms of haem groups of haemoglobin to from oxyhaemoglobin. This means that iron (II) is not oxidized to iron (III) as haemoglobin combines with oxygen.

In the presence of carbon monoxide and oxygen, haemoglobin combines readily with carbon monoxide to form a permanent compound known as **carboxyhaemoglobin**rather than combining with oxygen.

A permanent carboxyhaemoglobin compound is formed because carbon monoxide oxidizes iron (II) to iron (III). This reduces the free haemoglobin molecules available to transport oxygen molecules to the tissues, which makes the tissues develop symptoms of **anoxia** (total lack of oxygen in the tissues).

Therefore, carbon monoxide is referred to as a respiratory poison because it can readily combine with haemoglobin much more than oxygen and the product formed i.e. carboxyhaemoglobin does not dissociate.

Note; smokers have 10% of their total haemoglobin in form of carboxyhaemoglobin.

Myoglobin and other pigments

(Kent **f**ig 3 pg 131 OR Clegg fig 17.31 pg 360**)**

Myoglobin is a respiratory pigment which also contains iron containing haem groups mostly found in the muscles where it remains fully saturated at partial pressures below that required for haemoglobin to give up its oxygen.

Myoglobin has a higher affinity for oxygen than haemoglobin in a way that it combines readily with haemoglobin and it becomes fully saturated with oxygen at a lower partial pressure of oxygen.

Myoglobin acts as a store of oxygen in resting muscles in form of **oxymyoglobin** and only releases the oxygen it stores only when oxyhaemoglobin has been exhausted i.e. many vigorous activities because myoglobin has a higher affinity for oxygen than haemoglobin. The oxygen dissociation curves for myoglobin lies to the left of that of haemoglobin as shown in the graph

Note;

i. High affinity refers to low rate of dissociation to release oxygen and a higher rate of association of haemoglobin with oxygen.
ii. Low affinity refers to higher rate of dissociation to release oxygen and a lower rate of association of haemoglobin with oxygen.
iii. There are other respiratory pigments mostly found in the lower animals which include **haemocyanin** which consists of copper and mostly found in some snails and crustaceans
iv. Other pigments include**haemocrythrin** which contains iron and is also found in some in annelids
v. **Chlorocruorin**which also contains iron is also found in some annelids.
vi.

Comparison between the oxygen dissociation curve for Lugworms' haemoglobin and that of Man

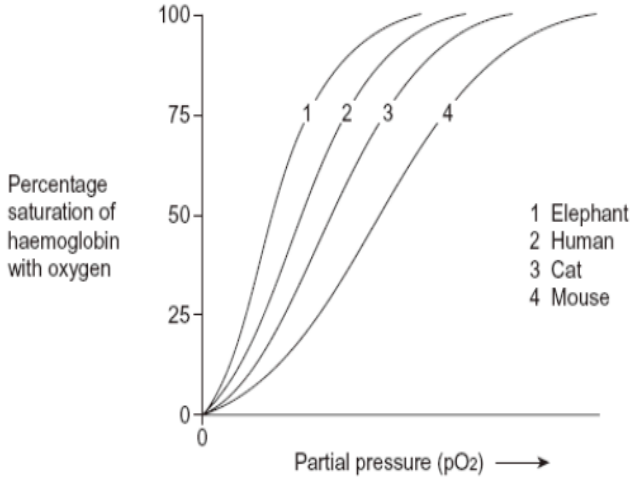
(Clegg fig 17.32 pg 360 OR Toole fig 21.5 pg 416)

The oxygen dissociation curve of the lugworm's haemoglobin lies on the left of that of man's haemoglobin as shown in the graph besides;

This indicates that the haemoglobin of the lugworm has a higher affinity for oxygen than that of man. This is because the lugworm lives in oxygen deficient mud and so in order to extract enough oxygen from that environment of low oxygen tension, the haemoglobin of the lugworm must have a higher affinity for oxygen than that of man thriving in a well supplied environment with oxygen.

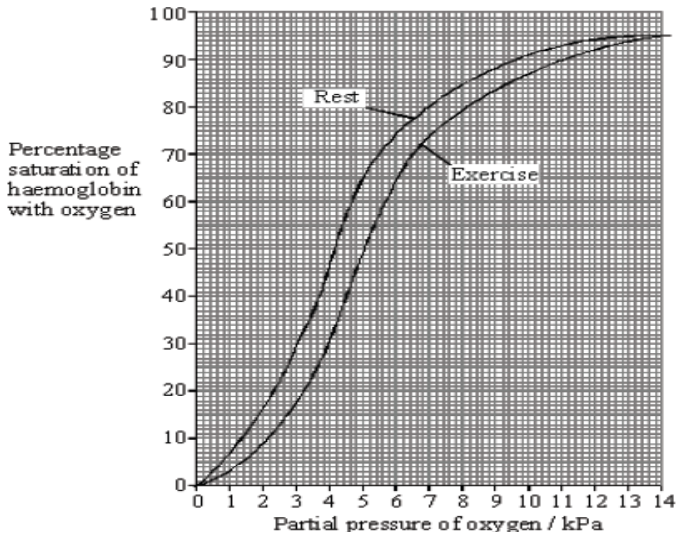
This implies that the lugworm's haemoglobin dissociates to release oxygen to its tissues compared to that of man which makes the lugworm less active than man, who releases much oxygen rapidly to the tissues.

Comparison between the oxygen dissociation curves of different sized mammals



Small animals have higher metabolic rates and so need more oxygen per gram of tissue than larger animals. Therefore they have blood that gives up oxygen more readily i.e. their dissociation curves are on the right of the larger animals

Comparison between the oxygen dissociation curves at rest and during exercise



During exercise, the oxyhaemoglobin releases oxygen more readily hence the oxygen dissociation curve during exercise is to the right of that when the individual is at the right of the curve when at rest.

P 53(

Comparison between the oxygen dissociation curve of maternal haemoglobin and that of the foetal haemoglobin

The oxygen dissociation curve of foetal haemoglobin lies to the left of maternal haemoglobin as shown in the diagram besides;

This indicates that the foetal hemoglobin has a higher affinity for oxygen than that of the mother. This enables the foetal haemoglobin to pick sufficient oxygen from the mother via the placenta and also increases on the oxygen carrying capacity to the tissues, especially when the foetus needs a lot of energy.

It also increases on the oxygen carrying capacity to the tissues of the foetus in the situation whereby deoxygenated and oxygenated blood are mixed due to the bypasses of ductus arteriosus and foramen ovale in the foetus.

(Clegg fig 17.36 pg 363 OR Toole fig 21.7 pg 416 OR Soper fig 14.32 pg 481)

Effect of changing altitude on oxygen carriage

There is a decrease in the partial pressure of oxygen in the atmosphere with increase in altitude from sea level. Therefore the volume of oxygen is less at high altitudes than at sea level. When an organism moves from the sea level to high altitudes, very fast, such an organism tends to develop symptoms of anoxia (lack of oxygen) which include headache, fatigue, nausea, and becoming unconscious.

However, when an organism moves slowly from sea level to high altitudes like the mountain climbers, such an organism can at first develop symptoms of anoxia but later on such symptoms disappear due to adjustments in the respiratory and circulatory systems in response to insufficient oxygen reaching the tissues from the surrounding.

The amount of haemoglobin and the red blood cell count increases together with the rate of breathing and the heart beat. More red blood cell formation occurs in the bone marrow under the control of the hormone called *erythropoietin* secreted by the kidney. Secretion of erythropoietin is stimulated by lower oxygen tension in the tissues. Increase in the amount of haemoglobin and red blood cells together with increase in the breathing rate and heart beat increases the oxygen carrying capacity of the blood to the tissues which leads to the disappearance of the symptoms of anoxia and which also makes the individual organism to be acclimatized. Acclimatization is therefore a condition whereby an organism carries out a series of physiological adjustments in moving from a low altitude area to a high one to avoid symptoms of anoxia so that such an organism can survive in an environment of low oxygen content.

The graphs below show the oxygen dissociation curves of people living at sea level and at high altitude

(Clegg fig 17.37 pg 363 OR Toole fig 21.4 pg 415 OR Soper fig 14.31 pg 481 OR Simpkins fig 8.19 pg 145)

The mammals that live in regions of the world beyond the sea level e.g. mountains solve the problem of lack of enough oxygen in the atmosphere by possessing haemoglobin with a higher affinity for oxygen than that of mammals at sea level. This enables the high altitude mammals to obtain enough oxygen through the oxygen deficient environment e.g. the llama. This explain why the oxygen dissociation curve of the haemoglobin of the llama lies to the left of that of other mammals at sea level e.g. the horse as shown in the diagram besides

Describe the acclimation changes undergone by humans at high altitudes

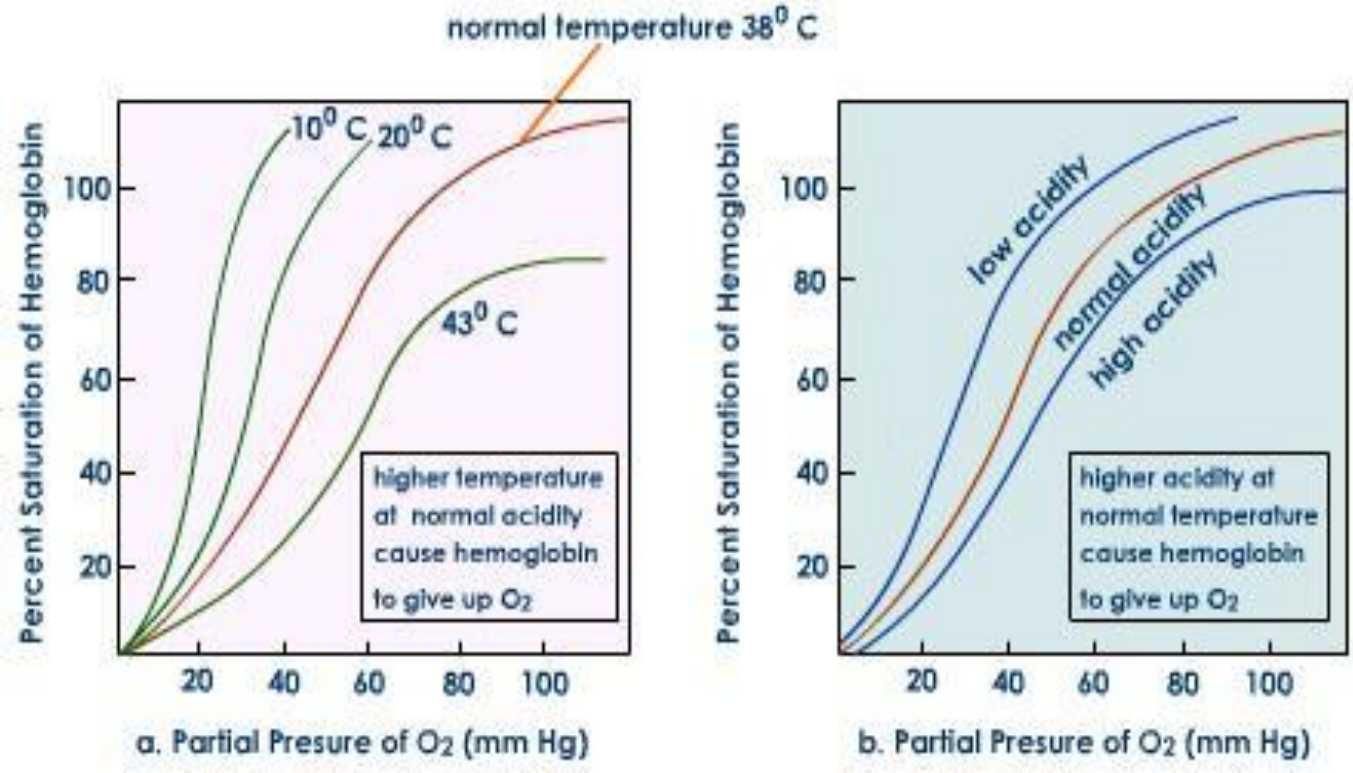
Describe the adaptations of diving mammals

Effect of temperature on haemoglobin oxygen dissociation curve

A rise in temperature lowers the affinity of haemoglobin for oxygen thus causing unloading from the pigment i.e. a rise in temperature increases the rate of dissociation of oxyhaemoglobin to release oxygen to the tissues.

Increased tissue respiration which occurs in the skeletal muscles during exercise generates heat. The subsequent rise in temperature causes the release of extra oxygen from the blood to the tissues. This is so because increase in temperature makes the bonds which combine haemoglobin with oxygen to break, resulting into the dissociation of oxyhaemoglobin.

Oxygen dissociation curve for haemoglobin at different temperatures



TRANSPORT OF CARBON DIOXIDE

Carbon dioxide is transported from the body tissues mainly inform of bi-carbonate ions in blood plasma to the lungs for removal.

Although carbon dioxide is mainly transported inform of bi-carbonate ions i.e. 85%, carbon dioxide can also be transported in the following ways;

a. About 5% of carbon dioxide is transported in solution form. Most of the carbon dioxide carried in this way is transported in physical solution. A very small amount is carried as carbonic acid. In the absence of haemoglobin, the plasma proteins buffer the hydrogen ions to form weak proteionic acids.
b. About 10% of carbon dioxide combines with the amino group of haemoglobin to form a neutral compound known as **carbamino haemoglobin ($HbCO_2$).**If less oxygen is being carried by haemoglobin molecule, then more carbon dioxide is carried in this way as $HbCO_2$.

Transportation of carbon dioxide inform of hydrogen carbonate ions

When carbon dioxide is formed during respiration, it diffuses from the tissues into the erythrocytes, via their thin and permeable membrane. Inside the erythrocytes, carbon dioxide reacts with water in the presence of carbonic anhydrase enzyme to form carbonic acid as shown below;

$$H_2O_{(l)} + CO_{2(g)} \xrightarrow{\text{Carbonic anhydrase}} H_2CO_{3(aq)}$$

The formed carbonic acid then dissociates into hydrogen ions and bicarbonate ions as shown below

$$H_2CO_{3(aq)} \longrightarrow H^+ + HCO^-_{3(aq)}$$

The formed hydrogen ions decrease the pH in erythrocytes which results into the dissociation of oxyhaemoglobin being carried from the lungs to the tissues into the free haemoglobin molecules as free oxygen molecules.

$$HbO_8 \longrightarrow Hb + 4O_{2\,(g)}$$

The free oxygen molecules diffuse into the tissues to be used in respiration. The free haemoglobin molecules buffer the hydrogen ions (H^+) inside the red blood cells into a weak acid known as **haemoglobinic acid**

$$H^+ + Hb \longrightarrow HHb$$

In case of excess H^+ plasma proteins are used to buffer them into another weak acid called **proteinic acid.**

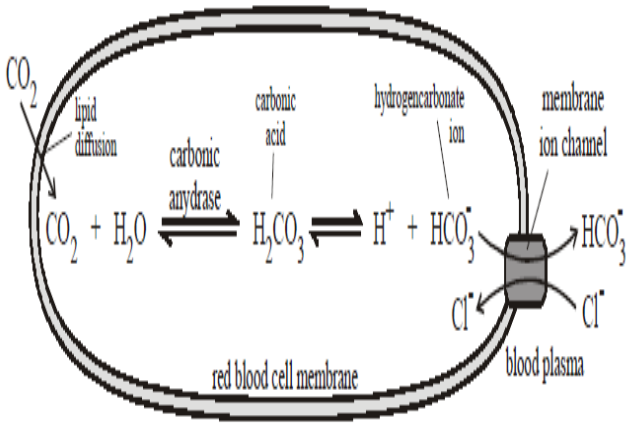
The formed hydrogen carbonate ions within the erythrocytes diffuse out into the plasma along the concentration gradient and combine with sodium to form sodium hydrogen carbonate which is then taken to the lungs.

The outward movement of bicarbonate ions from the erythrocytes into the plasma results into an imbalance of positively charged and negatively charged ions within the cytoplasm. In order to maintain electrochemical neutrality, to remove this imbalance in the red blood cells, chloride ions diffuse from the plasma into the red blood cells, a phenomenon known as the **chloride shift**

When the bicarbonate ions reach the lungs, they react with H^+ to form carbonic acid which eventually dissociates into carbon dioxide and water.

$$H^+ + HCO_3^- \longrightarrow H_2CO_3$$
$$H_2CO_3^- \longrightarrow H_2O + CO_2$$

The carbon dioxide and water formed from the dissociation of carbonic acid in the lung capillaries are then expelled out by the lungs during exhalation so as to maintain the blood pH constant



VASCULAR SYSTEMS IN ANIMALS

In animals, every vascular system has at least three distinct characteristics.

a. It has a circulating fluid e.g. blood
b. It has a pumping device inform of a modified blood vessel or a heart.
c. It has tubes through which the fluid can circulate e.g. blood vessels

Note; animals require a transport system because of;

- Surface area of the organism
- Surface area: volume ratio of the organism
- Activity of the organism
- The diffusion distance for the transported substances between the tissues to and from their sources.

