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.

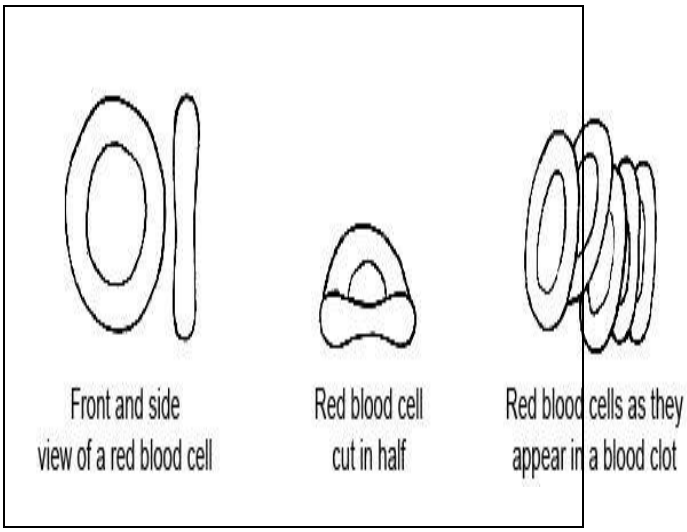
Adaptations of erythrocytes

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 lack a nucleus so as to provide enough space for haemoglobin in order to carry a lot of oxygen in form of oxyhaemoglobin.
iii. They have a red pigment called haemoglobin in their cytoplasm which has a high affinity for oxygen and therefore rapidly transports oxygen.
iv. They have a thin and permeable membrane which enables faster diffusion of oxygen and carbon dioxide into them.
v. 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.

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

vi. 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.

Diagrams 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;

a. Granulocytes
b. Agranulocytes

a) Granulocytes (polymorphonuclear leucocytes)

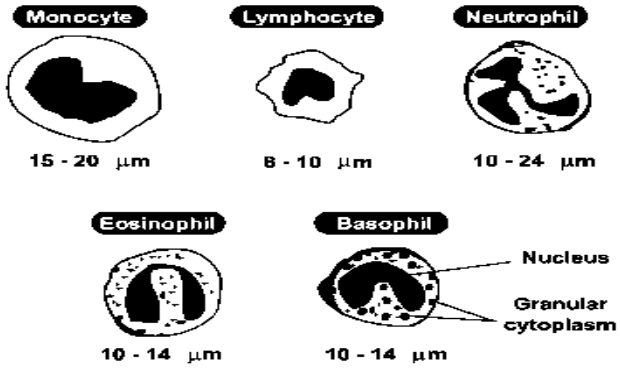
These are leucocytes with granules in there cytoplasm and a lobed nucleus. They originate in bone marrow. There are three types of granular leucocytes which include;

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.



b) 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.

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.

Assignement;\

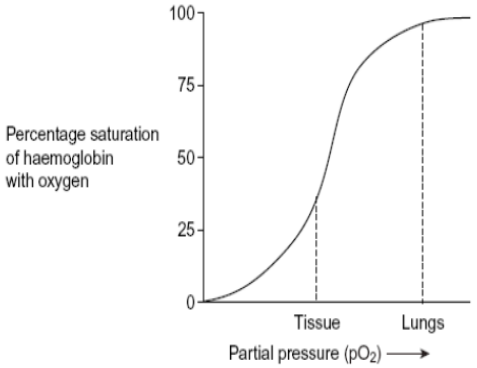
a. With the aid of a diagram, describe the structure of the haemoglobin molecule

b. 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.



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.

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

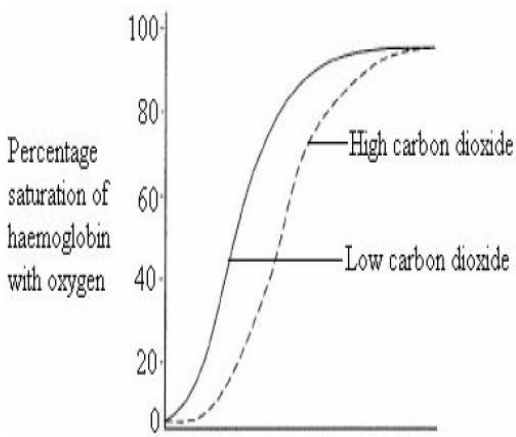
$$C_6H_{12}0_6 + 6O_2 \quad \leftrightarrow \quad 6CO_2 + 6H_2O$$

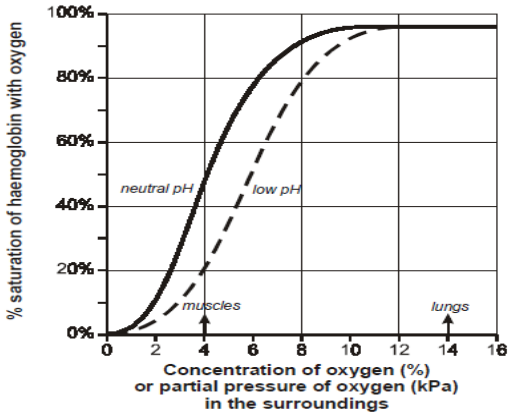
Increase in carbon dioxide concentration decreases the affinity of haemoglobin for oxygen, by making the pH of the surrounding medium more acidic (low), thereby shifting the oxygen dissociation curve to the right. This shifting of the curve to the right is known as **Bohr's effect** i.e. the shifting 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.

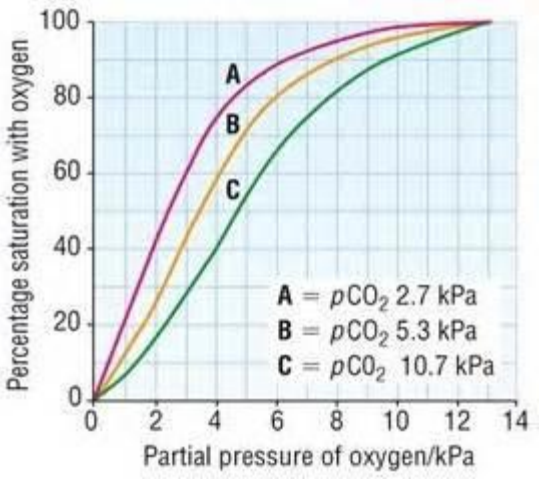
Bohr's effect may be defined as the lowering of the affinity of blood's haemoglobin for oxygen due to increased acidity caused by increase in carbon dioxide concentration.

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 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.

