TRANSPORT

Contents

TOPIC TRANSPORT IN LIVING ORGANISMS 2
Need for a transport system 2
BLOOD 3
TRANSPORT OF OXYGEN 5
Oxygen tension and oxyhaemoglobin formation 6
Effect of carbon dioxide on the oxygen dissociation curve (Bohr's effect) 7
TRANSPORT OF CARBON DIOXIDE 12
VASCULAR SYSTEMS IN ANIMALS 13
MAMMALIAN BLOOD CIRCULATION 16
THE MAMMALIAN HEART 16
Initiation of the heart beat 17
Intrinsic control of the heart beat 19
Control of the rate of the heart beat 20
BLOOD VESSELS 21
DEFENCE AGAINST DISEASES 24
Clotting of blood 24
THE LYMPHATIC SYSTEM 34
VACCINES 35
BLOOD TRANSFUSION 35
RHESUS FACTOR (D-Antigens) 36
UPTAKE AND TRANSPORT IN PLANTS 37
TRANSPIRATION 37
STOMATA 41
LENTICELS 44
WATER UPTAKE BY THE ROOTS 46
THE UPTAKE OF WATER FROM THE ROOTS TO THE LEAVES 49
UPTAKE AND TRANSLOCATION OF MINERAL IONS 50
TRASLOCATION OF ORGANIC MOLECULES 52
SAMPLE QUESTIONS 56
REFERENCES 69

TOPIC TRANSPORT IN LIVING ORGANISMS

Need for a transport system

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 platyhelminthes 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;

a. 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.
b. 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.
   Defence. Blood defends the body against diseases through the following ways;
   By using some white blood cells (leucocytes) which phagocytotically ingest and destroy pathogens that cause diseases.
   By formation of a blood clot around the wound so as to prevent entry of microbes or pathogens into the body.

. 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 in 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;
e. Erythrocytes (Red blood cells)
f. Leucocytes (White blood cells)
g. 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

1. They have a red pigment called haemoglobin in their cytoplasm which has a high affinity for oxygen and therefore rapidly transports oxygen.
2. They have a thin and permeable membrane which enables faster diffusion of oxygen and carbon dioxide into them
3. 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

Diagram showing the shapes of erythrocytes

NOTE; Erythrocytes have a life span of 120 days.

4. 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.

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

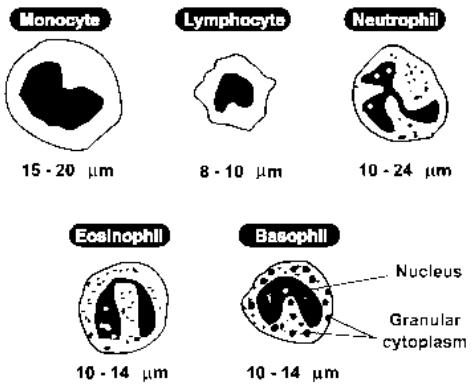
5. They lack a nucleus so as to provide enough space for haemoglobin in order to carry a lot of oxygen in form of oxyhaemoglobin.
6. They have a bi-concave disc shape which provides a large surface area that enhances maximum diffusion of enough oxygen into them.

LEUCOCYTES (white blood cells)

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

Granulocytes (polymorphonuclear leucocytes)	**Agranulocytes** (mononuclear 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.	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.

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



Adaptations of white blood cells to their function

a. They are larger than the pathogens
b. They are numerous
c. Some lymphocytes produce antibodies which attack pathogens
d. They have a sensitive cell surface membrane that detects micro organisms

i. They have enzymes in their cytoplasm to digest the engulfed micro organisms
ii. They do not have a fixed shape and hence the amoebic movements used to engulf pathogens.
iii. They have an irregular shaped nucleus which allows them to squeeze through the narrow capillaries
iv. They have a large nucleus which contains many genes for the control of antibody production.

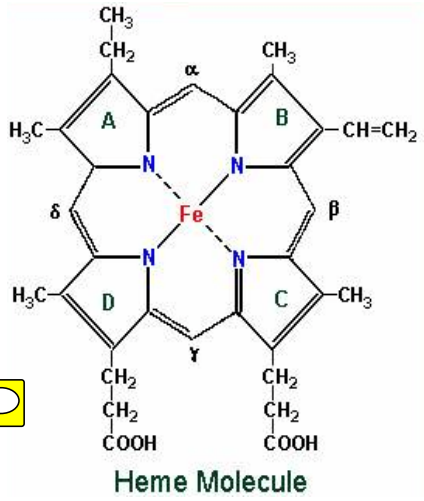
BLOOD PLATELETS (thrombocytes)
These are irregularly shaped, membrane bound cell fragments lacking the nuclei and are formed from the bone marrow cells. They are responsible for starting up the process of blood clotting. There are abound 250,000 blood platelets per mm^3 of blood.