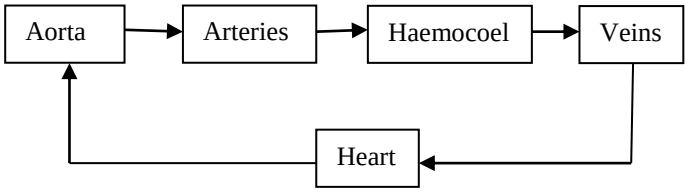
There are two types of vascular systems, the open vascular system and the closed vascular system.

Open vascular system

Open circulation is the flow of blood through the body cavities called **Haemocoel** instead of flowing in blood vessels. This exists in most arthropods, molluscs and tunicates.

In this system, blood is pumped by an aorta which branches into a number of arteries which open into the haemocoel. From the haemocoel, blood under low pressure moves slowly to the tissues where there's exchange of materials e.g. gases, nutrients e.t.c. from the haemocoel blood percolates back into the heart via the open ended veins.

In insects the haemocoel is divided into two parts by a transverse pericardial membrane forming a pericardial cavity dorsally and the ventral perivisceral cavity. In the body of the insects there are no blood vessels except the tubular heart which is suspended in the pericardial cavity by slender ligaments and extends through the thorax and abdomen. The heart is expanded in each segment to form a total of 13 small chambers which are pierced by a pair of tiny tubes called **ostia**. The ostia allow blood to flow from one segment of the chamber to another. Alary muscles are located at each chamber of the heart.



Transverse section through the insect's heart

(Clegg fig 17.5b pg 344

Mechanism of open circulation

Blood flows through the heart from the posterior end to the anterior end by waves of contractions (systole) which begin from the posterior end and proceed to the anterior end. These waves of contractions enable blood to flow through the heart and then enter the perivisceral cavity.

During systole, the heart ligaments are stretched with a result that during diastole they pull the heart walls outwards, thereby decreasing the pressure in the heart and increasing its volume. This results into sucking of blood into the heart via the ostia from the perivisceral cavity which has a higher pressure than the pericardial cavity. The back flow of blood is prevented by the valves found between the ostium.

During diastole, the alary muscles contract which increases the volume of the heart and reduces the pressure at the same time. The drop in pressure leads to movement of blood from the haemocoel through the ostia into the heart. Contraction of the alary muscles also has the effect of pulling the pericardial membrane downwards, thereby raising the blood pressure in the perivisceral cavity and decreasing it in the pericardial cavity, hence blood flows into the pericardial cavity. The heart chambers are equipped with valves which allow blood to enter, but not to leave, the heart through them.

Closed vascular system

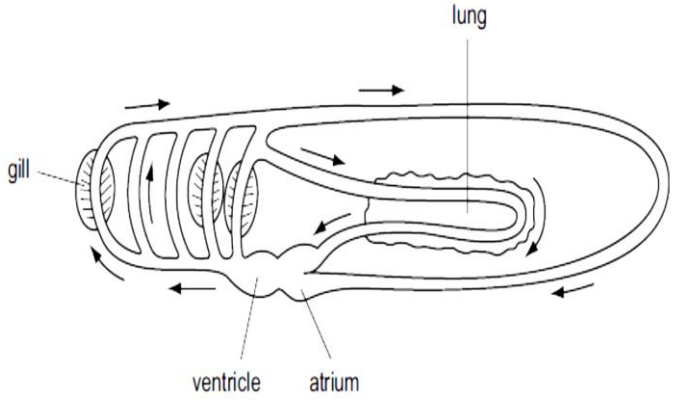
In a closed vascular system, blood flows in blood vessels or sinuses. It occurs in all vertebrates, annelids such as earthworms, cephalopods and echinoderms. The distribution of blood in this system is therefore adjustable e.g. blood from the heart is at high pressure and that to the heart is at low pressure. Closed vascular systems are further divided into single and double circulation.

A. Single and double circulation

Single circulation is the flow of blood through the heart once for every complete circulation around the body. Single circulation occurs in fish and the deoxygenated blood from the body tissues is pumped by the heart to the gills from where it flows back to the body tissues and eventually returns to the heart.

The problem of single circulation is that blood tends to move very slowly at the venous side due to the significant drop in pressure before completing the circulation. The drop in pressure is as a result of capillaries having a considerable resistance to blood flow i.e. capillaries in the gills and body tissues. The sluggishness of blood flow at the venous side is solved by replacing the veins with large sinuses which offers minimum resistance towards blood flow.

Diagram showing single circulation in fish



Vascular system of the earthworm (annelid)

The earthworm belongs to phylum annelida. Annelids are coelomate animals i.e. they have a body cavity that separates the muscular wall of the animal from the internal organs.

T.S of the annelid vascular system

Clegg fig 17.6 pg 344

The largest vessel is the longitudinal muscular-walled dorso vessel and it is above the alimentary canal (gut). The peristaltic contraction from the posterior end of the vessel drives blood forward to the anterior end of the animal. The backflow of blood is prevented by valves. Each valve originates from a fold of an internal membrane or tissue of any blood vessel that is called an endothelium.

The dorso vessel collects and receives blood from the body wall, the gut, the nerve cord and the nephridia via capillaries. The dorso vessel connects with the smaller more contractile ventral vessel via five pairs of contractile pseudo hearts.

Each pseudo heart has four valves which permit the blood to flow towards only the ventral vessel and back to the posterior end of the animal.

Between the ventral vessel and the organs in the coelom e.g. nephridia and gut, there are a series of segmented blood vessels which run between them and they end up forming capillaries where there is exchange of materials between the organs and the blood in the capillaries. From the capillaries, blood fills its way back to the dorso vessel for its flow to the anterior side due to the peristaltic movement of the dorso vessel.

The blood is red in colour with haemoglobin.

B. Double circulation

Double circulation is the flow of blood through the heart twice for every complete circulation around the body.

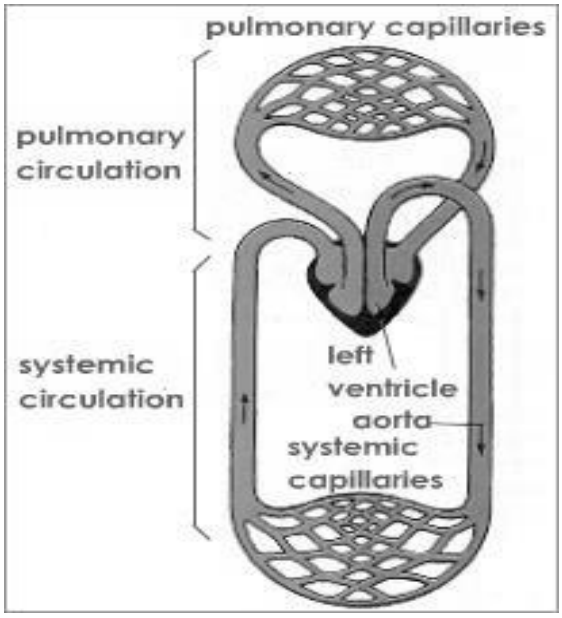
In double circulation deoxygenated blood from body tissues is pumped from the heart to the lungs from where it returns to the heart after being oxygenated and it is then re-pumped to the body tissues so as to supply oxygen to the body tissues. A double circulation serves as one of the solutions towards the sluggish flow of blood at the venous side in single circulation

In double circulation, the heart must be divided into the left and right chambers to prevent oxygenated blood from mixing with deoxygenated blood e.g. in reptiles, birds and mammals have a four chambered heart made up of the right atrium and ventricle and the left and atrium and ventricle.

The frog experiences double circulation although its heart has three chambers namely; one ventricle and the two atria i.e. the left and right atria. Both deoxygenated and oxygenated blood in the frog flow through the same ventricle and conus arteriosus at the same time without mixing. This is achieved due to the folding in the walls of the ventricle which enhances the separation of deoxygenated blood from oxygenated blood and this separation is also facilitated by the spinal valves in the conus arteriosus.

Some organisms e.g. the octopus and squids solve the problem of sluggish flow of blood of the venous side by possessing brachial hearts which pump deoxygenated blood from the body tissues of the gills and eventually back to the main heart. The main heart pumps, oxygenated blood to body tissues from the gills.

Diagram showing double circulation in a frog and a mammal



(Roberts fig 11.17 pg 175)

MAMMALIAN BLOOD CIRCULATION

The mammalian blood circulation is a double blood circulation which is mainly based on the heart and blood vessels,

BLOOD VESSELS

There are three main types of blood vessels; arteries, veins and capillaries. The walls of these blood vessels occur in three layers, namely;

a. Tunica externa (outer most layer)
b. Tunica media (middle layer)

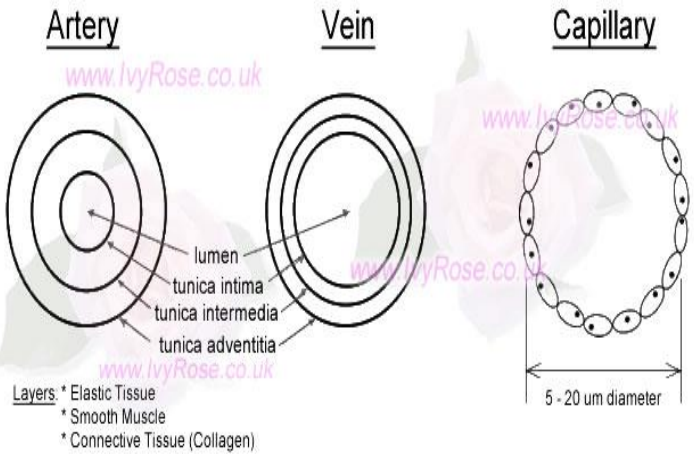
c. Tunica interna (inner most layer

Tunica externa, this is the outermost layer which is tough and made up of thick collagen fibres which provide strength and prevents extensive stretching.

Tunica media is the middle layer which consists of smooth muscles, collagen and elastic fibres. The structural proteins allow for the stretching of the walls of blood vessels during vaso-dilation. The smooth muscles allow for the distension and constriction of the walls of the blood vessels.

Tunica interna is the innermost layer composed of a single layer of squamous endothelium. It is found in all walls of blood vessels. Capillaries have only the tunica interna.

Diagrams showing the transverse sections of the vein, artery and capillary



Comparison between arteries and veins

Both tunica media and tunica externa are more developed in arteries than veins and therefore arteries have thicker walls than those of veins. Arteries have thicker walls than veins because blood flows through them at a higher pressure than in the veins, due to the pumping action of blood by the heart. Arteries therefore have thicker walls to counteract the pressure by which blood moves through them. The capillaries lack both the tunica externa and the tunica interna.

In addition the walls of the arteries are more elastic than those of veins, in order to overcome the pressure by which blood flows through them by rapidly stretching without bursting.

Also arteries have a narrower rumen than veins, which increases the pressure of the blood flowing through them.

Arteries also lack valves while veins haves valves which prevent the backflow of blood in veins. However, arteries do not need valves since they transport blood under high pressure, which pressure ensures that blood flows forward.

Blood in arteries moves inform of pulses while in veins is flows smoothly without any pulse. ***A pulse*** is a series of waves of dilation that pass along the arteries caused by the pressure of the blood pumped from the heart through contractions of the left ventricle.

Arteries transport oxygenated blood from the heart to the tissues except the pulmonary artery which transports deoxygenated blood from the heart to the lungs while veins transport deoxygenated blood from tissues to the heart except the pulmonary vein which transports oxygenated blood from the lungs to the heart. Therefore ***arteries*** can be defined as blood vessels which transport blood away from the heart and ***veins*** are defined as blood vessels which transport blood from the tissues to the heart.

Adaptations of blood capillaries

4. Blood capillaries are the smallest blood vessels found in close contact with tissues in form of a dense network which allows a high rate of diffusion of materials during their exchange between the blood circulatory system and the tissues.
5. They are numerous in number to provide a large surface area which increases the rate of diffusion and allows rapid exchange of materials between blood and the tissue fluid.
6. They have a thin and permeable membrane which is made up of thin flattened pavement cells which allow rapid diffusion and exchange of materials between blood and tissues with minimum resistance.

4. They possess the capillary sphincter muscles which contract and relax so as to regulate the amount of blood entering into the capillary network.
5. Some capillaries have a bypass arterio-venous shunt vessel which links the arterioles and venules directly so as to regulate the amount of blood which flows through the capillary network e.g. in the capillaries of the feet, hands, stomach e.t.c.
6. The capillary network offers maximum resistance to blood flowing through them hence decreasing the speed of blood flow which allows the maximum diffusion and exchange of materials between blood and the tissues.

Diagram showing the capillary network

Clegg fig 17.18 pg 353

THE MAMMALIAN HEART

Structure of the mammalian heart

The heart is the muscular organ pumping blood to all body organs using its chambers. It is made up of four chambers which include the right and left atria (auricles) and the right and left ventricles. The four chambers enhance the blood flow through the heart at the same time without mixing it i.e. deoxygenated blood is separated from oxygenated blood. The oxygenated blood flows through the left atrium and ventricle while the deoxygenated blood flows through the right atrium and ventricle.

Clegg fig 17.8 pg 347

The heart is composed of the **cardiac muscles** within its walls which are **myogenic** in nature, in a way that, the initiation of their contraction is not under the control of the central nervous system but is within the muscles themselves. This enables them to contract continuously and rhythmically without fatigue and therefore enables the heart to beat and pump without stopping.

The heart consists of atrioventricular valves/ pocket valves and semi lunar valves. The atrioventricular valves include the following;

a. The three (3) flapped tricuspid valves found between the right atrium and the right ventricle
b. The two (2) flapped bicuspid valves which prevent back flow of blood from the left ventricle to the left ventricle.

The semi lunar valves are prevented from turning inside out by connective tissues called **tendinous cords**

The heart linked with four blood vessels which include the following;

i. **The venacava** which transports deoxygenated blood from body tissues through the right atrium of the heart.
ii. **The pulmonary artery** which transports deoxygenated blood from the right ventricle of the heart to the lungs.
iii. **The pulmonary vein** which transports oxygenated blood from the lungs into the left atrium of the heart.
iv. **The aorta** which is the biggest vessel and it transports oxygenated blood from the left ventricle of the heart to the body tissues.

The left ventricle is more muscular (thicker) than the right ventricle because the left ventricle has to contract more powerfully than the right ventricle in order to enable oxygenated blood with high pressure to move for a long distance to the body tissues unlike the right ventricle which pumps deoxygenated blood with low pressure for a short distance to the lungs.

Initiation of the heart beat

The cardiac muscle within the walls of the heart is myogenic in nature in a way that the initiation of its contraction is within the muscle itself, but not under the control of the central nervous system (brain and spinal cord). This enables the muscles to contract continuously and rhythmically without fatigue to enable the heart to beat continuously and rhythmically without stopping. The intrinsic initiation of the heart beat enables the heart to remain beating even it is surgically removed from the body, provided it is under ideal conditions.

The rhythmic contraction of the cardiac muscles is initiated by specialized network of fine cardiac muscles network found inside the wall of the right atrium close to the entrance of blood from venacava into the right atrium. This network of fine cardiac muscle fibre is known as Sino Atrial Node (SAN) and it serves as a pace maker by giving off a wave of electrical excitations similar to impulses, which spread out very rapidly over both atria causing them to contract and force blood into the ventricles via the open atrial ventricular valves.

When the electrical excitations reach the junction at the boundary of the atria, they excite another specialised plexus of other cardiac muscle chambers known as Atrio Ventricular Node (AVN). When excited, the AVN sends waves of electrical excitations down to another bundle of cardiac muscle of fibres formed along the inter-ventricular septum called the Purkinje tissue or Bundle of His to the apex of the heart. This conducts and spreads the excitement to both ventricles which eventually pump blood into the arteries.

Diagram showing how the waves of electrical excitations spread from the SAN

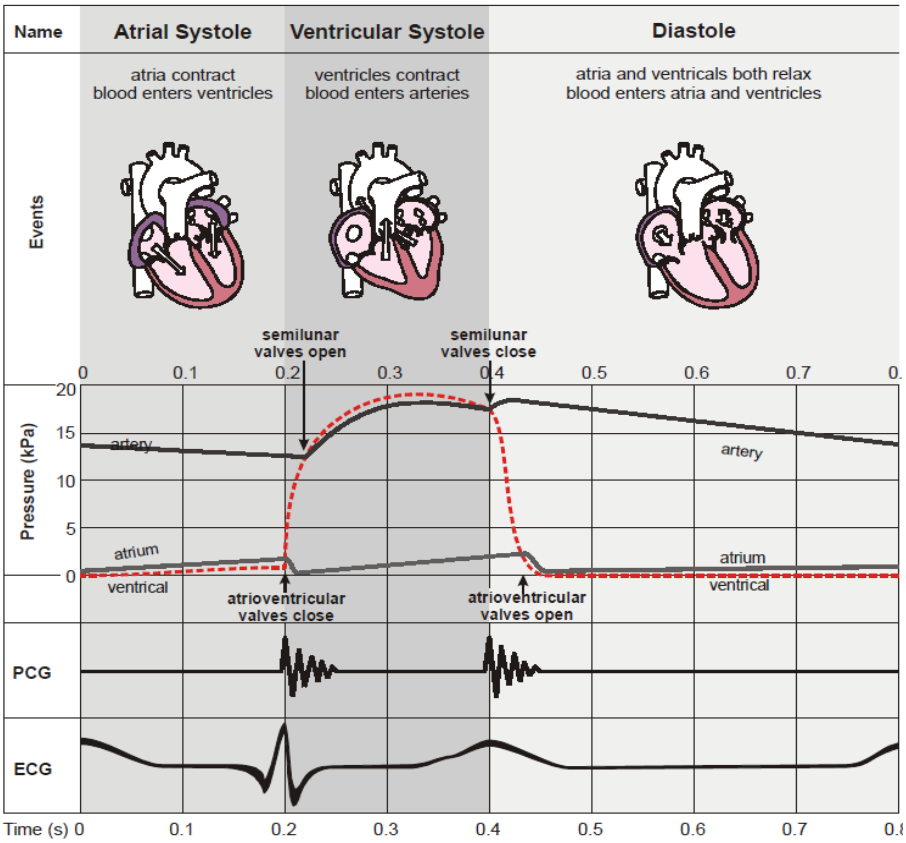
Clegg fig 17.10 pg 349

NOTE;

a. The closing of the atrioventricular valves during ventricular systole produces the first heart sound, described as ***lub.***
b. The closing of the semi lunar valves causes the second heart sound, described as ***dub.***
c. The pulse in the arteries is due to ventricular systole and elastic recoil of the arteries due to high pressure of blood.
d. The pulse is more pronounced in the arteries

The PCG (phonocardiogram) is a recording of the sound the heart makes. The cardiac muscle itself is silent and the sounds are made by the valves when closing. The first sound (lub) is the atrioventricular valves closing and the second sound (dub) it is the semi lunar valves closing.