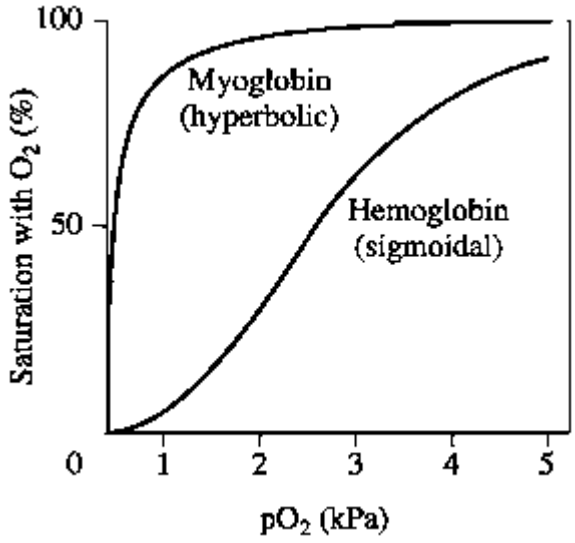
Note; smokers have 10% of their total haemoglobin in form of carboxyhaemoglobin.

Myoglobin and other pigments

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 below.

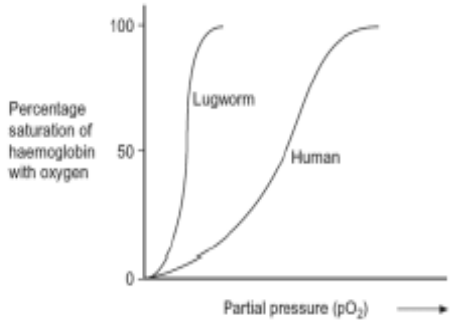


Note;

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.

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

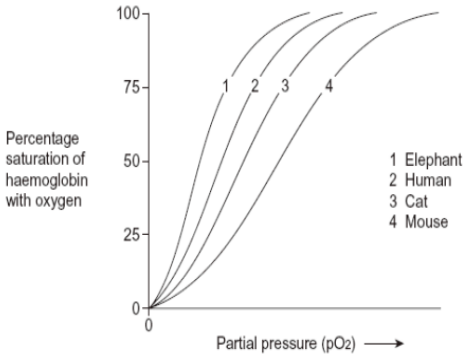
The oxygen dissociation curve of the lugworm's haemoglobin lies on the left of that of man's haemoglobin as shown in the graph below;



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.

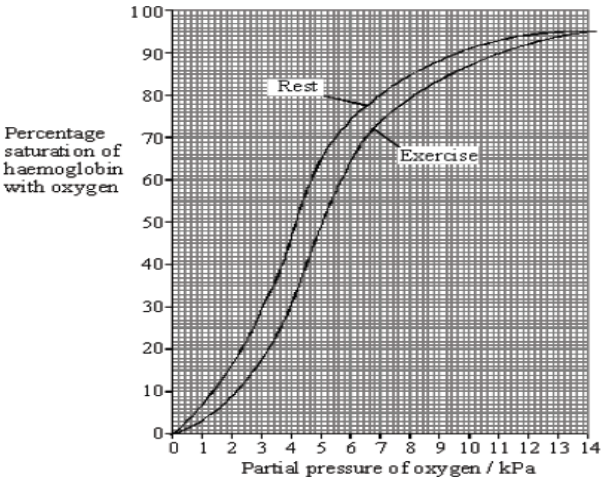
This implies that the lugworm's haemoglobin dissociates to release oxygen to its tissues compared to that of man which makes the lugworm less active than man, who releases much oxygen rapidly to the tissues.

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

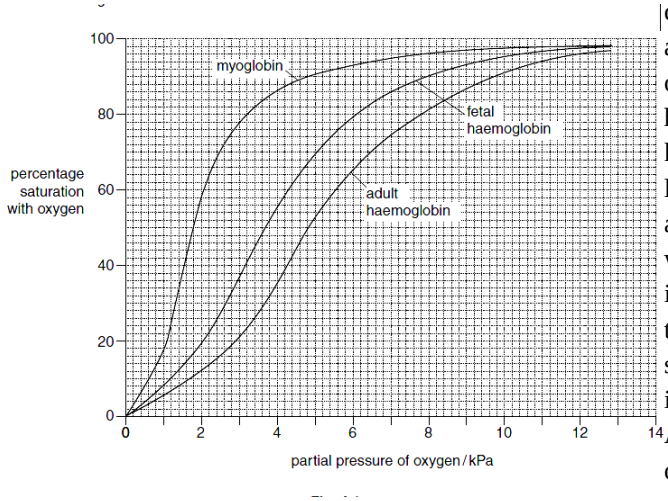
Comparison between the oxygen dissociation curves at rest and during exercise



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.

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 below;



This indicates that the foetal hemoglobin has a higher affinity for oxygen than that of man. 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.

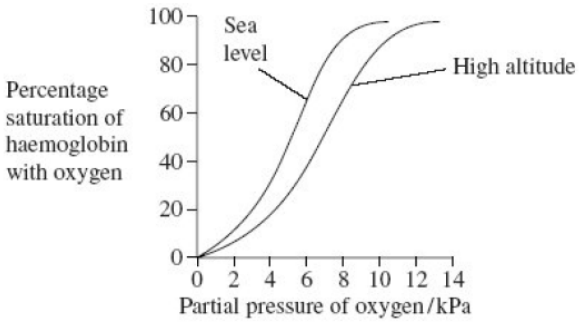
Effect of changing altitude on oxygen carriage

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.

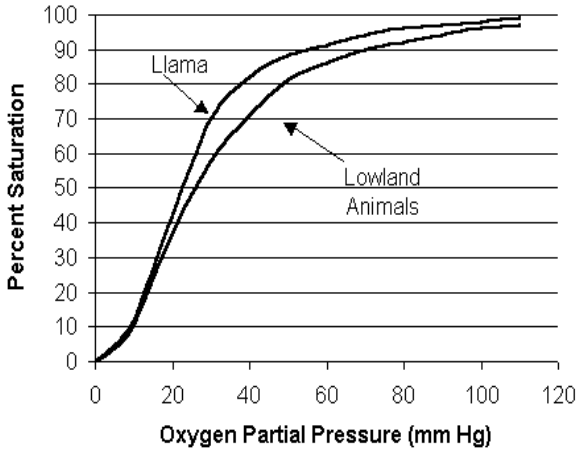
The amount of haemoglobin and the red blood cell count increases together with the rate of breathing and the heart beat. More red blood cell formation occurs in the bone marrow under the control of the hormone called *erythropoietin* secreted by the kidney. Secretion of erythropoietin is stimulated by 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



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 below;

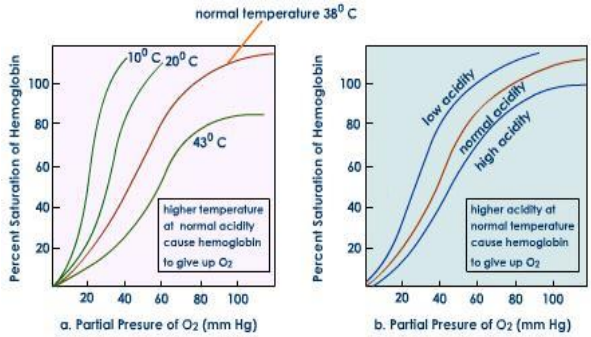


Effect of temperature on haemoglobin oxygen dissociation curve

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;

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

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

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.