TRANSPORT OF OXYGEN

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

$$Hb + 4O_2 \leftrightarrow HbO_8$$

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



Heme Molecule

The prosthetic group is haem and it is to the iron atom in the middle of it that the oxygen molecule become 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.

Other oxygen carrying pigments
There are several other groups of blood pigments and they differ mainly in the nature of prosthetic group. Chlorocruorin and haemoerythrin both contain iron, and haemocyanin contain copper. These three pigments are confined to invertebrate groups, particularly annelids and molluscs.
Pigments differ in their oxygen0-carrying capacities and are located in different areas

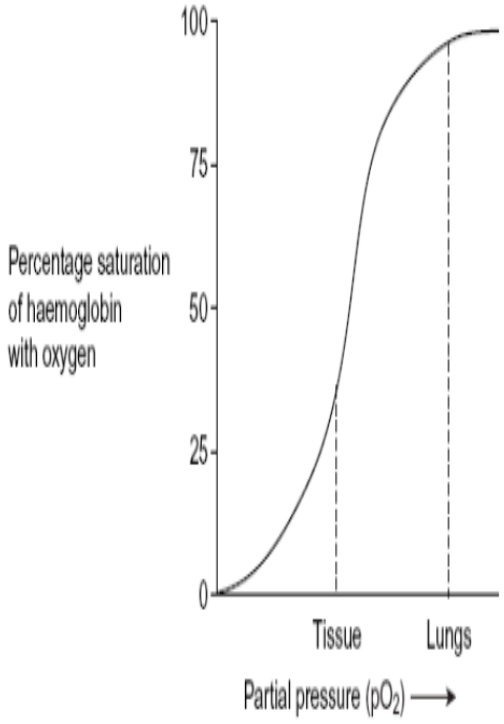
	Haemoglobin	Chlorocruorin (some annelids)	Haemocyanin (snails and crustaceans)	Haemoerythrin (some annelids)
Colour of pigment	Red	Green	Blue	Red
Metal in prosthetic group	Iron	Iron	Copper	Iron
Molecule of oxygen carried per atom metal	1:1	1:1	1:2	1:3
Location in blood	Cells or plasma	Plasma	Plasma	Cells or plasma

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 on the right

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

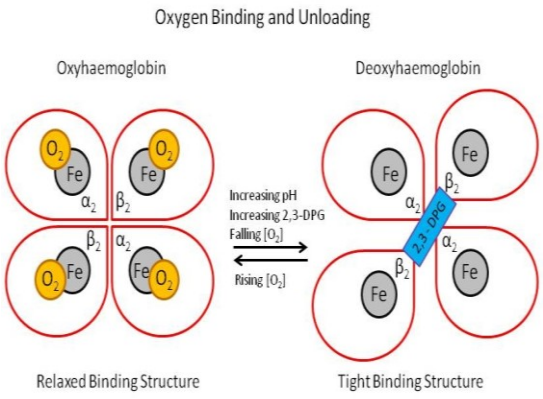


The curve indicates that a slight increase in the partial pressure of oxygen leads to a rapid increase in the percentage saturation of haemoglobin with oxygen. This indicates that haemoglobin has a high affinity for oxygen in that it readily combines with it and become saturated with it at low partial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

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

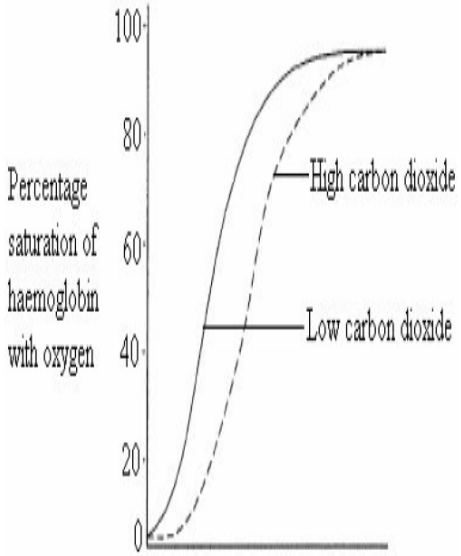
Note: loading tension is the partial pressure of oxygen at which 95% of the pigment is saturated with oxygen, and the unloading tension is the partial pressure at which 50% of the pigment is saturated with oxygen.