The ECG (electrocardiogram) is a recording of the electrical activity of the heart. There are characteristic waves of electrical activity marking each phase of the cardiac cycle. Changes in these ECG waves can be used to help diagnose problems with heart.



The cardiac cycle (Sequence of the heart beat)

This is the sequence of events of heart beat by which blood is pumped around the body. The pumping action of the heart consists of alternate contractions of heart muscles (cardiac muscles) called **systoles** and relaxations called **diastoles**. The term cardiac output refers to the volume of blood pumped from each ventricle.

The cardiac cycle begins with the contractions of the atria i.e. **atrial systole,** which is initiated by SAnode and it which causes the atria volume to decrease and the atria increases. As the atria contracts, the ventricles relax i.e. undergo ventricular diastole, causing the bicuspid and tricuspid valves to close. The contraction of the atria due to blood entering the atria forces the bicuspid and tricuspid valves to open so that blood moves from atria into the ventricles.

Contraction of atria walls has an effect of sealing off the venacava and pulmonary veins, thereby preventing the back flow of blood into the vessels as the blood pressure rises within the atria. It takes 0.1 seconds.

When the ventricles are filled with blood from atria, their walls contract simultaneously i.e. **ventricular systole**, and the atria relax i.e. **atrial diastole.** Ventricular systole is initiated by impulses from AVnode to the bundle of His, Purkije fibres and rapidly through the ventricle muscles. The ventricles' volume reduces while the pressure increases, forcing the bicuspid and tricuspid valves to close and prevent the back flow of blood into the atria. The increased pressure in the ventricles also forces blood to be pumped into the pulmonary artery via the open semi lunar valves from the ventricles. This enables the blood to be pumped into the lungs via the pulmonary artery and into the body tissue via the aorta.

The ventricular systole is more powerful than the atrial systole because the ventricles are more muscular than the atria and therefore generate more pressure. The powerful ventricular systole forces blood into the atria and pulmonary artery.

After ventricular systole, there's a short period of simultaneous atrial and ventricular relaxations. In the **ventricular diastole**, the high pressure developed in the ventricles causes a slight back flow of blood which closes the semi lunar valves, thereby reducing blood back flow.

Relaxation of the atrial wall and contraction of the ventricle, initiates the refilling of the atria by blood under relatively low pressure i.e. deoxygenated blood in the venacava flows into the right atrium and oxygenated blood from the lungs flows into the left atrium via the pulmonary vein.

Intrinsic control of the heart beat

The cardiac muscle in the heart is myogenic. It contracts and relaxes automatically and does not depend on stimulation by nerves. The initial stimulus originates from the sino-atrial node (SAN), often called the pacemaker. The pacemaker is found in the right atrium wall at the entrance of the superior venacava. The membranes of the cells of the SAnode are permeable to sodium ions. Sodium ions enter into these cells and the cell membranes are depolarized.

An excitatory wave of depolarization is generated which spreads rapidly from the SA node across the two atria causing them to contract simultaneously. A slowing down occurs as depolarization of the atrio-ventricluar node (AVN) is delayed for about 0.1s to allow the atria to complete their contraction and empty the blood into the ventricles. Impulses from the AV node are conducted by specialized muscle fibres called bundle of His in the inter-ventricular septum towards the heart apex. Impulses are conducted by Purkinje fibres (Purkyne tissue) throughout the ventricular walls. This causes the contraction of both ventricles forcing blood into the pulmonary arteries and the aorta.

Characteristics of the cardiac muscle in relation to excitation and contraction

a. The absolute relative refractory period is longer than that of other muscles i.e. the heart cannot be fatigued easily
b. The generation of the wave from the SAN has a refractory period between contraction of the heart and relaxation of the heart i.e. the waves are not generated continuously.

Control of the rate of the heart beat

Though the initiation of the contraction of cardiac muscle and hence initiation of heart beat are not under the control of the central nervous system, the rate at which the heart beats to pump blood is under the control of the autonomic (Involuntary) nervous system.

The heart is innervated by the sympathetic nerve from the sympathetic autonomic nervous system and by the vagus nerve, a branch of a parasympathetic autonomic nervous system. The nerves modify the rate at which the pace maker gives waves of electrical excitations hence controlling the speeding up or slowing down of the rate of the rate of heart beat.

(Clegg fig 17.13 pg 350 OR Soper fig 14.24 pg 475)

When the rate of heart beat increases beyond the normal rate, the vagus nerve (parasympathetic nerve) is stimulated such that it lowers back to normal the rate of heart beat. If however, the rate of the heart beat lowers below the normal rate or if there's need for higher rate of heart beat the sympathetic nerve is stimulated to bring back or increase to the cardiac frequency usually to the normal rate. Therefore the sympathetic and vagus nerves are antagonistic, functionally.

NOTE;

Cardiac output (volume of blood going out of the heart) = **Rate of heart beat** **X** **Cardiac frequency**

Soper fig 14.25 pg 476

Internal factors affecting the heart beat

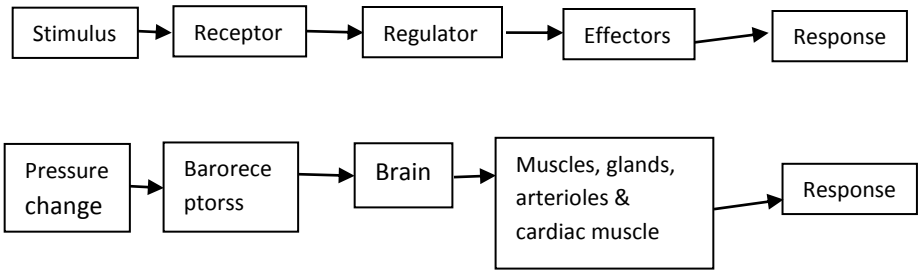
1. Body temperature
2. Blood pH
3. Carbon dioxide concentration
4. Partial pressure of oxygen
5. Hormonal balance
6. Salt balance
7. Blood pressure
8. Emotional situations
9. Impulses from the venacava and aorta

Control of blood pressure

Small receptors which are sensitive to stretching, called **baro receptors** are found in the walls of aortic arc, carotid sinuses, vena cava and the right atrium become stimulated when blood pressure increases above the norm. They fire impulses to the vasomotor centre and cardio vascular centre found in the medulla oblongata of the brain via the afferent nerves (sympathetic nerves). The cardio vascular centre sends impulses to the heart via the efferent nerves (vagus nerves), which results into reduction of the cardiac output. The vasomotor centre on receiving impulses, its sympathetic output is suppressed and this lowers the blood pressure by causing vasodilation of the arterioles

When the blood pressure lowers below the norm, the baro receptors stop being stimulated and this leads to impulses being fired from the cardio vascular centre to heart. The cardiac output is then increased. Decrease in blood pressure also increases the vasomotor centre sympathetic output which results into vasoconstriction of the arterioles hence increasing the blood pressure back to normal.

NOTE: When the arterioles constrict (vasoconstriction) blood pressure is raised and when they dilate (expand) the blood pressure decreases.



The brain includes the vasomotor, cardiovascular centre and the medulla oblongata

[Clegg fig 17.17 pg 352 OR Soper fig 14.26 pg 477]

Note:-Blood pressure depends on the following factors;

- Blood volume
- Force of the heart
- Blood vessel radius/ diameter of the lumen

Blood volume is adjusted to some extent through contraction of the spleen and liver which bring stored blood into circulation. The stored blood is due to the regulation of the fluid intake and fluid loss by organs such as the kidney and the skin during homeostasis.

Blood vessels offer resistance **(R)** to blood flow. The resistance is inversely proportional to the fourth power of the radius **(r)** of the vessel **(R** $\alpha \frac{1}{r^4}$ **).**

Therefore, the resistance increases as the vessel becomes narrower and since we are dealing with the fourth power of the radius, small changes in the arterioles radius will make a large difference to the resistance.

NOTE:

Blood is expelled from the heart only when it contracts. Blood flow through the arteries is therefore *intermittent,* the blood flowing rapidly during systole and slowly during diastole. However, by the time the blood reaches the capillaries it is flowing evenly. The gradual change from intermittent to even flow is made possible by the elasticity of the of the arterial walls which contain elastic tissue and smooth muscles

DEFENCE AGAINST DISEASES

Every mammal is equipped with a complex system of defensive mechanisms which are designed to enable it prevent the entry of microbes into it, to withstand attacks by pathogens (disease causing micro-organisms) and to remove foreign materials from the system.

The defensive mechanisms of blood include the following;

a. Clotting of blood
b. Phagocytosis
c. Immune response to infection

Clotting of blood

When a tissue is wounded, blood flows from it and eventually coagulates to form a blood clot which covers the entire wound. This prevents further blood loss and entry of pathogens. The process of blood clotting is described below.

When blood platelets and damaged tissues are exposed to air, the platelets disintegrate and release an enzyme called **thromboplastin** or **thrombokinase,** which in the presence of plasma proteins and calcium ions catalyses the conversion of a plasma protein derived from vitamin K called **Prothrombin** into **thrombin** enzymes.

Thrombin is a proteolytic enzyme that hydrolyses a plasma protein called **fibrinogen** into an insoluble protein called **fibrin**. Fibrin forms fibres at the wounded area. Within the fibrous network of fibrin blood cells become trapped, thereby forming a fibrin clot or a blood clot.

The clot not only prevents further blood loss, but also prevents the entry of bacteria and other microbes which might otherwise cause infection.

(Clegg fig 17.41 pg 365)

Note:

a) **Heparin** is an anticoagulant which inhibits the conversion of prothrombin to thrombin thereby preventing blood clotting.
b) Apart from blood clotting, the entry of microbes into the body can be prevented by the following;
    i. Using impermeable skin and its protective fluid called sebum (oily secretion in the skin)
    ii. Using mucus and cilia to trap the microbes and then remove them
    iii. By using hydrochloric acid in the stomach
    iv. By using lysozyme enzyme in the tears and nasal fluids
    v. By vomiting and sneezing

Why blood does not clot in the vessels

1. Connective tissue plus the liver produce chemical, heparin, which prevents the conversion of prothrombin to thrombin, and fibrinogen to fibrin.
2. Blood vessels are smooth to the flow of blood. Damage to the vessel's endothelium can lead to platelets breakdown which leads to clotting of blood.

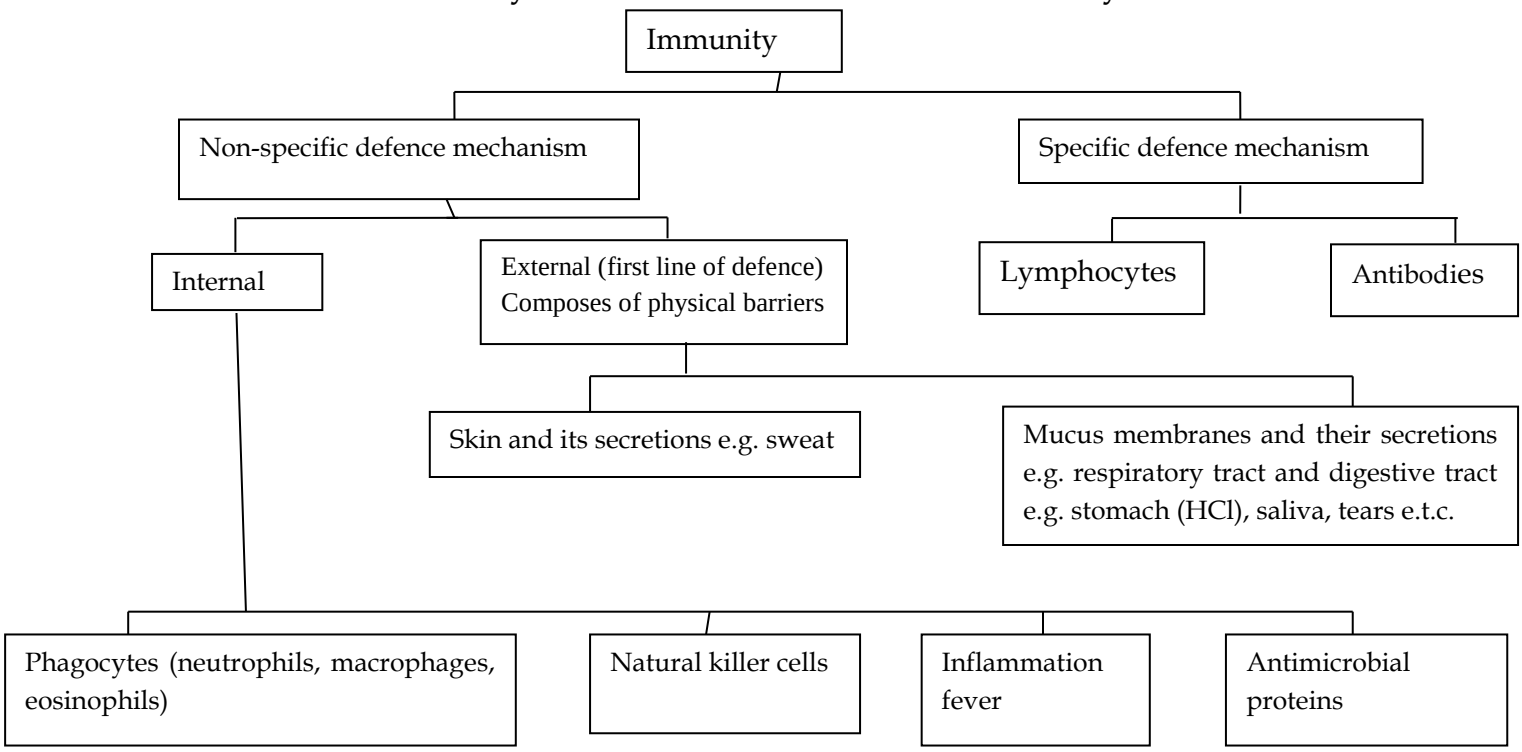
BODY DEFENCE SYSTEM AND MECHANISM IN MAMMALS (HUMANS)

An animal must defend itself against unwelcome intruders e.g. dangerous viruses and other pathogens it encounters in the air, water and food. The body also deals with abnormal cells (cancer cells) that develop periodically in the animal's body.
Two comparative defensive systems are used to fight pathogenic and abnormal cells in the body. One of the system is **non-specific** in nature i.e. it does not distinguish ones infections agent from another. The other defence system is **specific** in nature and constitutes the **immune system**. The non-specific system includes two lines of defence which an invader encounters in sequence. The first line of defence is external comprising of epithelial tissues that cover and line our bodies (skin and mucus membranes) and other secretions these tissues produce. The second line of non-specific defence is internal. It is triggered by chemical signals and uses antimicrobial proteins and phagocytic cells that indiscriminately attack any invader that penetrates the body's outer barrier (inflammation is a sign that tins second line of defence has been deployed.
The immune system constitutes a third line of defence which comes into place simultaneously with the second line of specific defence. However, the immune system responds specifically to a particular type of invader. This immune response includes

the production of specific defence proteins called **antibodies**. It also involves participation of several different types of cells that are derived from the white blood cells called **lymphocytes**.

NOTE: the non-specific defence system which involves use of phagocytes, natural killer cells and antimicrobial proteins is said to offer innate immunity (defence) which is abroad defence mechanism against infection. The immune response offers a specific defence against infection. It is also described as **acquired immunity**. Immunity is the ability of an organism to resist infection or to counter the harmful effects of toxins produced by infecting organisms.

A summary of defence mechanisms in an animal's body



NON SPECIFIC DEFENCE MECHANISM

The non-specific defence mechanism act in 6 ways i.e.