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

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**

$H^+ + Hb \longleftrightarrow HHb$

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.

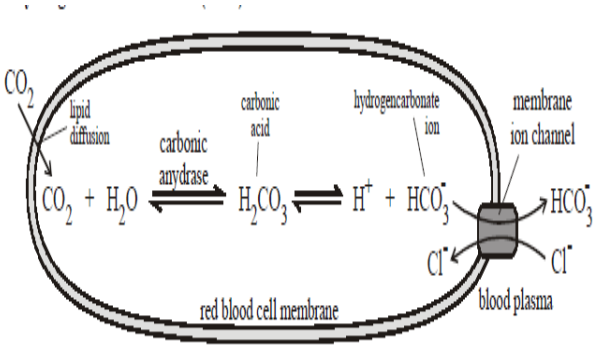
The outward movement of bicarbonate ions from the erythrocytes into the plasma results into an imbalance of positively charged and negatively charged ions within the cytoplasm. In order to maintain electrochemical neutrality, to remove this imbalance in the red blood cells, chloride ions diffuse from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

$H^+ + HCO_3^- \longleftrightarrow H_2CO_3$

$H_2CO_3^- \longleftrightarrow H_2O + CO_2$

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;

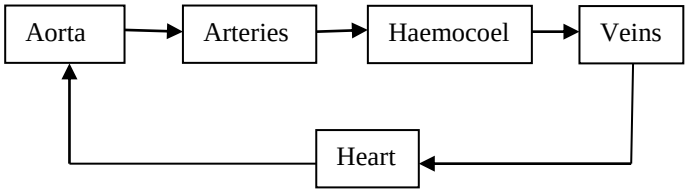
- Surface area of the organism
- Surface area: volume ratio of the organism
- Activity of the organism
- The diffusion distance for the transported substances between the tissues to and from their sources.

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.

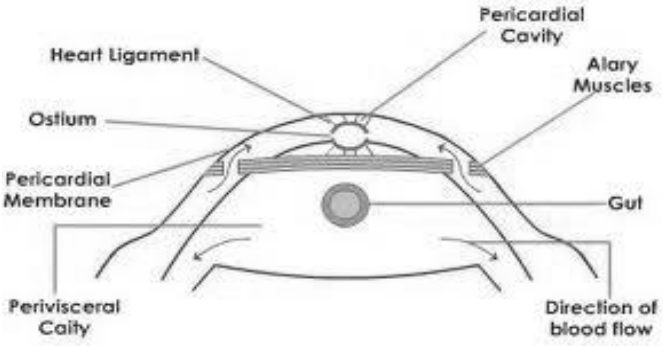
In this system, blood is pumped by an aorta which branches into a number of arteries which open into the haemocoel. From the haemocoel, blood under low pressure moves slowly to the tissues where there's exchange of materials e.g. gases, nutrients e.t.c. from the haemocoel blood percolates back into the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

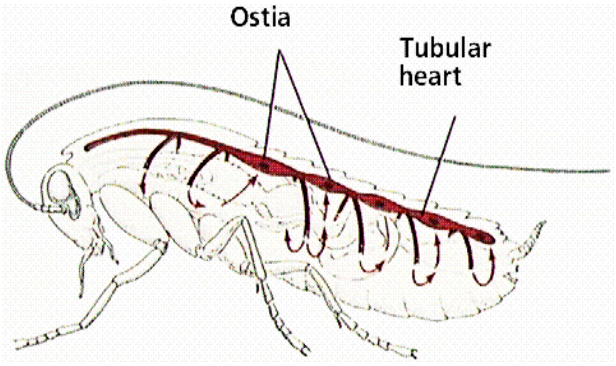


In insects the haemocoel is divided into two parts by a transverse pericardial membrane forming a pericardial cavity dorsally and the ventral perivisceral cavity. In the body of the insects there are no blood vessels except the tubular heart which is suspended in the pericardial cavity by slender

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





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

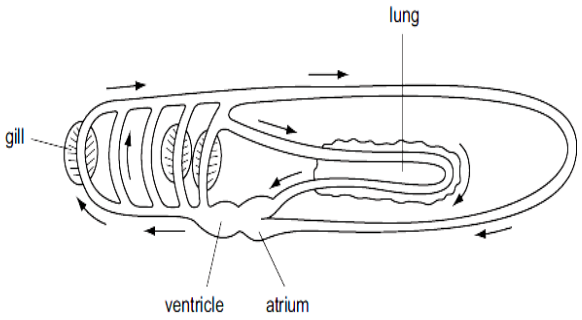
In a closed vascular system, blood flows in blood vessels or sinuses. It occurs in all vertebrates, annelids such as earthworms, cephalopods and echinoderms. The distribution of blood in this system is therefore adjustable e.g. blood from the heart is at high pressure and that to the heart is at low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

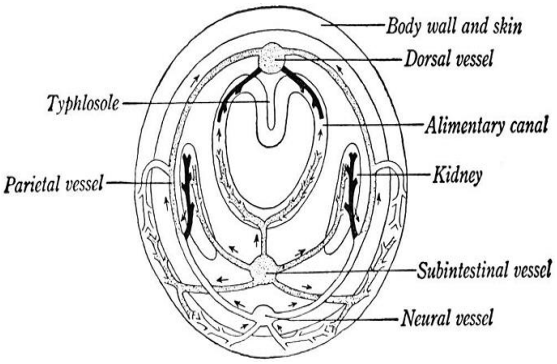
Diagram showing single circulation in fish



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



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

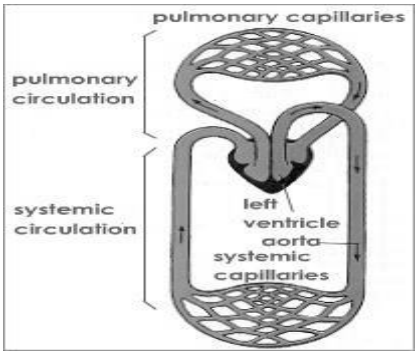
Double circulation is the flow of blood through the heart twice for every complete circulation around the body.