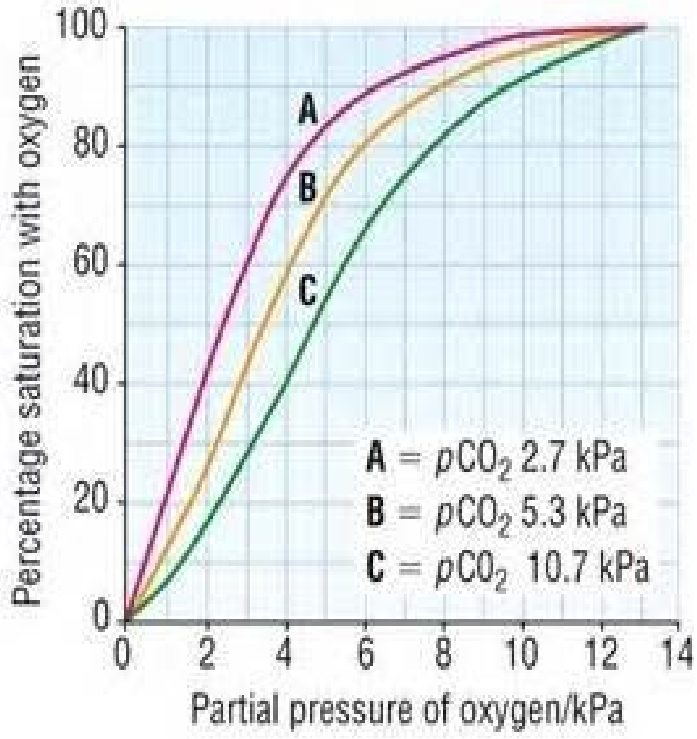
Effect of carbon dioxide on the oxygen dissociation curve (Bohr's effect)

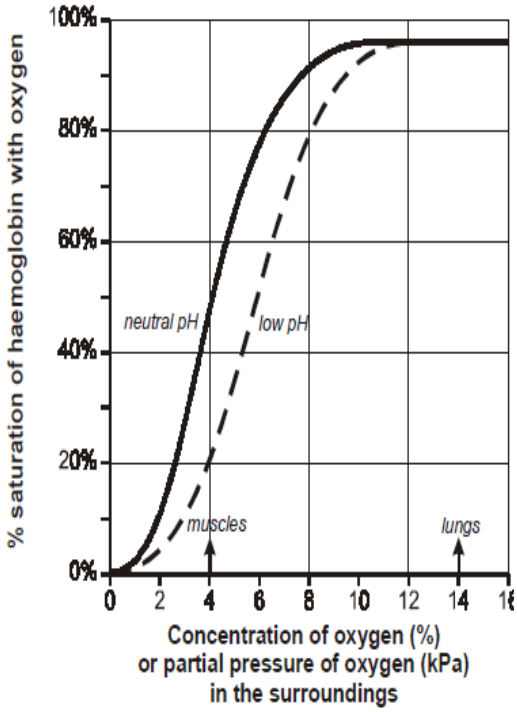
Within tissues there is a high concentration of carbon dioxide produced during aerobic respiration

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

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







From the dissociation curves above, shifting the oxygen dissociation curve to the left means that haemoglobin has a higher affinity for oxygen and therefore becomes fully saturated with oxygen it at very low partial

pressures of oxygen. It also means that haemoglobin has a low rate of dissociation to release oxygen to the tissues but a high rate of combining with oxygen.
Shifting of the oxygen dissociation curve to the right means that haemoglobin has a lower affinity for oxygen and a higher rate of dissociation to release oxygen to the tissues rapidly to support tissue respiration