- Through physical barriers e.g. skin.
- Phagocytosis.
- Natural killer cell.
- Anti-microbial proteins.
- Inflammation.
- Fever

THE SKIN AND MEMBRANES

The intact skin is a barrier that cannot be penetrated by bacteria or viruses, although minute abrasions allow their passage. In the same way, the mucus membranes which line the digestive, reparatory and urinal genital tracts prevent the entry of potentially harmful microbes. Apart from their role as physical barriers, the skin and mucus membranes produce secretion that counter pathogens e.g. in humans, secretions from the oil and sweat gland give the skin a pH ranging from 3-5 which is acidic enough to discourage micro-organism from colonizing their bacteria that make the normal flora of the skin are adapted to its acidic relatively dry environment. Saliva, tears and mucus secretions that bathe the surface of the exposed epithelia wash away many potential invaders and in addition to these secretions contain various antimicrobial proteins.

E.g. the enzyme cysotyme which digests the cell walls of many bacteria, destroys many microbes entering the upper respiratory system and openings around the eyes.

Mucus, which is a viscous secreted by cells of the mucus membranes also traps particles that contact it. Microbes entering the upper respiratory system are caught in the mucus and are the swallowed or expelled.

The lining of the trachea has specialized epithelial cells equipped with cilia which sweep out microbes and other particles trapped by mucus, preventing them from entering the lungs.

Microbes prevent in food or trapped in swallowed mucus from the upper respiratory system pass through the highly acidic gastric juice produced by the stomach lining which destroys most of the macrobes before enter the intestinal tract.

PHAGOCYTIC DEFENCE MECHANISM

Certain white blood cells particularly neutrophils and monocytes are attracted by chemicals released by body cells which have been damaged by invading pathogens. These white blood cells show amoeboid movements which engulf, ingest and destroy pathogens.

Neutrophils can squeeze through blood capillary walls a process called diapedesis and move about in tissue spaces. The monocytes migrate out of blood stream then become larger white blood cells (leucocytes) called macrophages. Some macrophages are permanently located in tissues and organs such as the liver, spleen, kidney and lymph nodes while other circulate throughout the body.

The term macrophage means "**big eater**" and these cells are long lived phagocytes which even engulf much larger particles like old red blood cells and protozoan parasites.

The eosinophils have low phagocytic activity but are critical to defence against multicellular parasitic invaders such as the blood fluke (*Schistosoma mansoni*) they rarely engulf such a large parasite but position themselves against the parasites body and though discharged destructive enzymes which demage the invader.

A drawing to summarize the phagocytic process affected by neutrophil, macrophage or monocytes.

NATURAL KILLER (NK) CELLS

This is a class of white blood cells which attack virus injected body cells and abnormal cells that could form tumours.

The virus infected cells have viral proteins displayed on their surfaces and these are recognized by the natural killer cells contains perforin – filled vesicle.

When an N.K encounters a virus infected cell, perforin molecules are released by exocytosis. Perforin molecules make large holes of pores in the turgid cells plasma membrane, causing leakage of the cytoplasmic contents. This results into cell death. The membrane of NK cell is not affected by these membranes dissolving molecules.

INFLAMMATION

This is a localized non-specific response initiated by the defence system of the body, in which the part of the body infected by a micro –organism has its blood vessels dilated, more permeable to blood components, having increased blood flow swells up, becomes warm and red as the phagocytes destroy the invading pathogens.

An inflammation is usually by physical damage to the skin or mucus membranes by bacteria.

This physical damage causes release of chemical signals such as histamine and prostaglandins. The chemical signals induce increased permeability of the blood capillaries and the flow of blood to the affected area respectively. They also attract phagocytic cells and lymphocytes which on arrival at the site of injury, the phagocytes consume pathogen and the cells debris and consequently the tissue heals.

N.B. it is the damaged cells and certain leucocytes that produce histamine and

Prostaglandins. The histamine cause vasodilatation i.e. the capillaries dilate and the walls become leaky. As more fluid collects around the wound, the site becomes red, swollen and warm. The localized swelling is called **oedema**. The prostaglandins are the ones that promote blood flow to the site of injury and increase the sensation of pain.

FEVER

Fever refers to increase in body temperature. It is triggered if microbes infect larger areas of the body in response to infection, certain leucocytes releases pyrogens which are also anti-microbial protein of the complement system. The pyrogen stimulate the hypothalamus to rise the body temperature set point from its normal value about 39^0C hence casing a fever. The fever has several beneficial effects;

- It increases the activity of phagocytes which then attack the invading microbes more efficiently.
- It increases the production of interferon in virus infected cells. Interferons are proteins which inhibit viral replication, activate natural killer and stimulate macrophages to destroy tumour cells and virus infected cells.

ANTIMICROBIAL PROTEINS

These are proteins that function in the mechanisms by attacking microbes directly of by impeding the production e.g. lysozyme.

Other antimicrobial proteins include about 30 serum proteins that make up the complement system proteins through a sequence of stops, leading to lysis (bursting) of invading cells.

Some complement proteins initiate inflammation and also play a role in acquired defence

(specific defence system) interferon is one of the proteins of the complement system which provides innate defence against viral infection the interferon protein is secreted by virus infected body cells and induce neighbouring uninfected to produce other substances that inhibit viral reproduction. In this way, inteferons limit the cells spread of viruses in the body helping control of viral infections such as colds and influenza.

SPECIFIC DEFENCE SYSTEM /IMMUNE SYSTEM/ACQUIRED IMMUNITY

The specific immune response confers immunity against specific microbes. (immunity is the capacity of an organisms body to recognize the intrusion of foreign materials in the body and mobilize cells and cell products (anti bodies) to remove a particular sort of foreign material to a greater speed and effectiveness) the specific defence system involves immune system whose response result from the interaction among several types of lymphocytes, the molecules they produce (antibodies) and the foreign material introduced by microbes (antigens)

MAJOR CELLS IN THE IMMUNE SYSTEM.

1. B-CELLS (B-LYMPHOCYTES)

These are lymphocytes that produce antibodies when stimulated. They are produced and mature in the bone marrowsfrom the **stem cells**. They have glycoprotein receptors on their cell surface membranes which bind specific antigens. Mature B-cells become plasma cells and memory cells produce much more antibodies in terms of quantity and effectiveness than plasma cells.

2. T-CELLS (T-LYMPOCYTES)

The T-lymphocytes regulate the immune response (in case of T_H-cells) or kill certain types of cells (Tc-cells) the T cells are produced in the bone marrow but mature in the thymus gland where they develop specific receptors which recognise specific antigens. These are two main categories of T cell namely

- T_4 cell which have the CD4 receptor cites

- Thelper cells.
- TC/T.cytotic cells recognize and destroy cells with foreign antigens on their surface. They mainly attack virus infected cells, cancerous body cells and foreign grafted tissues

T_4 cells recognize and destroy cells with foreign antigens on their surface. They mainly attract virus infected cells, cancerous body cells and foreign grafted tissues.

T_4 cells stimulates and enhance the immune responses by both B and Tc cells. T cells include the following;

Killer T-cells

These are cells which attach to invading cells and secrete a number of cellular toxic substances called ***lymphokines*** which kill the invading cells called microbes.

Helper T-cells

These are cells that recognize a specific antigen on an antigen-presenting cell, binds to it, and then assists a B-cell binding the same antigen to proliferate into specific antibody secreting cells.

Suppressor T-cells

These suppress the activity of the killer T-cells and B-cells after the microbes have been cleared out of the body to prevent these cells from attacking and destroying the body cells. Suppressor T-cells therefore regulate the immune response and prevents antibodies from being produced by the B-cells.

MEMORY CELLS

These are derived from B cells and T-cells. They are long lived and confer future immunity against subsequent infections by the same antigen i.e. they are the ones responsible for causing the secondary immune response.

MOLECULES OF THE IMMUNE SYSTEM

1. Antibody

This is a specific protein (immunoglobin) which recognizes and binds to specific antigens. Antibodies either neutralise antigens or tag cells that are antigens for easy attack by macrophages.

N.B. Macrophages are also taken to be part of the immune response i.e. involved in specific defence mechanism through indirectly since they are phagocytes which destroy microbes and alert other immune cells the infection.

2. Epitopes

These are antigens determinants with specific sequences of amino acids that confer as specific shape to the antigen molecules which is then recognized by an antibody or T-cell receptor. An antigen can have several different epitopes on its surface and different antibodies can therefore bind a single antigen.

3. Cytokines (**lympokines**)

These are peptides and proteins that regulate many cell activities (growth and repair) and act as signal in both the specific and non-specific immune responses

Examples of cytokines include

- Interferons
- Interleukin

4. Complement system.

This is a group of about 20 proteins found in plasma and other body fluid. These are inactive until the body is exposed to antigens e.g. histamines.

CHARACTERISTICS OF THE IMMUNE SYSTEM

The immune system develops specific response against each type of foreign microbes, toxin or transplanted tissues.

The immune system has 4 features i.e.

- Specificity.
- Diversity
- Memory
- Self/non self-recognition.

Specificity

The immune system has the ability to recognize and eliminate particular microorganism, and foreign molecules. The immune system responds to an antigen by activating specialized lymphocytes and producing specific proteins called antibodies.

Antigens that trigger an immune response include molecules belonging to viruses, bacteria, fungi, protozoa and parasitic worms.

Anti-bodes recognize antigens using epitopes which are antigenic determinants on the surfaces of the antigens. If an antigen has several epitopes, it stimulates several different B cells which secrete specific distinct antibodies against it. Therefore each antigen has a unique molecular shape and stimulate the production of the very type of antibody that defends against that specific defences, each response the immune system targets a specific invader distinguishing it from other foreign molecules that may be very similar.

Diversity

The immune system has the ability to respond to very many kids of invaders each recognized by its antigenic markers. This diversity of response is possible because the immune system is equipped with an enormous variety of lymphocyte population among the antibody producing lymphocytes (B-lymphocytes) each population is stimulated by a specific antigen and response synthesizing and secreting the appropriate type of antibody.

Memory

The immune system has the ability to "remember" antigen encountered and react more promptly and effectively on the subsequent exposures. This characteristics also known as acquired immunity.

Self/non self-recognition

The immune system distinguishes the body's own molecules from foreign molecules (antigens). Failure of self/non self-recognition leads to anti immune disorders in which the immune system destroys the body's own tissues

.TYPES OF ACQUIRED IMMUNITY

There are two types of acquired immunity namely:

- Active acquired immunity.
- Passive acquired immunity.

Active acquired immunity depends on the response of a person's own immune system. Here the individual organism produces antibodies using the B-lymphocytes against the infectious agent. Active immunity is naturally acquired but it can also be artificially acquired by vaccination.

In **passive immunity**, antibodies are transferred from one individual to another as in the case that occurs naturally when a pregnant woman's body passes some of her antibodies across the placenta to the fetus. The new born's immune system is not fully operative and depends on the mothers immune system. Certain antibodies are also passed from the mother to her nursing infant in breasts milk especially in her colostrum or fast secretions.

NB. Passive immunity can also be transferred artificially by introducing antibodies from an animal or human who is already immune to the disease e.g. rabies is treated in humans by injecting antibodies from people who have been vaccinated against rabies. This produces an immediate immunity which is important because rabies progress rapidly and the response to vaccination would take too long.

TYPES OF NATURAL IMMUNITY

1. Natural passive immunity

This involves passing antibodies in the body of an organism into the body of another organism of the same species e.g. from the mother to the foetus via to the placenta to defend the body against disease and also via the first milk called **colostrum** to the child. This type of immunity is temporary.

2. Natural active immunity

This is the immunity that involves formation of antibodies by the body of an organism in the presence of certain antigens.

This type of immunity is permanent because during the immune response, memory B-cells are produced which recognize the microbes on reinfection (second infection) and then stimulate the rapid production of large amounts of antibodies to curb down the microbes before causing significant damage. Memory B-cells stay for long in blood.

MECHANISM OF IMMUNE RESPONSES

The immune system mounts two different types of responses to antigens namely;

- Cell-mediated response.
- Humoral response.

HUMORAL RESPONSE

The humoral immunity results in the production of antibodies which are secreted by B-cells, the antibodies circulate as soluble proteins in blood plasma and lymph, the fluids that were once called humors.

In the cell mediated response, the immunity depends on the direct action of the T-lymphocytes rather than antibodies.

N.B: The circulating antibodies of the humoral branch of the immune response defends the body against toxins, free bacteria and viruses present in the body fluids. In contrast, lymphocytes of the cell mediated branch are active against bacteria and viruses inside the body's cells and against fungi protozoa and worms. The cell mediated immunity is also involved in attacks on transplanted tissue and cancer cells both of which are perceived as non self.

HOW ANTIBODIES WORK

An antibody does not directly destroy an antigenic invader. However antibodies bind to antigens to form an antigen antibody complex which is the basis for several effector mechanisms which make macrophages recognize the antigens and destroy them. The binding of antibodies to antigens takes various forms, some of which include the following.

Neutralisation

Here the antibody blocks certain sites on an antigen or toxins making it effective. Antibodies neutrallise a virus by attacking to the sites the virus uses to bind to its host cell. Also bacterial toxins become coated with antibodies hence getting neutralised, eventually, phagocytic cells (macrophages) destroy these antigen-antibody complexes.

Agglutination (**clumping**)

This is when antibodies cross link adjacent antigens. This is made possible because certain antibodies possess at least two antigen binding sites. The clumping of antigens e.g. bacteria makes it possible to be recognized by macrophages and other phagocytes which destroy the antibody-antigen complex

Precipitation

This is similar mechanism to agglutinations except that here the antibody-antigen complexes are formed when soluble antigen molecules rather than cells are licked to form immobile precipitates which are captured by phagocytes and macrophages that destroy them.

Opsonisation

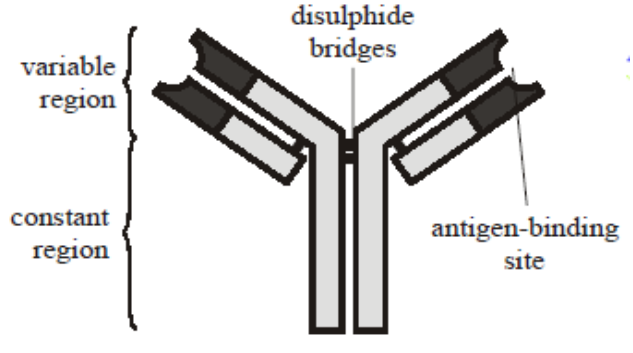
Here, the antibody molecule oats the surface of a microbe making it easier for phagocyte leucocytes to engulf it.

Complement fixation

Here, the antibodies activate the complement proteins which then leads to lysis of foreign cells.

TYPES OF ANTIBODIES

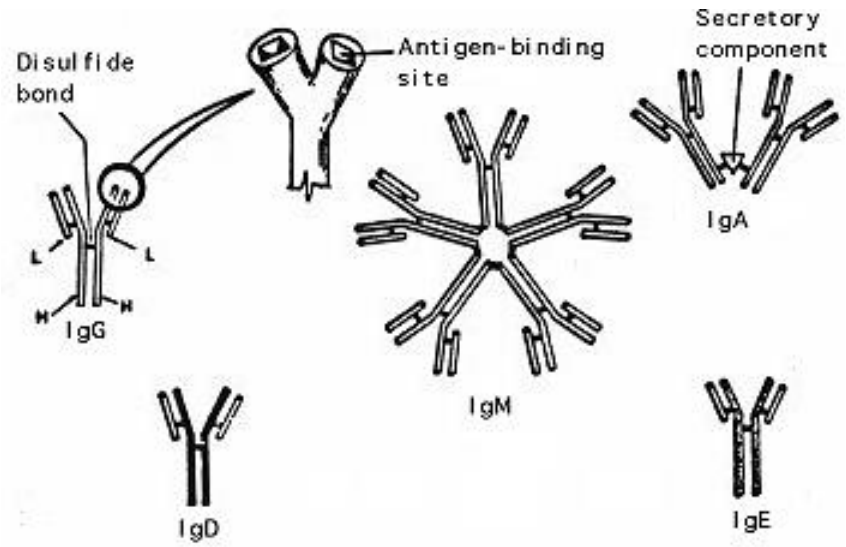
Antibodies constitute a class of proteins called immunoglobulins (igs). Every antibody molecule has at least two identical sites that bind to the epitope that provide its production. The typical structure of an antibody molecule is composed of two light and two heavy linked together by sulphide bridges (s-s) and has got a Y shaped molecule. Most of the molecule is the same for all antibodies of the same immunoglobulin class.



stylised diagram

There are 5 classes of immunoglobulins namely

- IgM (pentamer)
- IgG (monomes)
- IgA (dimes)
- IgD(monomers)
- IgE (monomes)



IgMs

These are the 1st circulating antibodies to appear in response to an initial exposure to an antigen. Their concentration in blood declines rapidly and this is useful diagnostically because their presence indicates a current infection by the pathogen, causing its formation. The IgM consists of 5 Y shaped monomers arranged in a pentamer structure.

Note. The numerous antigen-binding sites of an IgM make it very effective in agglutinating antigens and in reaction involving complements. However the IgM is too large to cross the placenta and does not confer material immunity

IgG

IgG is the most abundant of the circulating antibodies. It readily crosses the wall of blood vessels and enters tissue fluids. IgG crosses the placenta and confers passive immunity from the mother to the fetus. IgG protects against bacteria, viruses and toxin circulating in blood and lymph and triggers action to the complement system.