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.

Diagram showing double circulation in a frog and a mammal



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.

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;

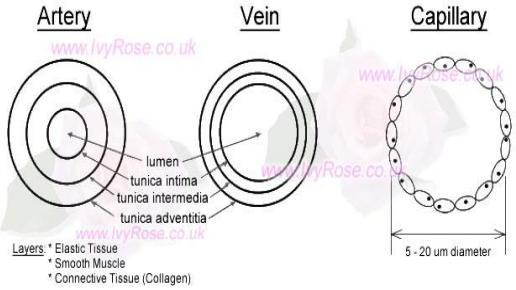
a. Tunica externa (outer most layer)
b. Tunica media (middle layer)
c. Tunica interna (inner most layer

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.

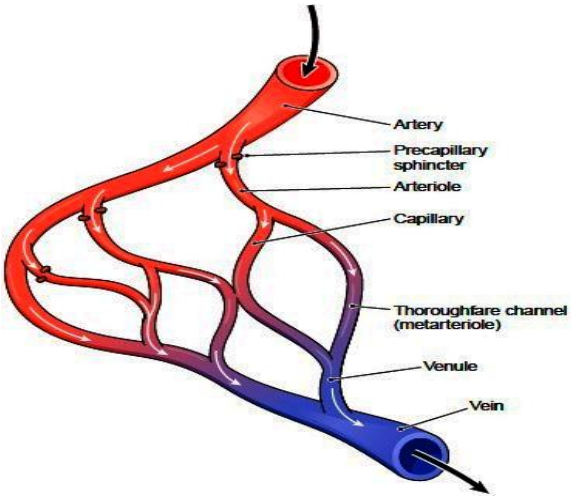
Arteries transport oxygenated blood from the heart to the tissues except the pulmonary artery which transports deoxygenated blood from the heart to the

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

1. 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.
2. 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.
3. 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 arteriovenous 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



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.

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

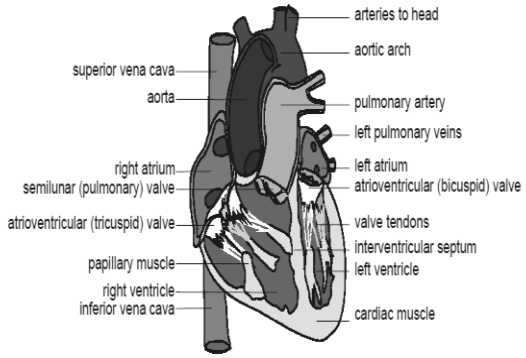
b. The two (2) flapped bicuspid valves which prevent back flow of blood from the left ventricle to the left ventricle.

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.



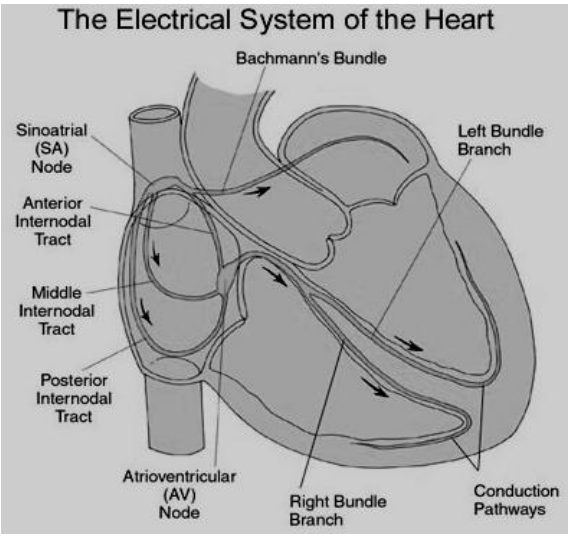
Initiation of the heart beat

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.

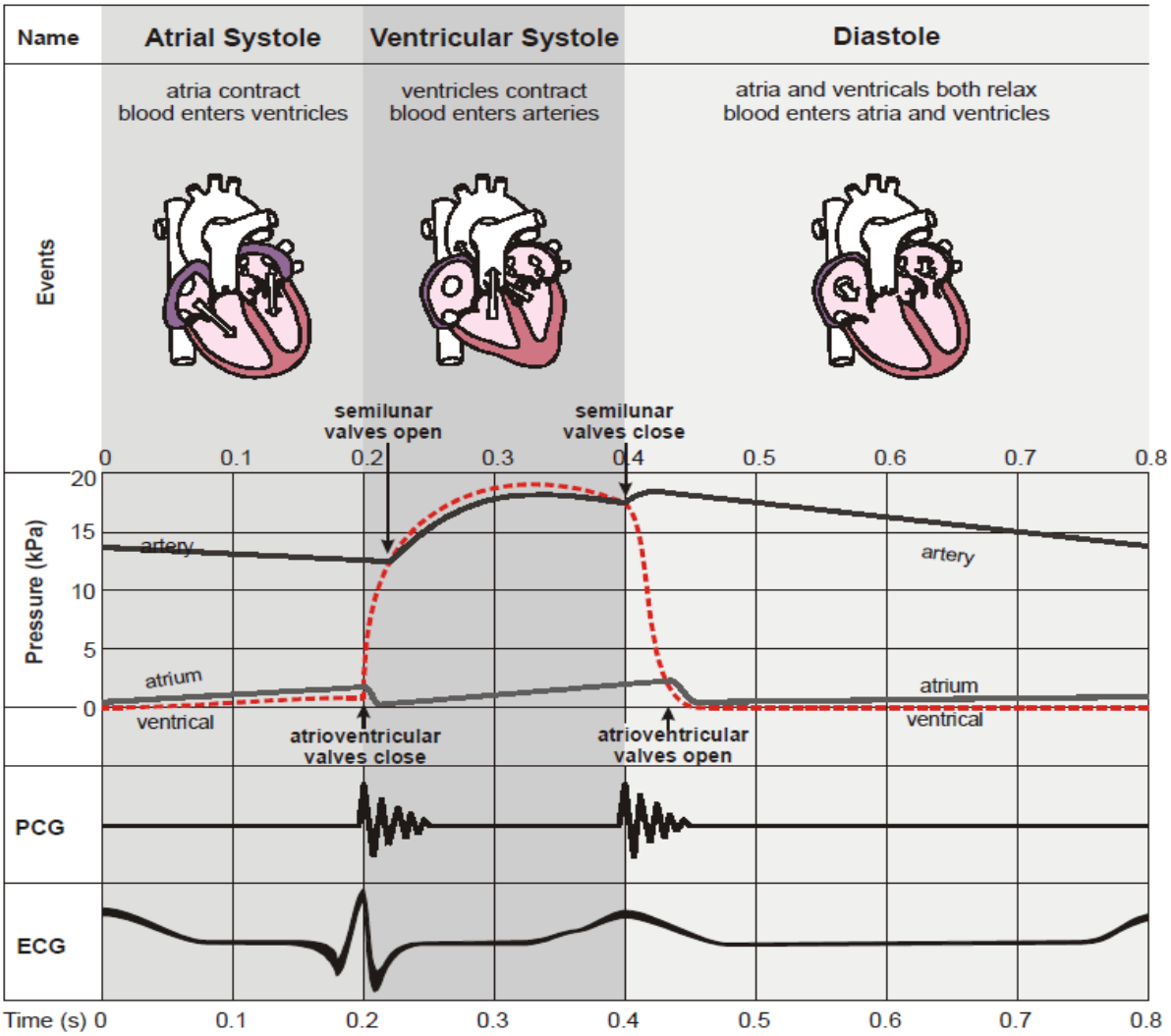
When the electrical excitations reach the junction at the boundary of the atria, they excite another specialised plexus of other cardiac muscle chambers known as Atrio Ventricular Node (AVN). When excited, the AVN sends waves of electrical excitations down to another bundle of cardiac muscle of fibres 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



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 (or 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 o 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 SAnode 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 AVnode 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.

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**

Internal factors affecting the heart beat

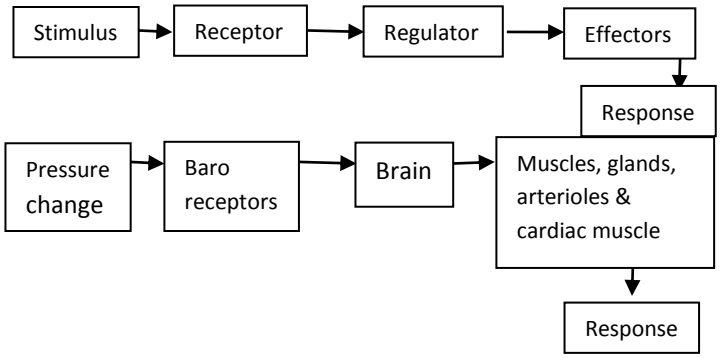
1. Body temperature
2. Blood pH
3. Carbon dioxide concentration
4. Partial pressure of oxygen
5. Hormonal balance
6. Salt balance
7. Blood pressure
8. Emotional situations
9. Impulses from the venacava and aorta

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

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.

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.

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.

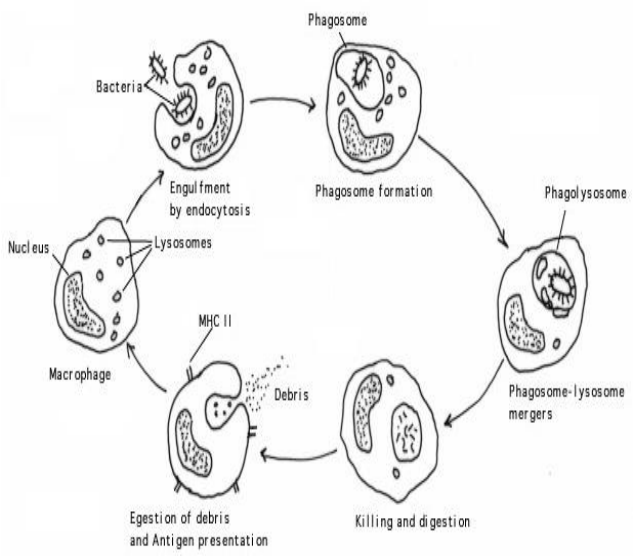
Phagocytosis

This is mainly carried out by neutrophils and macrophages obtained from Monocytes. These are amoeboid cells attracted to areas where cell and tissue damage has occurred. The neutrophils are able to recognize any invading bacterial cells. This capability of neutrophils is enhanced by plasma proteins called opsonins which become attached to the surface of the bacteria and in some way make them easily recognize by the neutrophils. The neutrophils bind to the bacteria so as to carryout Phagocytosis. After binding themselves to the bacteria, the bacteria are engulfed in an amoeboid fashion and then a **phagosome** is formed. Small lysosomes called primary lysosomes within the neutrophils fuse with the phagosome to form a **phagolysosome**. Hydrolytic enzymes are then poured into the phagolysosomes from which the lysosomes and the bacteria are digested. The soluble materials of bacterial secretion are then absorbed in the surrounding cytoplasm of neutrophils.

Neutrophils are able to squeeze themselves through the walls of blood capillaries, a process called ***diapedesis*** and move about in the tissue spaces.

In organs such as the liver, spleen and lymph nodes are large resistant phagocytic monocytes known as **macrophages.** The macrophages together with the neutrophils form the body's reticulo-endothelial system that defects the body against diseases.

Diagrams showing the process of Phagocytosis of a bacterium by a neutrophil



Immune response to infection

Immunity is the capacity of an organism to recognize the entry of materials foreign to the body and mobilize cells and cell products to remove such foreign materials with greater speed and effectiveness.

Immunity involves recognition of the foreign material (antigen) and production of chemicals which destroy it (antibodies). **An antibody** is a protein synthesized by plasma cells derived from lymphocytes in response to the presence of the foreign substance called **antigen** for which it has a high affinity. Antigens are foreign materials such as pathogens, toxins and foreign blood cells to the body which stimulate antibody formation to fight them. When antigens gain entry into the body, they stimulate the production of antibodies which react with antigens and destroy them or inactivate them. Antibodies are formed in response to specific antigens and are named according to the type of their activity as follows;

a) Opsonins
These are antibodies which get attached onto the surface of the pathogens to enable phagocytic leucocytes such as neutrophils to

recognize the pathogens, then engulf and destroy them.

Opsonisation is the coating of bacteria with proteins called opsonins so that they can be easily destroyed by phagocytic enzymes.

b) Agglutinins

These are antibodies which cause foreign cells in the specific antigen to clamp together making them more vulnerable to attack from other types of antibodies. The process is called **agglutination.**

c) Lysins

These are antibodies which attach themselves on the antigens (foreign bodies) causing such antigens to burst and rapture in smaller pieces. The process is called **lysis.**

d) Antitoxins

These are antibodies produced in response to particular bacterial toxins to which they bind and neutralize their harmful effect. The process is called **neutralization.**

e) Precipitin

This is antibody which combines with its specific soluble antigen to form a precipitate which is more easily ingested by phagocytes. This process is called **precipitation** i.e. a process in which precipitin antibodies binds together soluble antigens into larger units which are easily ingested by the phagocytes.