IgA

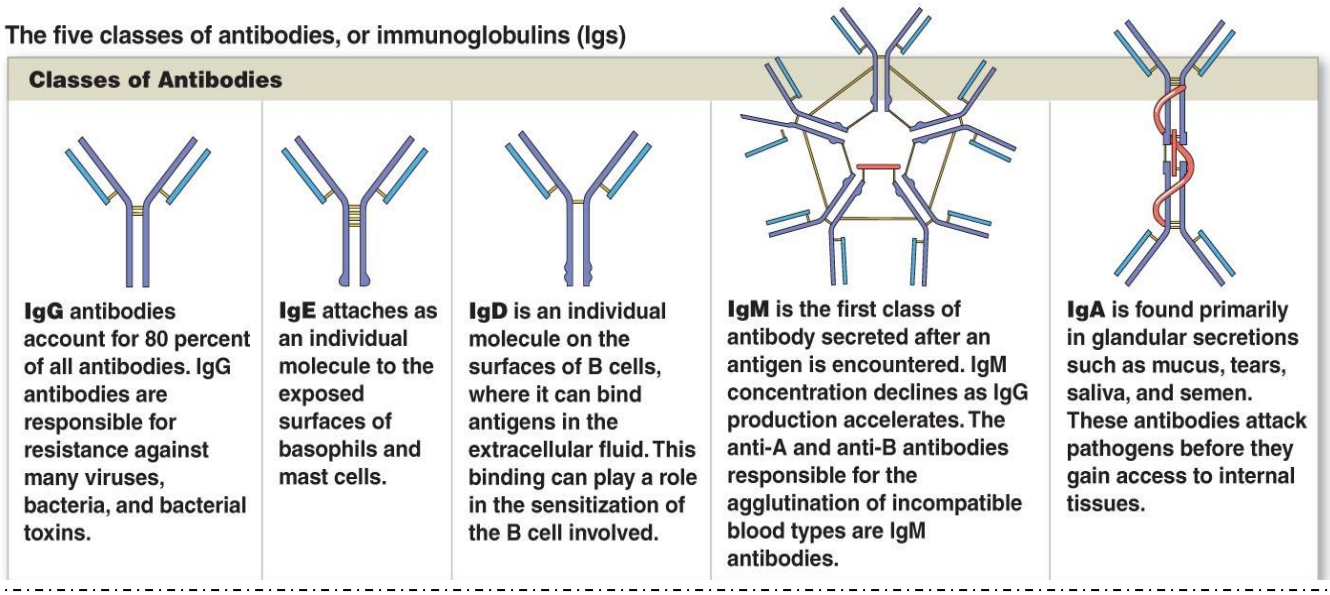
This is produced inform of 2 Y shaped monomers (it is a dimer) by cells abundant in mucus membranes. The main function of IgA is to prevent the attachment of viruses and bacteria to epithelial surfaces. IgA is also found in many body secretion such as saliva perspiration (sweat) and tears. It is also present in colostrums (1st milk of nursing mammal) it protects the infant from gastro-intestinal infections.

IgD

IgD antibodies do not activate the complement system and cannot cross the placenta. They are mostly on the surfaces of the B cells where they function as antigen receptors required for initiating the differentiation of B-cells into plasma and memory cells

IgE

These are slightly larger than IgG molecules and represent only a very function of the total antibodies in blood. The tail region attach to receptors of most cells and basophiles and when triggered by an antigen, cause the cells to release instamine and other chemicals that cause an allergic reaction.



Cell mediated immune response.

When a microphage ingests a bacteria, most of the bacteria antigens are destroyed by its enzymes. However some fragment of the foreign antigens combine with the major histo compatibility class II proteins (MHC-Class II) which are found on the macrophages cell surface membrane. In this way, the macrophage becomes an antigen presenting cell (APC). The APC interacts with helper T-cells especially those with CD4 receptors. The CD4 receptors hold the APC and TH cells together while activation occurs.

The APC is stimulated to several interleukin–I (IL-I) which then activates the TC cells to start dividing and to produce interlenkin-2 (IL-2). IL-2 stimulates the TH cell to divide more rapidly and produce even more interleukins.

IL-2 also stimulates the development of natural killer cell and B-cells. Interlenkin-2 also stimulates cytotoxic T-cell which generally have the CD8 receptors on their cell membranes. These receptors enable the TC cells to interact with the class I MHC molecule. If these cells are infected by viruses, the fragments of virus are displayed on the membrane with the aid of MHC protein. The T cell is also activated when it is in contact with the class I MHC antigen complex on an infected cell. The stimulated TC cell release perforins a protein that forms pores in the infected cell membrane. This results in the lysis of the infected cell. The pathogen e.g. a virus becomes exposed and it is destroyed by the circulating antibodies.

NB. In the same way, the T-cells attack tumour cells which display fragments of tumour antigen.

The Major Histocompatibility Complex (MHC) is a set of closely linked genes which code for a set of proteins (antigen marker) found on the surface of cells.

It is divided into two main classes i.e.

- The MHC class 1 antigens are carried by most nucleated cells and are important in self /non self-recognition.
- The MHC class-2 antigen are mostly found of B-cells, macrophages and some T-cells. However the components of the complement system are made of special class namely: the MCH class 3 proteins.

EXPLANATION OF HOW THE KEY FEATURES OF AN IMMUNE SYSTEM ARE REALIZED DURING THE SPECIFIC DEFENCE MECHANISM.

SPECIFITY AND DIVERSITY

Immunological specificity and diversity is based on clonal selection of lymphocytes if the antigen enters the body and binds to receptors on the specific lymphocytes, the nasal those lymphocytes are activated to mount an immune response. The selected cells proliferate by cell division and develop into a large number of identical effector cells known a clone. This clone of cells combat the very antigen that provoked the response e.g. plasma cells that develop from that function as the antigen receptor on the original B-cell. Which first encountered the antigen. The antigen specific selection and cloning of lymphocytes is called clonal selection.

In clonal selection, each antigen by binding to specific receptors selectively activate a tiny traction of cells from the body's diverse pool of lymphocytes. These relatively small numbers of selected cells, all dedicated to eliminating the specific antigen that stimulated the humoral or cell mediated immune response.

N.**B**. Antigens are molecules (usually proteins, polysaccharides or glycoproteins carried on the surface of cells which cause antibody formation. All cells have antigen makers on their cell surface membranes but the body can distinguish between its own antigen (self) and foreign antigen (non self)

Memory and secondary immune response

Memory cells function in secondary immune response. In primary immune response there is selective proliferation (multiplication) of lymphocytes to form clones of effector cell upon the first exposure to an antigen. Here there is a lag period between initial exposure to an antigen and maximum production of effector cells.

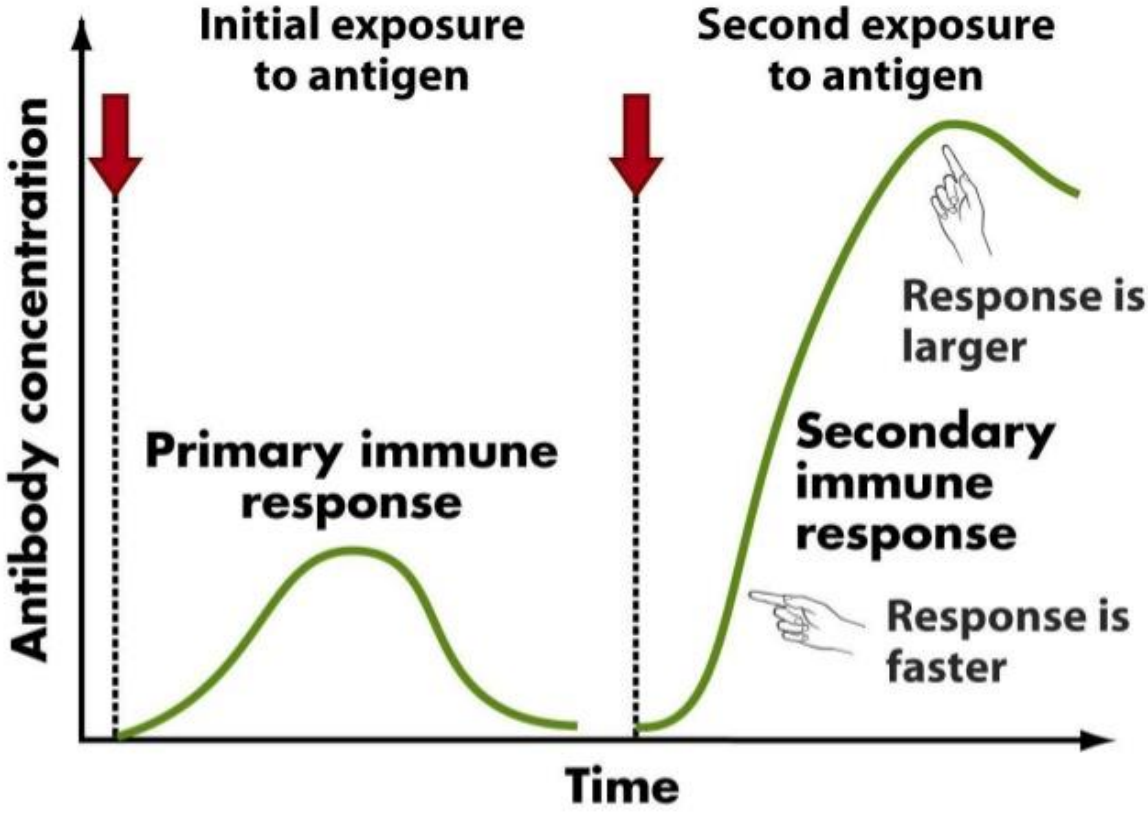
During the lag period, the lymphocytes secreted by the antigen differentiates into effector Tcells (TH and TC) and antibody producing plasma cells

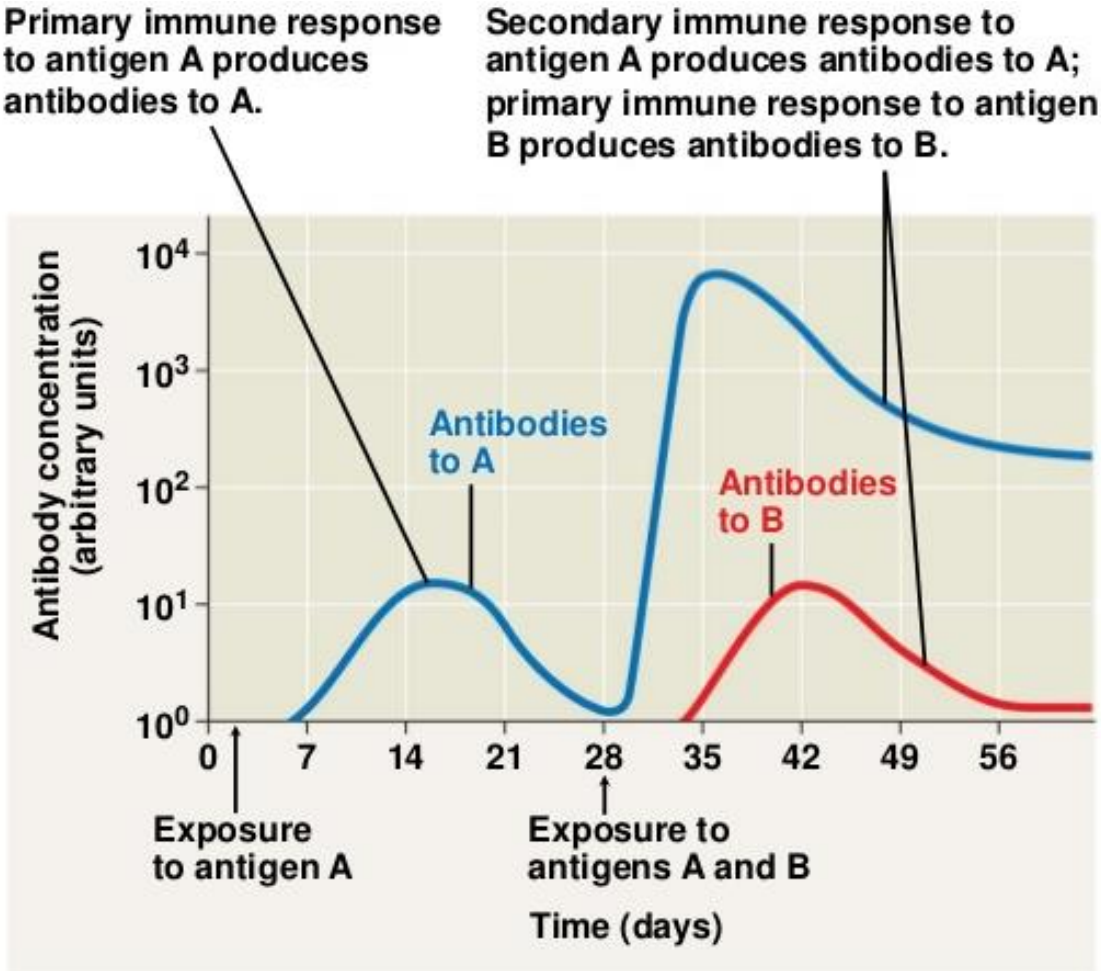
If the body is exposed to the same antigen at a later time, the response is faster one/more prolonged than the primary immune response. This is the secondary immune response.

Secondary immune response is the rapid response that results in faster production of effector Tcells and antibody molecules when the body is exposed to subsequent infection of the same antigen that has ever invaded the body. Antibodies produced during the secondary immune response are more effective in binding to the antigen than those produced during the primary immune response.

The immune systems' ability to recognize an antigen as previously encountered is called immunological memory. The ability is based on long lived effector cells of the immune response, memory cells are not active- memory cells survive for long periods and proliferate rapidly when expose to the same antigen that caused their formation secondary immune gives rise to new clone to memory cells as well as effector cells.

Graph to illustrate changes in antibody concentration during primary and secondary immune responses to antigens





Self and non-self-recognition

Here, molecular markers on cell surface, function in self and non-self-recognition. The antigen receptors on the surface of lymphocytes are responsible for detecting molecules that enter the body. Normally, there are no lymphocytes that are reactive against the body's own molecules. Self-tolerance begins to develop as T and B lymphocytes bearing antigen receptors mature in the thymus and bone marrow and continues to develop with receptors for molecules present in the body are destroyed or rendered passive (non-functional) leaving only lymphocytes that are reactive against foreign molecules tolerated by an individual's immune system, are a collection of molecules encoded by a family of genes called the Major Histocompatibility complex (MHC) two main classes of MHC molecules mark cells as self. Class 2 MHC molecules are restricted to a few specialised cell types of the body's defence system e.g. macrophages, B-cells and activated T-cells.

NB. Class 2 MHC molecules play an important role in interaction between cells of the immune system.

ABNORMAL IMMUNE FUNCTION

Sometimes, the immune system fails to defend the animal against intruders instead turns against the components of the body which leads to certain disease. Conditions immune system abnormalities include;

- Auto immune disease.
- Allergy.
- Immune deficiency.

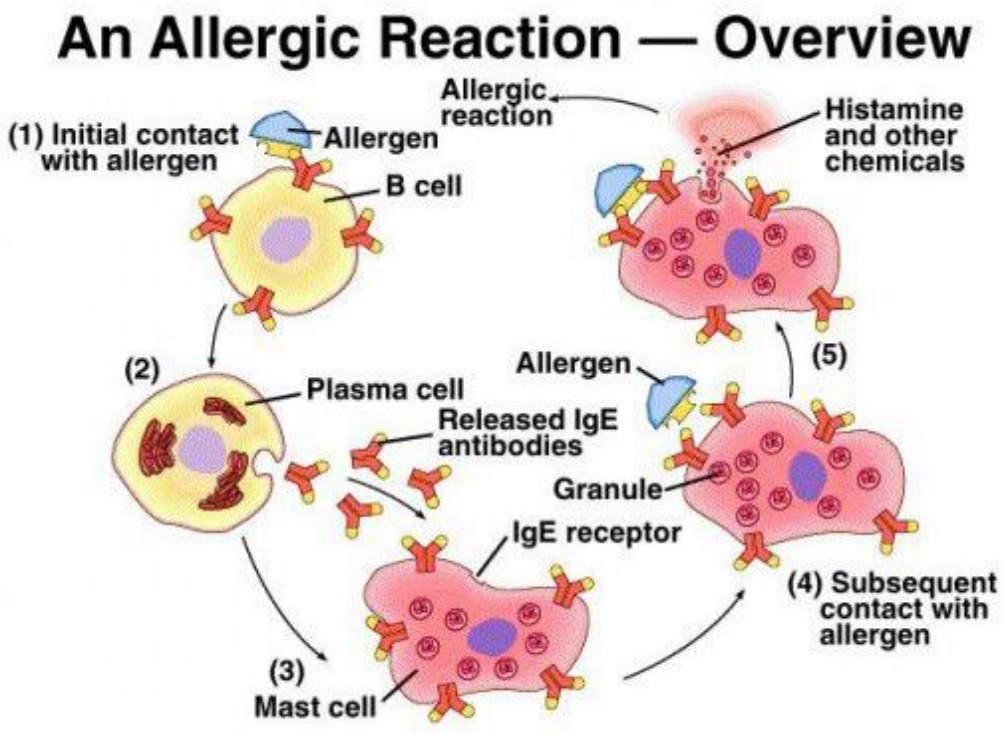
AUTO IMMUNE DISEASES

The immune system goes away and usually turns against component of the body. Leading to auto immune diseases. In insulin dependent diabetes, an auto immune reaction causes the destruction of insulin producing cells of the pancrease. In Rheumatioal arthritis is a crippling auto immune disease in which inflammation damages the cartilage and bone of joints Rheumatic fever is an auto immune condition in young adults where antibodies produced in response to streptococcal infection (such as strep throat) react with heart muscles tissue damaging the heart valves. Repeated episodes of infecting results in more antibodies and more heart damage.

Allergy

Allergies are hypersensitivities of the body's defence system to certain environmental antigens called allergens. The most common allergens involve antibodies of the IgE class e.g. hay fever and other allergies caused by pollen allergens. The IgE antibodies attach by their tails to mast cells which are non-circulating cells found in connective tissue. In this way, a susceptible person become sensitized to the specific foreign antigen later.

When a pollen grain binds to the IgE and bridges the space between 2 IgE monomers, the mast cells responds with rapid reaction called degranulation releasing histamine and other chemicals.



NB.

a) Histamine causes dilation and increased permeability of the small blood vessels. In an allergy response, histamine causes symptoms like sneezing, a runny nose and smooth muscle contraction that often result into breathing difficulty.
b) Antihistamines are drugs that interfere with action of histamine
c) Upon first exposure to an allergy. The plasma cells secrete the IyE specific for the allergy. Some of these antibodies are attached by their cells to the mast cells. When upon second exposure, the allergen binds to IgE already on the mast cell. It triggers the degranulation of the cell.
d) Degranulation releases histamine leading to most of the symptoms at allergy.

IMMUNE DEFICIENCY

Certain individuals are inherently deficient (lack) in either humoral or cell medicated immune defences. In a congenital disorder, this is known as severe combined immune deficiency. For people with this genetic disease, long term survival requires a successful bone marrow transplant that will continue to supply functional lymphocytes.

Adaptation of mammals to oxygen deprivation

Diving mammals e.g. seals, dolphins and whales.

a. They have a large spleen which can store large volumes of blood e.g. the seals spleen stores 24l of blood after the dive has begun, the spleen contracts and supplies the blood in circulation with additional erythrocytes that are highly leached with oxygen.
b. Have high concentration of myoglobin in their muscles. Myoglobin is an oxygen storing protein.
c. Mammals during the diving reflex slow down the pulse as the heart beat is also slowed down in order to effect an overall reduction on oxygen consumption since there is reduced cardiac output to the tissues.
d. Store oxygen in their blood as oxyhaemoglobin and this they achieve by having concentration of haemoglobin.
e. Blood supply to muscles is restricted and completely cut off during the longest dives hence encouraging anaerobic instead of aerobic respiration.
f. In this way, the muscles use sparingly oxygen stored in their myoglobin.

Mammals living at high altitudes

a. These possess an improved capillary network in the lungs which coupled with their deeper breathing (hyperventilation) insures increased oxygen uptake.
b. They have an increased red blood cell which increases the amount of oxygen transported by blood.
c. Increased haemoglobin concentration in the red blood cells which improves the amount of oxygen transported by the blood.
d. Changes in haemoglobin affinity for oxygen. Here the oxygen dissociation curve is shifted to the right to facilitate release of oxygen to the tissues. This particulary occurs at relatively lower altitudes.
    i. Mammals living at altitudes about 3500m have their oxygen dissociation curves shifted to the left this favours their survival by promoting an increased affinity for oxygen by haemoglobin.
    ii. Increased myoglobin levels in muscles myoglobin has a higher affinity for oxygen than haemoglobin. This facilitates the exchange of oxygen from the blood to the tissues making oxygen available to the tissues.

THE LYMPHATIC SYSTEM

The lymphatic system returns tissue fluid to the blood and also plays a role in the body defence. As blood passes through the capillaries, there is accumulative loss of fluid which is effected by ultra-filtration of blood and this forms tissues fluid that bathes cells. The lost fluid is similar to blood in composition except that of lacks blood plasma proteins and cells. The lost fluid returns to blood via the lymphatic system. It enters the system by diffusion into tiny lymph capillaries which are intermingled among the capillaries of the cardio vascular system. Once inside the lymphatic system, the fluid is called lymph. The lymphatic system drains into the circulator system near the shoulders where it pours its contents on the subclavian vein that leads to the anterior vena cava.

Along the lymph vessels are specialized swellings called lymph nodes. These filter the lymph and attack bacteria, virus infected cells and other antigens using the lymphocytes in them.

When the body is infected by an antigen the cells in the lymph nodes multiply rapidly and the lymph nodes become swollen and tender. Like the veins of the cardio vascular system lymph vessels have valves which prevent back flow of fluids towards the capillaries. In the same way, lymph vessels depend on the movement of skeletal muscles to squeeze the fluid along the vessel.

N.B the lymphatic system serves to;

- Defend the body against infection.
- Maintains the level of interstitial fluid (tissue fluid).
- Transports fats from the digestive tract to the circulatory system (the lymph capillaries called lacteals) penetrate the villi of the small intestine which absorb the fatty acids and glycerol.

Whenever the interstitial fluid accumulates rather than being returned to the blood by lymphatic system, the tissues and body cavities become swollen a condition known as oedema.

VACCINES

Vaccines are toxic chemicals or killed or attenuated (weakened) microbes introduced into the body of an organism to make it produce very many antibodies against a certain pathogen.

The killed microbes are usually viruses and bacteria. The attenuated microbes are living microbes which are inactivated and they lack powers to infect the body due to the chemical or temperature treatment given to them.

Note; toxins are toxic chemicals produced by microbes and therefore can work as antigens

BLOOD TRANSFUSION

This is the transfer of compatible blood from the donor to the recipient.

Blood transfusion based on the ABO system of grouping blood

Blood group A has antigen A on the surface of its red blood cells and antibody b in the blood plasma of that person. Blood group B has antigen B on the surface of its red blood cells and antibody a in the blood plasma of that person. Blood group AB has antigen B and A on the surface of its red blood cells and no antibody in the blood plasma of that person. Blood group O has no antigen on the surface of its red blood cells and both antibody b and a in the blood plasma of that person.

Blood group	Antigen on the red blood cell membrane	Antibody on plasma
A	A	b
B	B	a
AB	A and B	Lacks antibodies
O	No antigens	a and b

Blood plasma permanently contains antibodies depending on a particular blood group. However these antibodies do not correspond to a specific antigen, if they correspond then agglutination occurs (precipitation of blood). That is why an individual with blood A having antigen A cannot donate blood to an individual with blood group B having antibody a in the plasma which corresponds to antigen A to cause agglutination. Similarly, blood groups A and B cannot donate blood to an individual of blood group O because antigen A will be attacked by antibody a in blood group O and antigenB will be attacked

by antibody b in blood group O to precipitate the recipient's blood. The table below summarizes the possible blood transfusions and the impossible ones.

Blood group compatibilities

Recipient		Donor's blood group			
Blood group	**Antibody in plasma**	**A**	**B**	**AB**	**O**
A	B	✓	X	X	✓
B	A	X	✓	X	✓
AB	None	✓	✓	✓	✓
O	a and b	X	X	X	✓

✓ = compatible with recipients blood

X = Incompatible with recipient i.e. agglutination ocurs

Individuals with blood group AB posses antigen B which stimulates blood group B of the recipient to produce antibody a that reacts with antigen A in the donor's blood to cause agglutination and therefore this transfusion from AB to B is impossible. Similarly blood group O individuals can donate blood to blood group A because the donor's blood has no antigens which would react with antigen A in the recipient's blood and therefore agglutination is impossible.

Individuals with blood group O are called **universal donors** because they lack antigens which would react with the corresponding antibodies in the recipient's blood. Individuals with blood group AB are called **universal recipients** because they lack antibodies in their blood plasma which would have reacted with the corresponding antigens in the donor's blood.

NOTE; the recipient's antibody is the one expected to attack and react with the corresponding antigen in the donor's blood. Whenever the antigen of the donor corresponds with the antibody of the recipient's blood group, an antibody-antigen reaction occurs, leading to agglutination (precipitation or clotting of blood)

RHESUS FACTOR (D-Antigens)

These are antigens which were first observed in the bodies of the Rhesus monkeys. These antigens are also carried on the surface of the erythrocytes of some human beings. Those people with D-antigens on the surface of their red blood cells are called Rhesus positive (Rh^+) while individuals missing such D-antigens are called Rhesus negative (Rh^-).

The bodies of individuals do not have already manufactured antibodies against the D-antigens. When an expectant mother who is Rh^- bears the foetus with which is Rh^+, some foetal erythrocytes with D-antigens will cross the placenta and enter into the blood circulation of the Rh^- mother towards the end of the gestation period (pregnancy). It is also possible for the blood of the foetus to mix with that of the mother during birth so that the mother gets Rh^+ by getting the D-antigens from the child.

The D-antigens that have entered the mother's blood circulation stimulate the maternal body to manufacture corresponding antibodies (antibody-d or anti-D antibodies) which attack and react with the D-antigens in the mother. Some formed antibodies-d can also pass via the placenta and enter the foetal blood circulation where they attack and react with the D-antigens which results into clumping together and bursting of the foetal red blood cells, a condition called **erythroblastosisfoetalis** (Haemolytic disease of the new born). This disease results into acute anaemia which can lead to death of the feotus.

The first born rarely dies because the time is too short for the mother to produce enough antibodies that can pass to the foetus to cause death but subsequent Rh^+foetus can die due to the many antibodies of the mother entering its circulation to cause agglutination.

To prevent this disease, pregnant mothers are always given anti-D chemicals 72hours to delivery, to render her immune system insensitive towards the D-antigen i.e. the mother may be infected with antibody-d within 70-72hours to delivery or within 72 hours after her first born. Also the blood of the foetus can be transfused with normal blood to dilute antibody-D so as to save the child.

NOTE: if a rhesus negative mother of blood group O is carrying a rhesus positive child of any blood group other than O, the problem will not arise. This is because if fetal cells enter the mother's circulation, the mother's **a** and**b** antibodies will destroy the blood cells before the mother has time to manufacture anti-rhesus antibodies.

SAMPLE QUESTIONS

1. (a) State any two theories which have been put forward to explain stomatal movement?

(b) Describe the mechanism of stomatal movement basing on each of the theories stated above?

© State any weaknesses for the two theories described above

2. (a) Describe the structure of the phloem tissue

(b) Describe the mass flow theory of food transport in plants

3. The table below shows data obtained from a study of leaves of a tree

Time	**Percentage of open stomata**	**Relative amount of starch in guard cells**	**Relative intensity of light**
8:00 am	42	70	0
10:00 am	100	30	5
12:00 noon	100	13	50
02:00 pm	100	18	61
04:00 pm	80	30	76
06:00 pm	28	68	20
08:00 pm	0	100	0

a. Using the same axes, plot graphs for this data (13 marks)

b. Describe the nature of the graphs (08 marks)

c. What are the interrelationships between;

i. Stomata opening and relative amount of starch in guard cells (01 mark)

ii. Stomata opening and relative intensity of sunlight (01 mark)

iii. Percentage of open stomata and time of the day (01 mark)

d. Explain these interrelationships? (16 marks)

4. a) Differentiate between Natural active immunity and Artificial active immunity (02 marks)

5. b) State the different ways in which the mammalian body naturally prevents pathogens from accessing its internal environment (11 marks)

c) What is the significance of the high body temperature experienced when the mammalian body is attacked by *Plasmodium Spp?* (07 marks)

6. Explain how water moves from;

a) From soil into the xylem (10 marks)

b) Through the stem xylem to the leaf (10 marks)

7. a) What is meant by the term chloride shift? (03 marks)

b) Account for the relative position of the oxygen dissociation curves of the human and rat haemoglobin

c) Explain the rapid dissociation of oxyhaemoglobin of a rat during a vigorous activity (07 marks)

8.) Describe the events which occur during the heart beat (16 marks)

b) Outline the features which ensure efficient flow of blood within the mammalian body (04 marks)

9. a) Describe the mechanism of stomatal movement based on osmotic pressure (08 marks)

10. Explain how each of the following affect the rate of transpiration

i. Temperature (07 marks)

ii. Sunken stomata (05 marks)

11. An experiment was carried out with cells of the carrot tissue which was first thoroughly washed in pure water. The slices of carrot tissue were immersed in an aerated potassium chloride solution of known concentration at varying temperatures. The results are shown in the table below. At the fourth hour, the carrot tissue at 25^0C was treated with potassium cyanide. Absorption of potassium ions is given in micrograms of potassium per gram of fresh mass of carrot tissue.

Time in minutes	Potassium ion uptake in µg g^{-1} fresh mass	
	At temperature of 2^0C	At temperature of 25^0C
0	0	0
60	90	170
120	105	300
240	130	480
300	130	500
360	130	500

a. Represent the above data graphically (10 marks)

b. Describe the changes in the rate of potassium ions absorption within the first four hours at temperature of 250C. (02 marks)

c. During the first hour, some potassium ions enter the carrot cells passively. Suggest any two passive means of their movement and any two conditions needed for one of them to occur. (04 marks)

d. (i) calculate the mean rate of absorption of potassium ions at 25^0C, between the 2^{nd} and 6^{th} hour (03 mark)

(ii) Compare the rates of absorption of potassium ions at 2^0C and 25^0C during the experiment (06 marks)

(iii) Suggest an explanation for the differences in the rates of absorption of potassium ions at the two temperatures. (05 marks)

a) Explain the effects of treating the carrot cells with potassium cyanide on the rate of their absorption of potassium ions. (03 marks)

b) Suggest;

i. The aim of the experiment (01 mark)

ii. Why the carrot tissue was first washed pure water (01 mark)

iii. Why the potassium chloride solution was aerated (02 marks)

12. (a) What is the physiological significance of the Bohr effect in animals? (08 marks)

(b) Discuss the factors that may alter the rate of heart beat in mammals (12 marks)

13. a) What are the essential features of the immune system in mammals?

b) (i) Give an account of the ABO blood group system in humans, and explain how certain ABO group donations cause agglutinations with the recipients, while others do not.
(ii) Besides blood, other tissues can be transplanted from one individual to another. Mention problems associated with them, and steps taken to minimize the transplant failures

14. b) Define the term **facilitated diffusion**
c) State **three** ways how facilitated diffusion differs from simple diffusion
d) Describe **one** way how facilitated diffusion occurs across membranes
e) State **two** ways how the action of carrier proteins is similar to that of enzymes

15. (a) What is meant by pressure potential? (03 marks)

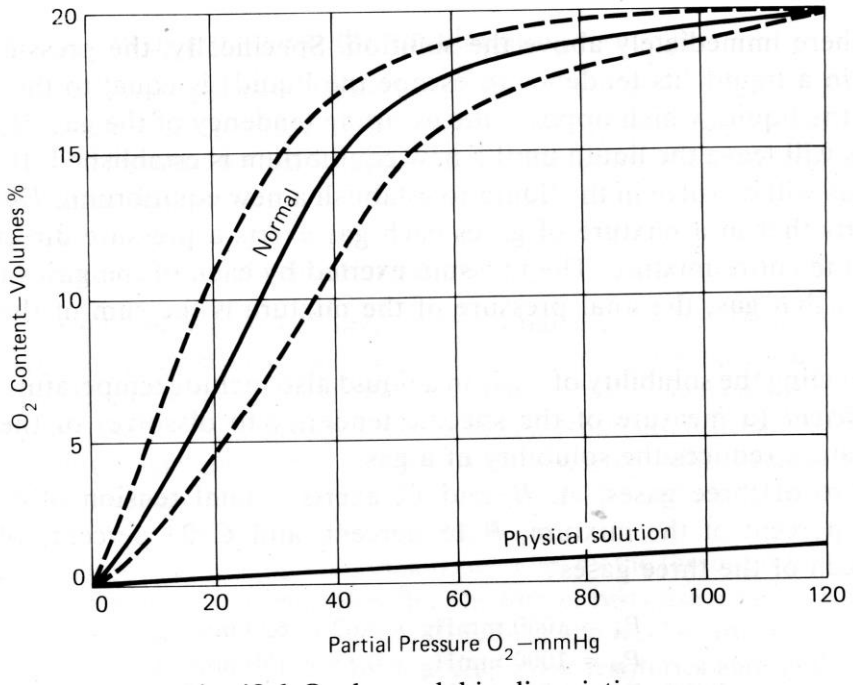
(b) What is the effect of lowering solute potential on the

i. Water potential of a plant tissue (03 marks)
ii. Mechanical support in herbaceous plants (04 marks

(c) Explain how organisms benefit from the possession of well developed transport systems (10 marks)

16. Briefly explain the significance of the existence of the Casparian strip within the endodermal cells of the root

17. Figure 3 shows the union of oxygen and haemoglobin in three different physiological conditions



The straight line near the bottom of the graph shows the uptake of oxygen by a solution when hemoglobin is not present while the dotted curves on either side of the solid curve shows the formation of oxyhaemoglobin under two different levels of carbon dioxide

a) Label the curves of blood in

(i) veins and muscles and
(ii) (ii) arteries and lungs (02 marks).

b) Explain the importance of the positions suggested above in the physiology of the animal (04 marks).

c) Explain the difference in the variation of the oxygen content of normal and physiological solutions(03 ma

17. (a) Describe the distribution of vascular and parenchyma tissues in plants
(b) Discuss the theories of stomatal opening in plants
(c) Discuss the theories of food transport in plants

18. (a) Describe the mechanism of mineral salt up take from the soil by the plant.