The production of antibodies in response to specific antigens is called **immune response.**

B and T-Lymphocytes

Lymphocytes are stimulated by antigens to produce an immune response. There are two types of lymphocytes, B and T, which produce antibodies directly or indirectly. The B-cells originate in the bone marrow from the **stem cells.** T-cells are so called because they are formed by a process in the thymus gland before entering the lymph nodes by osmosis. Inside the lymph nodes, the T-lymphocytes do not produce antibodies but in case of a particular antigen entering the lymph nodes, these divide by mitosis and give rise to different types of T-cells which include the following;

a. 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.

b. 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.

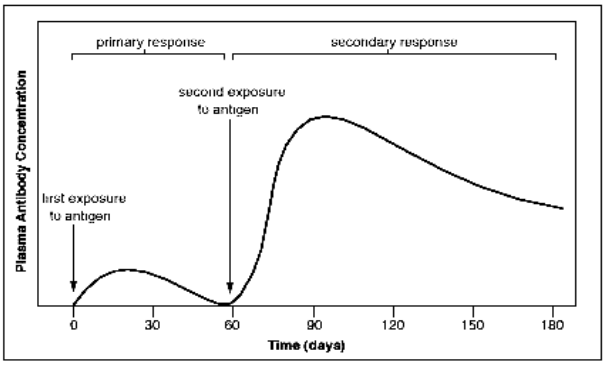
c. Suppressor T-cells

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 B-Cells

In the presence of microbes, the receptors on the surface of B-lymphocytes membranes, detect the microbes and become stimulated to undergo rapid proliferation to form memory B-cells and plasma cells.

The memory B-cells have the ability to identify the microbe on reinfection and then stimulate a rapid immune response in terms of antibody production such that the microbes are cleared out of the body rapidly before they cause a damage which is significant.

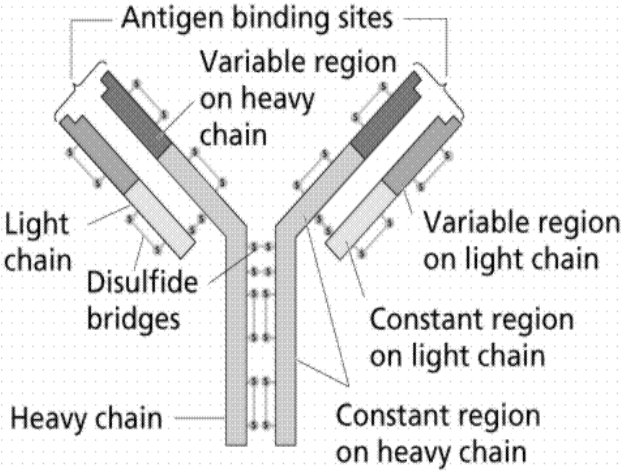


Structure of antibodies

An antibody is a protein molecule produced by the body of an animal in response to a particular antigen for which it has a high affinity.

An antibody is a protein molecule called **immunoglobulin (IG)** composed of four polypeptide chains linked together by disulphide bonds. Two chains are long and slightly bent at the hinge and are referred to as the heavy chains while the two other polypeptide chains are short poly polypeptide chains. Each polypeptide chain is composed of a constant and a variable region whereby the constant region is the one composed of the same amino acid sequence in all different molecules of antibodies while at the variable region, the amino acid sequence varies with different molecules of antibodies. At one end, the two linked heavy and light chains is an antigen binding site where a specific antigen becomes attached.

Its structure is shown in the diagram below.



An antigen is any foreign material to the body which stimulates the body to produce antibodies.

Types of immunity

These include the following;

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. **Acquired passive immunity**
   This is the immunity in the body whereby the antibodies in the body of an organism are extracted and injected into the body to offer temporary immunity e.g. the antibodies for tetanus.
3. **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.
4. **Acquired active immunity**
   This involves introducing a small amount of antigens (vaccines) orally or by injection into the body of an organism to provoke and stimulate it to produce corresponding antibodies. This results in rapid immune response towards the living microbes in case of an infection because of production of memory B-cells which cause greater production of many antibodies on second infection.

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 antigen B 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 occurs

Individuals with blood group AB posse 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 **erythroblastosis foetalis** (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.

UPTAKE AND TRANSPORT IN PLANTS

Water and mineral salts are necessary for photosynthesis 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.

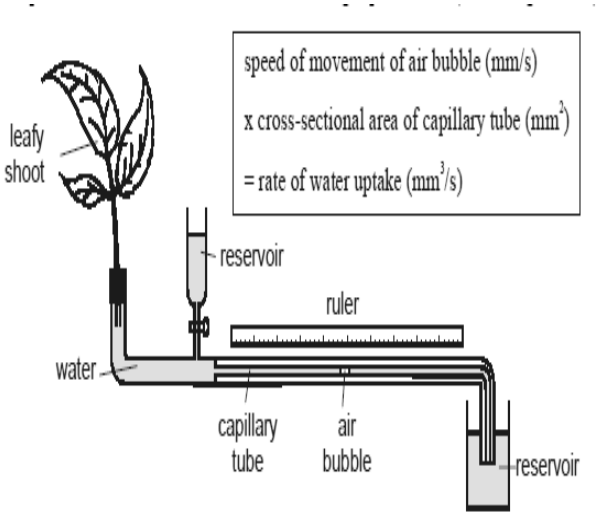
However, since most of the water taken up is lost by transpiration, it is assumed that water uptake ≈ water loss. The leafy shoot is cut under water to prevent the air bubbles from entering and blocking the xylem vessels. The cut leafy shoot is immediately fixed in the sealed vessel of connected to the 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

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

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.



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

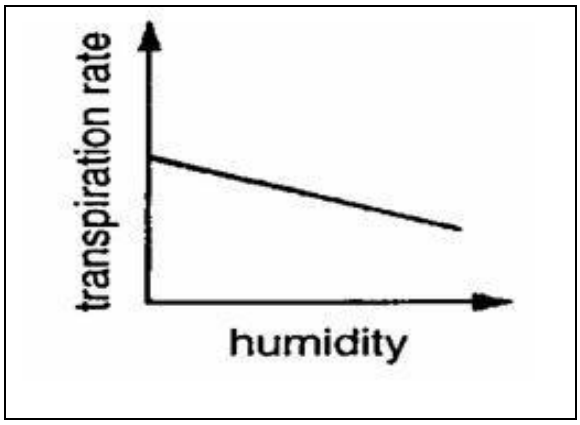
The potometer may be used to investigate the effect of environmental factors on the rate of transpiration i.e. it can be moved to a windy place or a place which is dark. Transpiration is affected by both environmental and non-environmental factors.

ENVIRONMENTAL FACTORS

1. Humidity

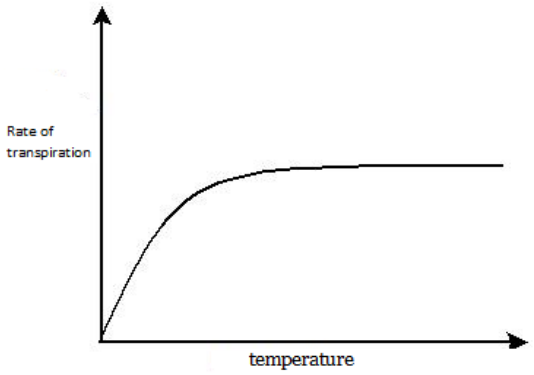
The humidity of the atmosphere affects the gradient of water vapour between the sub-stomatal air

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.



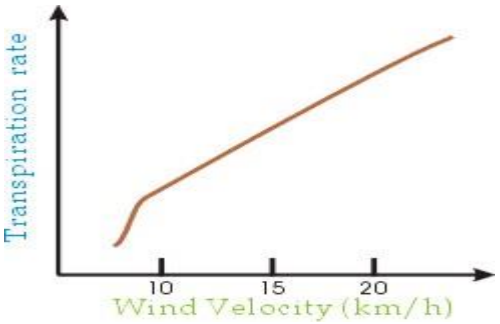
2. Temperature

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.



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.

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.

WATER UPTAKE BY THE ROOTS

Internal structure of the root

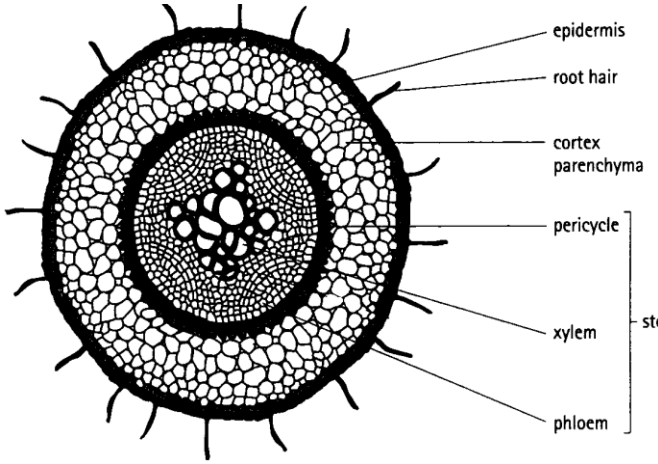
The root consists of various tissues which occur in concentric layers. The cells at the surface of the young root forming the peliferous layer are so called because it is by the root hairs. As the roots get older, they increase in girth (thickness or diameter) and the peliferous layer (breaks) raptures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

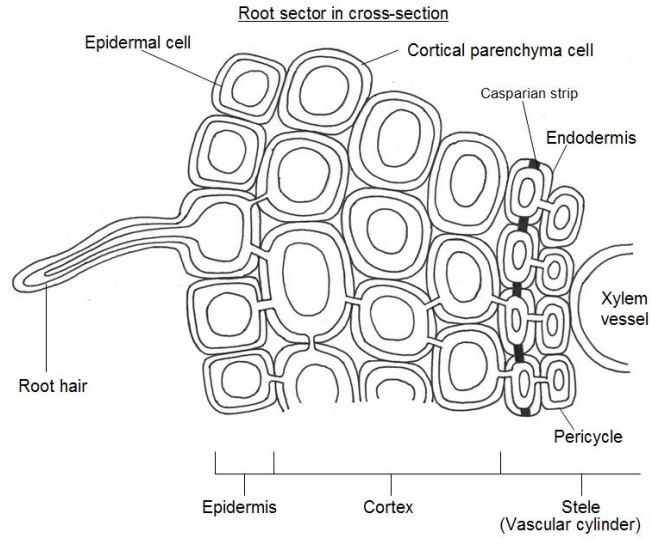
The endodermal cells have their radial and horizontal walls coated with a corky band called **casparian strip.** This strip is made up of a substance called **suberin**. The Casparian strip is impermeable to water and solutes due to the suberin that it contains and therefore prevents water and solutes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



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.

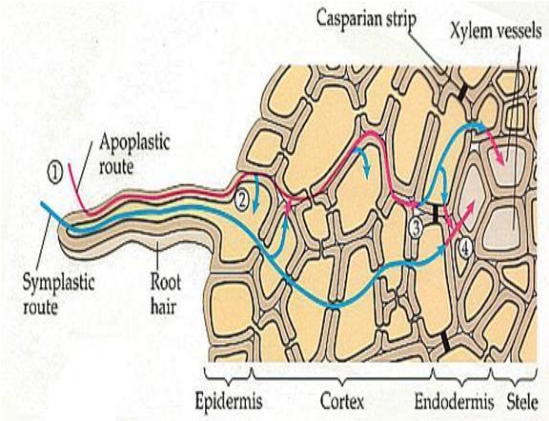
Vacuolar pathway

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



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

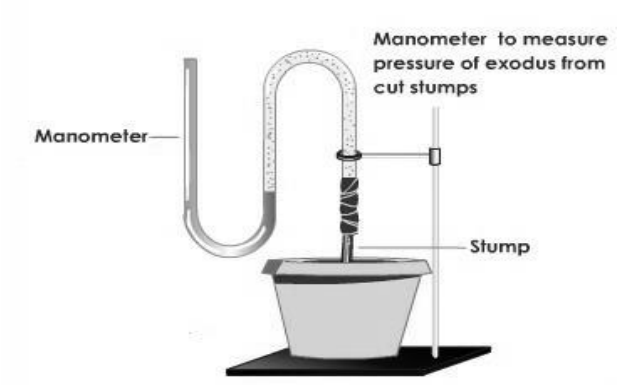
Root pressure is the force developed by cells of the roots which forces water from the endodermal cells into the xylem vessels of the root and constantly forces water upwards through the stem to leaves. This process is active and involves utilization of many ATP molecules. Root pressure occurs as a result 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.**