(b) Describe mass flow of organic food in plants

(c) What are the evidences and weaknesses of mass flow in plants?

19. (a) Give an account of the structures involved in the translocation of organic solutes between the different parts of a flowering plant.

(b) Briefly describe how dissolved blood carbon dioxide is expelled in gaseous form by the lungs.

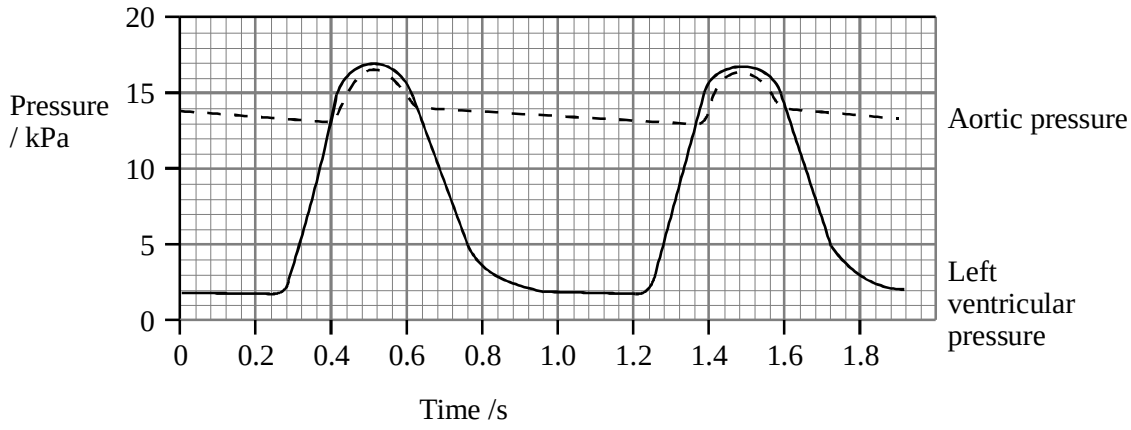
20. In fish, oxygen is transported in the blood in the form of oxyhaemoglobin. The table below shows the percentage saturation of blood with oxygen of a teleost (bony) fish after equilibrating with oxygen of different partial pressures. The experiment was carried out at two different partial pressures of carbon dioxide.

Partial pressure of oxygen in Pa	Percentage saturation of blood with oxygen	
	Partial pressure of carbon dioxide at 500 Pa	Partial pressure of carbon dioxide at 2600 Pa
500	30	5
1000	70	13
2000	90	24
3000	96	33
4000	98	41
5000	99	48
7000	100	60
9000	100	69
11000	100	76
13000	100	81

a) Present the data in a suitable graphical form.
b) Calculate the difference of percentage saturation of blood with oxygen at the two different partial pressures of carbon dioxide at oxygen partial pressures of 500 Pa.
c) With reference to the graph, describe the effects of different partial pressure of carbon dioxide on the percentage saturation of blood with oxygen.
d) Explain how changes in oxygen content of blood at different partial pressure of carbon dioxide are important in the release of oxygen to the tissues of fish.
e) What information do such experiments give about the environmental conditions in which fish would maintain a high level of growth as required in commercial fish farming?
f) Explain how the properties of haemoglobin molecule are affected by changes in the oxygen and carbon dioxide partial pressures.

21. (a) Distinguish between the terms **immunity** and **autoimmunity** (02 marks)
(b) Suggest **three** key roles played by the body's immune system (03 marks)
(c) State **three** ways body openings are protected from entry of pathogens (03 marks)
(d) State **two** human diseases resulting from autoimmune disorders (02 marks).

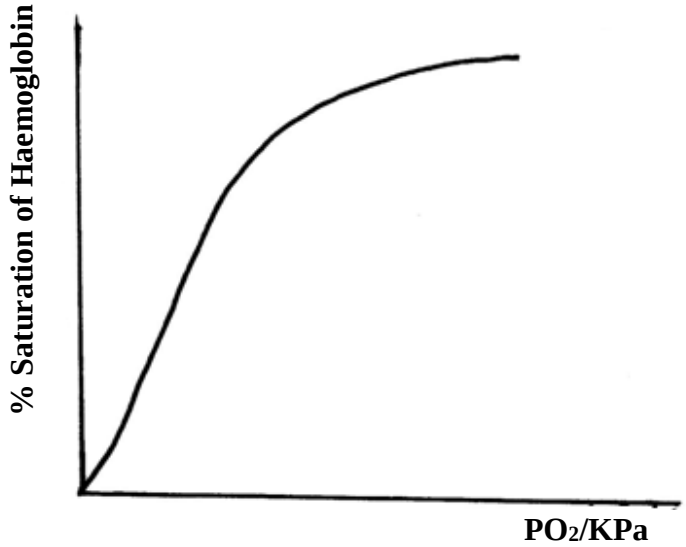
22. Figure below shows changes in the blood pressure in the aorta and the left ventricle during two complete cardiac cycles.



(a) On the graph, draw an arrow to show when the left atrioventricular (mitral) valve closes.(01 mark
(b) Use the information in the graph to calculate the heart rate. Show your working. (02 marks)

(b) During the cardiac cycle, the pressure in the left ventricle falls to a much lower level than in the aorta. Suggest an explanation for this difference. (03 marks)
(c) During the cardiac cycle, the pressure in the right ventricle rises to a maximum of about 3.3 KPa. Suggest reasons for the difference between this pressure and the maximum pressure in the left ventricle.(03 marks)

23. Blood that is fully saturated with oxygen carries 105cm^3 of oxygen in 1 dm^3(liter) of blood
(a) Calculate the volume of oxygen released from 1 dm^3 of blood when blood that has become 90% saturated at 38^{0}C reaches a part of the body where the partial pressure is 18% (03 marks)
(b) The figure below shows the oxygen dissociation curve of hemoglobin from a mammal at 38^{0}C.



(i) Draw the curve of hemoglobin when the body temperature is raised to 43^{0}C(01 mark)

(ii) Name one change in the conditions in the tissues which has the same effect on the oxygen dissociation curve as change in temperature (01 mark)

(iii) Explain the effect of increased body temperature on the oxygen dissociation curve for hemoglobin in mammals(03 marks)

(c) State how this effect of temperature on the oxygen dissociation curve of hemoglobin might be advantageous to the mammal (03 marks)

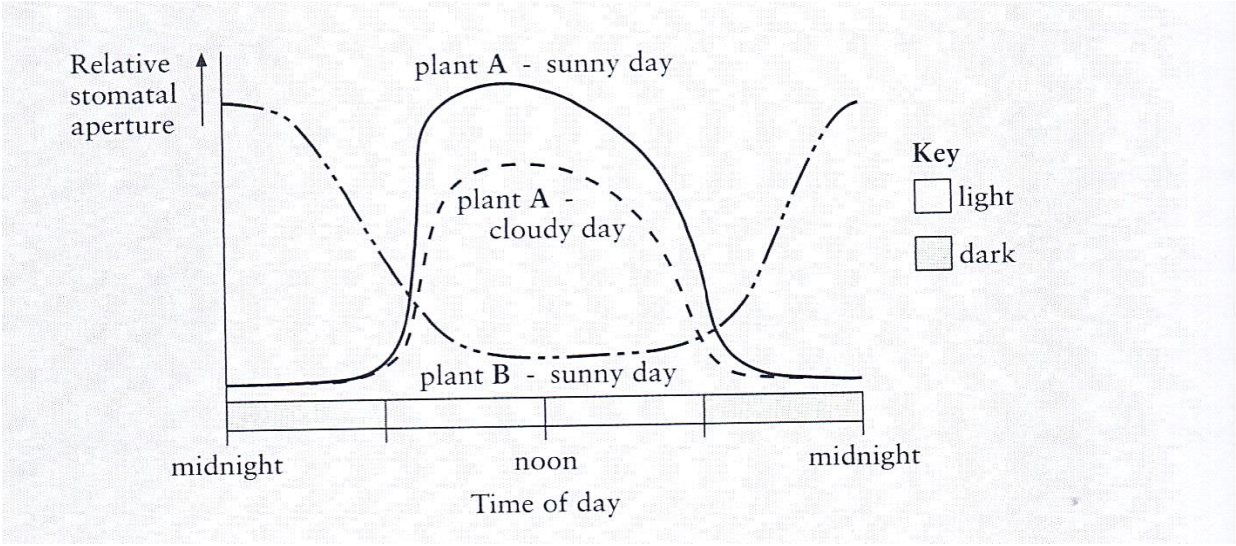
24.

a) State the parameters listed in **Fick's law** of diffusion (03 marks)

b) Explain how each parameter in **Fick's law** of diffusion is reflected in the structure of the mammalian lung (03 marks)

c) Explain the changes in oxygen delivery to the tissues that occur as a person proceeds from a resting state to intense exercise (04 marks)

25. The figure **below** shows the stomatal aperture changes in two plants ,**A** and **B** in different conditions



a) stomata open when guard cells absorb water because of a change in the water potential of their cell contents

b) Give **one** explanation for the mechanism that results in

i) a change in water potential of the guard cells in plant **A** between 06.00 and noon *(03 marks)*

ii) the stomata of plant **A** not operating as widely on the cloudy day as on the sunny day(*03 marks)*

b) Plant **B** is a succulent plant that lives in dry conditions

i) Give **one** advantage to plant **B** of the different behavior of its stomata *(03 marks)*

ii) Give **one** disadvantage to plant **B** of the different behavior of its stomata *(02 marks)*

26. The table below shows the results of an experiment on the rate of absorption of sugars by a mammalian intestine. Study it carefully and answer the questions that follow.

Sugar		Relative rates of absorption taking normal glucose uptake as 100	
		By living intestine	By intestine poisoned with cyanide
Hexose sugars	Glucose	100	30
	Galactose	106	35
Pentose sugars	Xylose	32	32
	Arabinose	30	31

a) Suggest a reason for the difference between the rates of absorption of hexose and pentose sugars in the living intestines (03 marks)

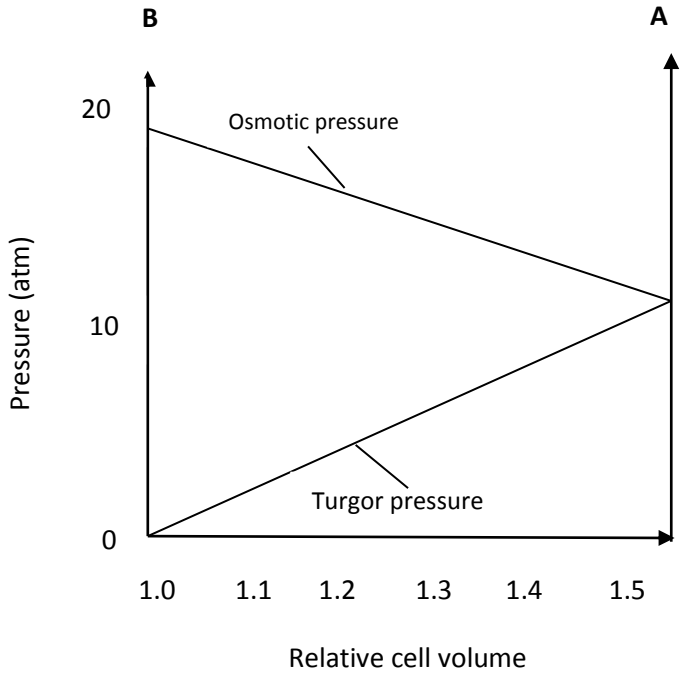
b) (i) Mention the mechanism by which hexose sugars are absorbed by living intestines ($0\frac{1}{2}$ mark)

ii) What is the advantage to the individual of having hexose sugars absorbed in the way mentioned above?

c) What could be the effect of cyanide on the mechanism of hexose absorption? (02 marks)

d) In an intact mammal, absorption of fatty acids is drastically curtailed by any clinical condition which leads to a reduction in bile salt excretion or release. Explain why this is so. (03 marks)

27. The figure below shows the relationship between pressure and cell volume of plant leaves. Study it and carefully and answer the questions that follow.

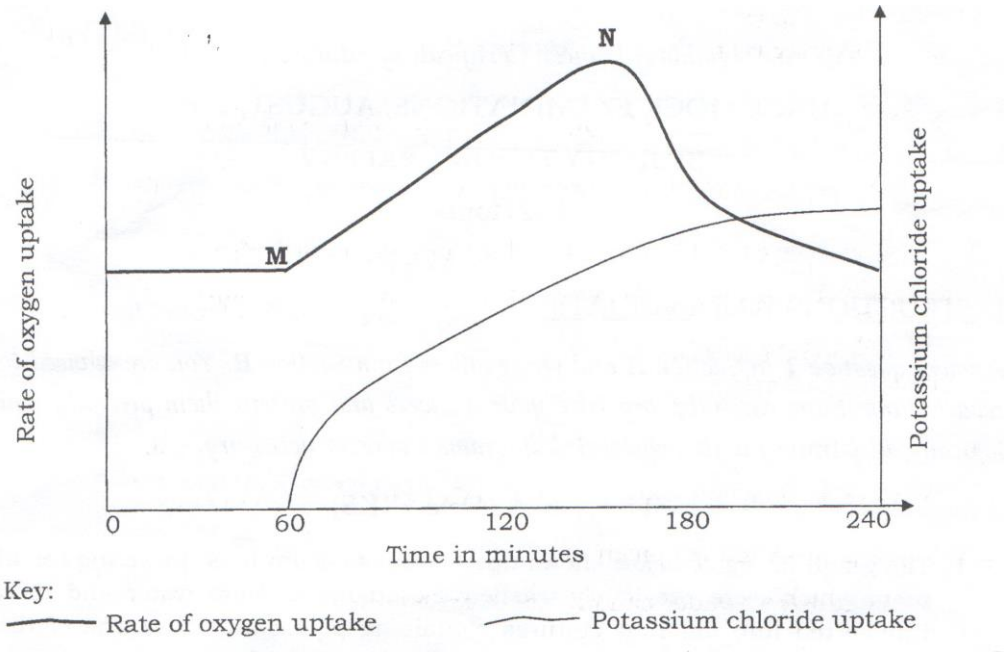


a. What is the condition of the cell at point (01 mark)
   i. A ii. B
b. State any effects of a cell at (04 marks)
   i. A ii. B
c. Explain why the osmotic pressure falls when the turgor pressure increases (05 marks)

28. (a) Explain why simple organisms do **not** have a transport system (02 marks)
(b) State three differences between vascular systems in higher plants and circulatory systems in higher plants and circulatory systems in mammals (03marks)
(c) Describe what happens in the following pathways during transport in plants
   i. The apoplast (02 marks)
   ii. The symplast (03 marks)

29. (a) What is meant by the term **Bohr's effect**? (02 marks)
(b) Briefly explain the following observations;
The oxygen dissociation curve of,
   i. man shifts to the right during exercise (03 marks)
   ii. the elephant is on th e left of the oxygen dissociation curve of a mouse? (03 marks)
   iii. thelungworm is on the left of that of man? (03 marks)

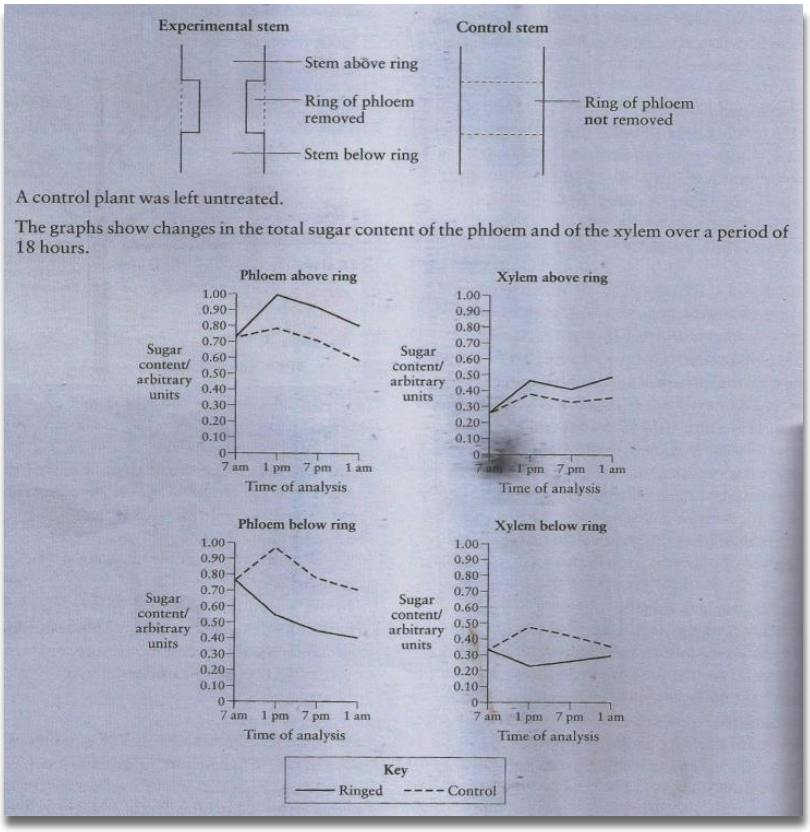
30. In an experiment a set of young cereal roots were washed thoroughly in pure water and transferred into culture solutions containing potassium chloride solution under varying oxygen concentrations (at point **M** on the graph below). After 160 minutes solution of unknown substance was introduced (at point **N** on the graph below). The rate of oxygen uptake and potassium chloride uptake were measured and recorded graphically as shown in the figure below.



a) Compare the rate of oxygen uptake with the rate of chloride uptake between 60 and 240 minutes.

b) Explain the rate of oxygen and potassium chloride uptake as shown in the graph above? (06 marks)

31. The figure **below** shows the effect of ringing the stem of a cotton plant with time



a) Explain the variation in the sugar content of the phloem of the plant over the period shown

i) above the ring *(03 marks)*

ii) below the ring *(02 marks)*

b) What evidence from the graphs supports the hypothesis that sugars can move laterally but not downwards in the stem ? *(02 marks)*

c) Explain why

i) both plants survive in the short run*(01 mark)*

ii) one of the plants eventually dies*(02 marks)*

32. **T**he relationship between potassium ion concentration in the roots and sugar consumption at different oxygen concentration was investigated.