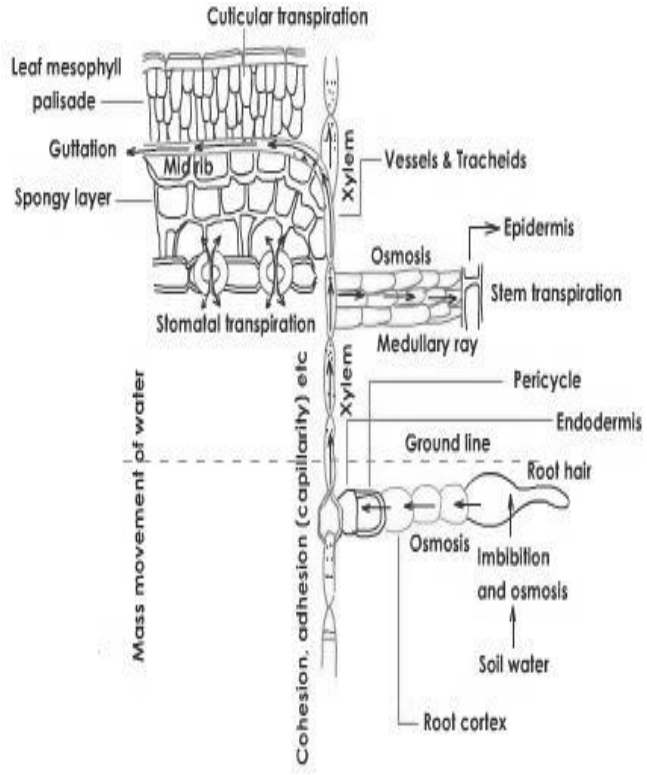
The upward movement of water through the xylem tissue from the roots to leaves is also facilitated by the **cohesive forces** of attraction which holds the water molecules firmly together, due to the hydrogen bonds which exist between them. This enables water to have a high tensile strength which enables 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.

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



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.

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.

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)

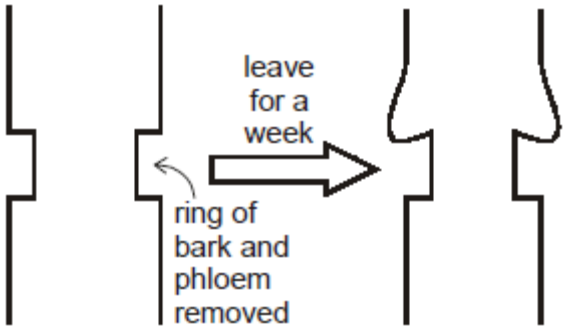
NOTE; Some plants absorb mineral salts by using mutualistic associations between their roots and other organisms e.g. the association between the fungus and the higher plant roots called **mycorrrhiza**.

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

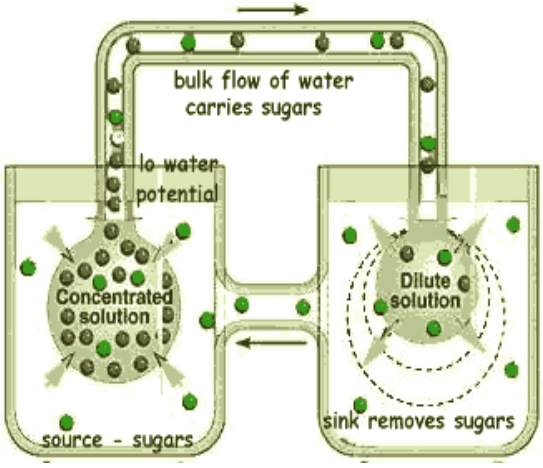
Mass flow or pressure flow hypothesis

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

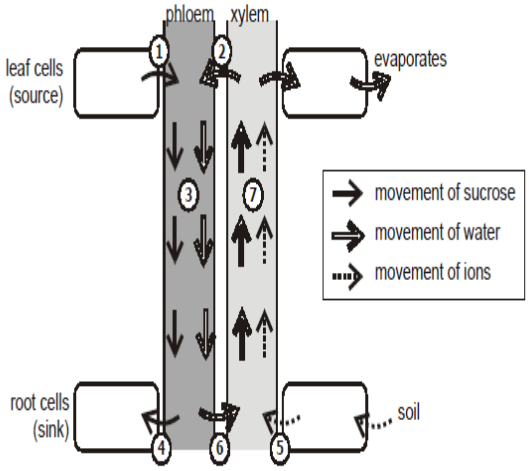
According to this theory, photosynthesis forms soluble carbohydrates like sucrose in the leaves. The photosynthesizing cells in the leaf therefore have their water potential lowered due to the accumulation of this sucrose. Sucrose is actively pumped into the phloem sieve cells of the leaf. As a result, 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



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.

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.

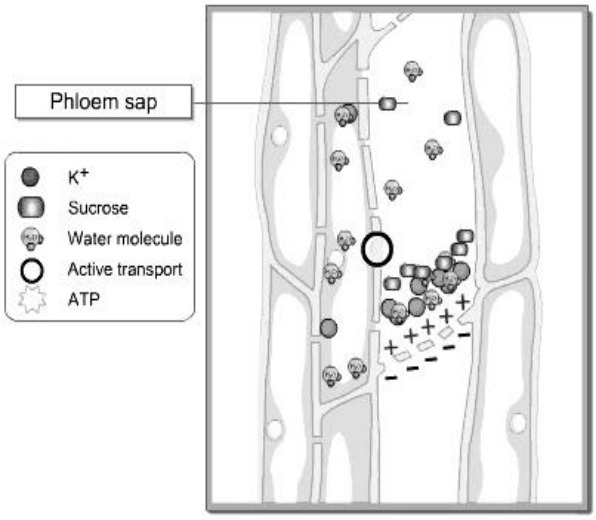
Organic solutes such as sucrose are transported across the sieve plates due to an electrical potential difference between the upper and the lower side of the sieve plate whereby the lower side is more negative than the upper side i.e. solutes move from the upper sieve tube element which is positively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

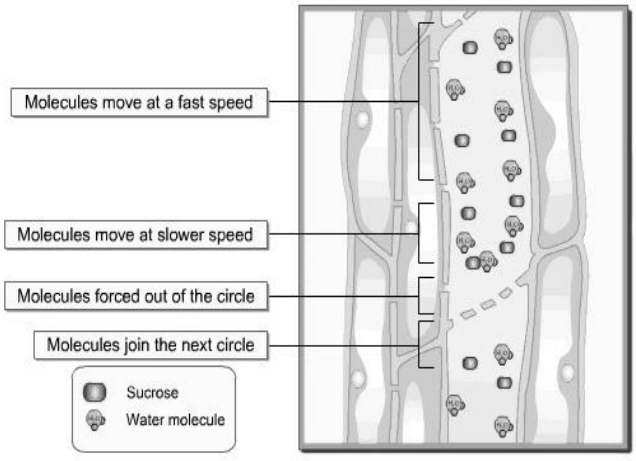


Cytoplasmic streaming theory

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



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.
2. The rate at which the protoplasm streams is far slower than the rate of translocation

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. (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?

4. (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.

5. 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.