The table below shows the concentration of potassium ions in $mgcm^{-3}$ and the rate of sugar consumption in $mghr^{-1}$ by roots of a freshly uprooted plant when inserted in a bathing fluid at different oxygen concentration.

Oxygen concentration (%)	0	2	5	10	20	30	50	70
Potassium ion concentration in gcm^{-3}	7	10	21	49	52	51	48	44
Rate of sugar consumption in $mghr^{-1}$	14	16	20	27	33	34	35	36

a) Represent the information above on the graph paper.(9 marks)

b) Compare the effect of oxygen concentration on potassium ion concentration in the roots and rate of sugar consumption from the graph.(3 marks)

c) Explain the:

i) Prescence of potassium ion concentration in the root wihout oxygen.(4 marks)

ii) Relationship between potassium ion concentration and oxygen concentration. (5 marks)

iii) Increase in the rate of sugar consumption with oxygen concentration (4 marks)

d) State two factors other than oxygen concentration that could affect the rate of potassium ion uptake by roots (2 marks)

e) Predict what would happen if the oxygen concentration was increased up to 98%. Explain your answer. (3 mar

f) State two main mechanisms of uptake of mineral salts by plants and give three differences between them

g) Outline two factors that can influence the process of potassium ion uptake investigated in this experiment other than sugar and oxygen concentration (02 mks)

33. a) Describe the Cohesion-tension theory water movement in the xylem

b) State the importance of transpiration to plants.

c) Briefly describe how xylem is formed from a meristematic cell

d) How is the rate of transpiration controlled in plants

e) Explain why certain plants may fail to absorb water in water logged soils

34. The table below shows the difference in percentage saturation in blood with oxygen at varying partial pressure of oxygen between a pregnant woman and that of the fetus developing in her uterus.

Partial pressure of oxygen /mmHg	Percentage saturation of blood with oxygen	
	mother	Fetus
1.3	8	10
2.7	20	30
3.9	40	60
5.3	65	77
6.6	77	85
8.0	84	90
9.3	90	92
10.6	92	92

i) Plot the results in a suitable graphical form. (08 marks)

ii) Compare the percentage saturation of blood for the mother and that of the fetus.(04 marks)

iii) State and explain the shape of the curve for the mother. (07 marks)

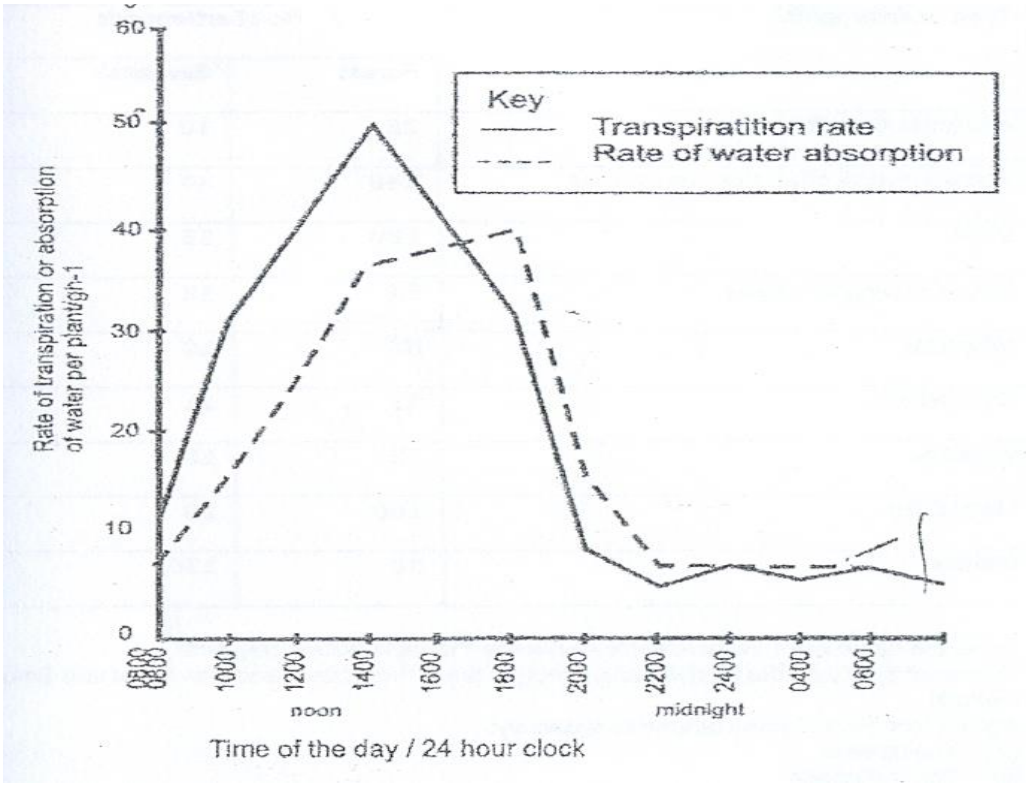
iv) Explain the physiological significance of the position of the fetal curve (05 marks)

b) Explain what is meant by: (06 Marks)

i) Bohr's effect ii) Loading tension iii) Un loading tension

c) Explain three factors that influence the affinity of haemoglobin for oxygen (06 marks)

35. An investigation was carried out to establish the relationship between the rate of water absorption and its rate of transpiration in sunflower plants at various times of the day. The results are shown in figure 1 below.



ai) Describe the changes in the rate of transpiration that took place during the experiment (10 marks)

ii) Suggest why these changes occurred (05 marks)

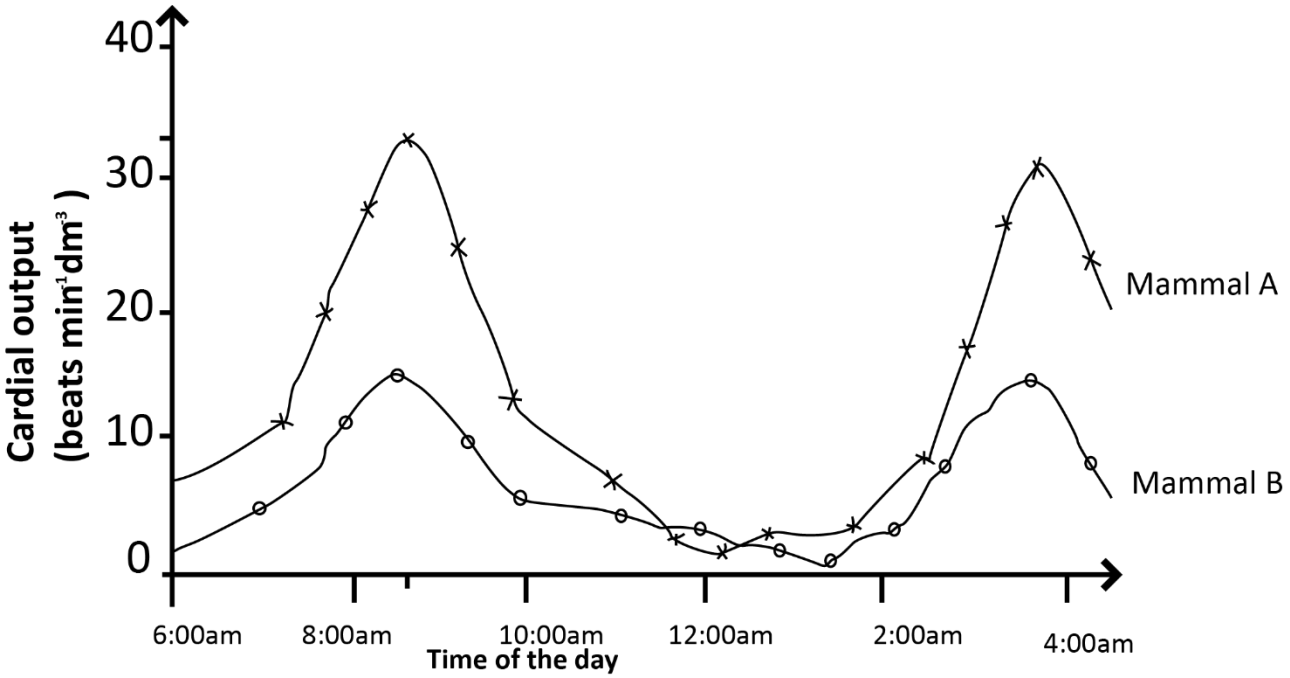
b) Comment on the relationship between the rate of transpiration and the rate of water absorption during the experiment. (04 m arks)

c) Why is transpiration a necessary evil? (06 marks)

d) Describe fully the passage of water from the soil to the xylem tissue of plant roots (10 marks)

e) Explain why according to pressure flow hypothesis, translocation can only take place in living phloem.

36. a) The figure shows the changes in the cardiac output of two individual Mammals and A and B of different sizes, determined from 6:00a.m up to 4:00p.m in the evening when the mammals were given a hot drink.



(i) Compare the cardiac output of both mammals. (04marks)

(ii) Explain the effect of day time on the cardiac output of both mammals. (08marks)

(iii) Comment on the difference in the cardiac output both mammals. (04marks)

(iv) Suggest factors that are likely to affect the cardiac output of a mammal. (03marks)

b) The table below shows the volume of blood flowing from the left vertical side of the heart of various parts of the body in one minute at rest and during a heavy exercise.

Organ	**Volume of blood/cm^3**	
	Rest	**Exercise**
Brain	750	750
Hear Muscle	250	750
Skeletal muscle	1,200	1,250
Skin	500	1,900
Kidney	1,100	600
Other organs	2,000	1,000

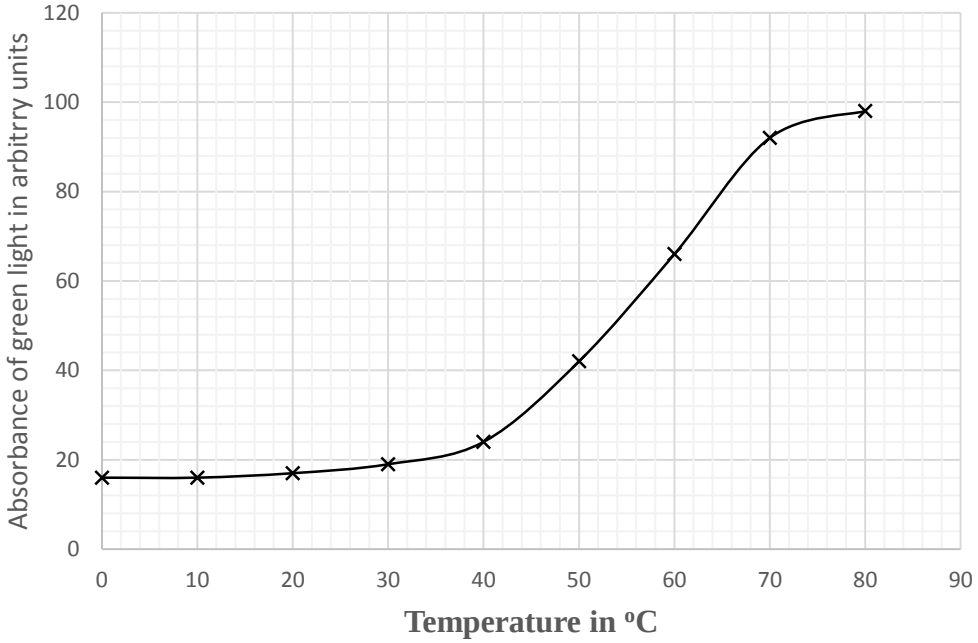
(i) Calculate the percentage increase in blood flow from rest to exercise in skeletal muscle. (03 marks)

(ii) Give three ways in which the increase in b(i) is achieved. (03 marks)

(iii) Explain the changes in volume of blood flow rest to exercise to various parts of the body. (11 marks)

(iv) Suggest with reasons the likely changes in composition of blood as it flows through the kidney. (04 marks)

37. Beet root cells contain a pigment that cannot normally escape from the cells through the cell surface membrane. The graph below shows the results of an investigation into the effect of temperature on the permeability of the cell surface membrane of beet root cells. The permeability was measured by using a calorimeter to measure the absorbance of green light by the solution in which samples of beet root had been immersed. The greater the absorbance, the more red pigment had leaved out of the beet root cells.



(a) Describe the changes in the absorbance of green light with temperature. (4 marks)
(b) What is the general effect of temperature on the absorbance of light? (1 mark)
(c) With reference to the structure of cell membranes, explain the effect of temperature on absorbance. (4 marks)
(d) State one other way in which membrane permeability could be altered. (1 mark)

38. An experiment was carried out with cells of the carrot tissue which was first thoroughly washed in pure water. The slices of carrot tissue were immersed in an aerated potassium chloride solution of known concentration at varying temperatures. The results are shown in the table below. At the fourth hour, the carrot tissue at 25^0C was treated with potassium cyanide. Absorption of potassium ions is given in micrograms of potassium per gram of fresh mass of carrot tissue.

Time in minutes	Potassium ion uptake in µg g^{-1} fresh mass	
	At temperature of 2^0C	At temperature of 25^0C
0	0	0
60	90	170
120	105	300
240	130	480
300	130	500
360	130	500

a. Represent the above data graphically
b. Describe the changes in the rate of potassium ions absorption within the first four hours at temperature of 25^0C.
c. During the first hour, some potassium ions enter the carrot cells passively. Suggest any two passive means of their movement and any two conditions needed for one of them to occur.
d. (i) calculate the mean rate of absorption of potassium ions at 25^0C, between the 2^{nd} and 6^{th} hour
(iii) Compare the rates of absorption of potassium ions at 2^0C and 25^0C during the experiment

(iii) Suggest an explanation for the differences in the rates of absorption of potassium ions at the two temperatures.

e) Explain the effects of treating the carrot cells with potassium cyanide on the rate of their absorption of potassium ions. Suggest;

iv. The aim of the experiment
v. Why the carrot tissue was first washed pure water
vi. Why the potassium chloride solution was aerated

f) Briefly explain the significance of the existence of the **Casparian strip** within the endodermal cells of the root

39. Two investigations concerning movement of substances in and out of cells were carried out in 2 different organisms and results were summarized in tables 1 and 2 as indicated below.

The first investigation had 2 experiments. In the first experiment the marine ciliate *corthurnia* was placed in a series of dilutions of sea water and the output of its contractile vacuole was measured. In another experiment, the change in volume of the organism in different dilution of sea water was recorded.

Added fresh water/%	0	10	20	30	40	50	60	70	80	90
Contractile vacuole out put/dm^{3}s^{-1}	0.7	0.6	1.1	1.0	1.5	2.4	6.3	18.2	35.1	9.5
Relative body volume	1.0	1.1	1.2	1.3	1.4	1.6	1.8	2.0	2.1	2.0

In the second investigation, the relative rate of uptake of glucose and xylose (a pentose) from living intestine and from intestine which had been poisoned with cyanide, was determined and results recorded in table 2

Sugar	Without cyanide	With cyanide
Glucose	100	28
xylose	18	18

a) Represent graphically the results in table 1 using a single set of axes (06 marks)

bi) Explain the effects of dilutions on the activity of the contractile vacuole(04 arks)

ii) what do changes in relative body volume indicate about the effect of the contractile vacuole activity?

c) Some species of marine protozoa form contractile vacuoles only the protozoan begins to feed . Suggest an explanation for this observation. (03 marks)

d) How is active transport:

i) similar to facilitated diffusion (02 marks)

ii) different from facilitated diffusion (03 marks)

e) Explain the relative uptake of the sugars by the intestines (05 marks)

f) How do the following factors affect the rate of diffusion across a membrane

i) concentration difference, (02 marks)

ii) the size of the molecules(02 marks)

iii) temperature (02 marks)

iv) polarity of the molecules(02 marks)

h) state the composition and major function of the animal's cell surface.(03 marks)

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