Effect of carbon monoxide on the affinity of haemoglobin for oxygen

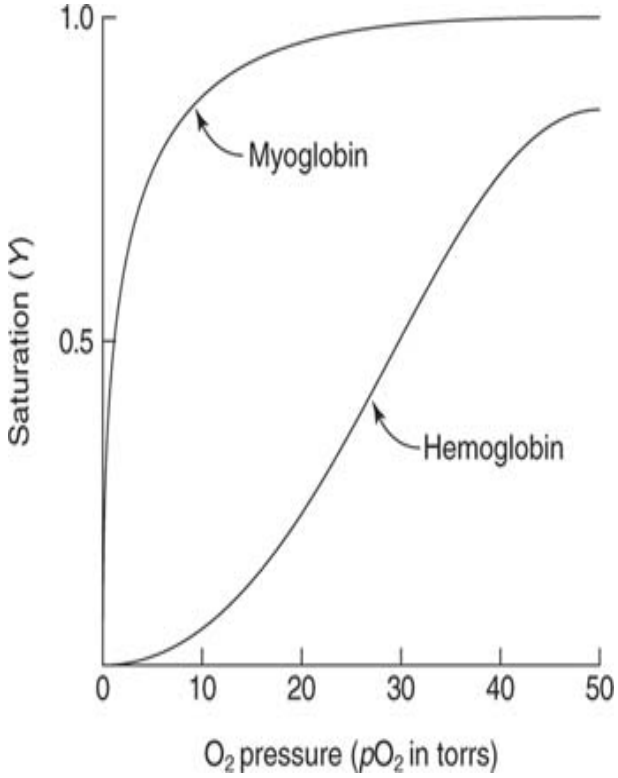
There's a loose and reversible reaction between oxygen molecules and iron (II) atoms of haem groups of haemoglobin to from oxyhaemoglobin. This means that iron (II) is not oxidized to iron (III) as haemoglobin combines with oxygen.
In the presence of carbon monoxide and oxygen, haemoglobin combines readily with carbon monoxide to form a permanent compound known as carboxyhaemoglobinrather 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

(Kent fig 3 pg 131 OR Clegg fig 17.31 pg 360)



Note;

1. High affinity refers to low rate of dissociation of oxyhaemoglobin to release oxygen and a higher rate of association of haemoglobin with oxygen.
2. Low affinity refers to higher rate of dissociation of oxyhaemoglobin to release oxygen and a lower rate of association of haemoglobin with oxygen.

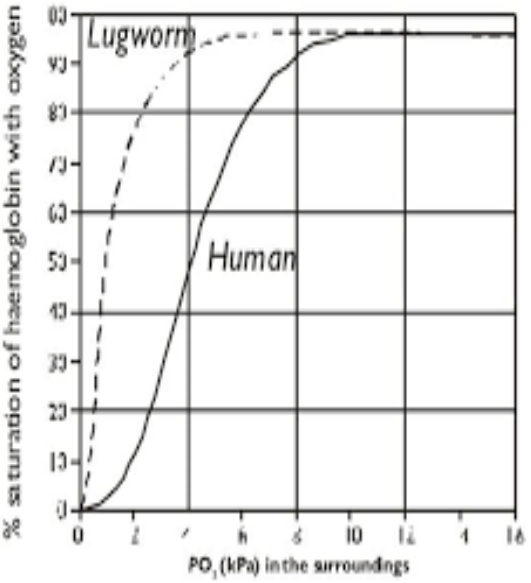
Comparison between the oxygen dissociation curve for Lugworms' haemoglobin and that of Man

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

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

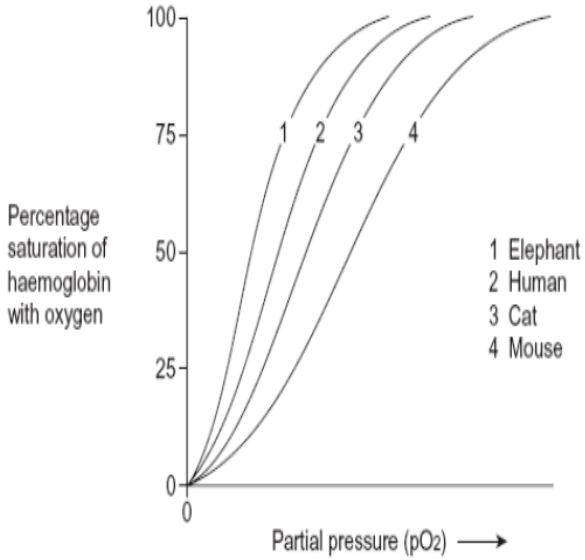
This implies that the lugworm's haemoglobin dissociates to release oxygen to its tissues compared to that of man which makes the lugworm less active than man, who releases much oxygen rapidly to the tissues.

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



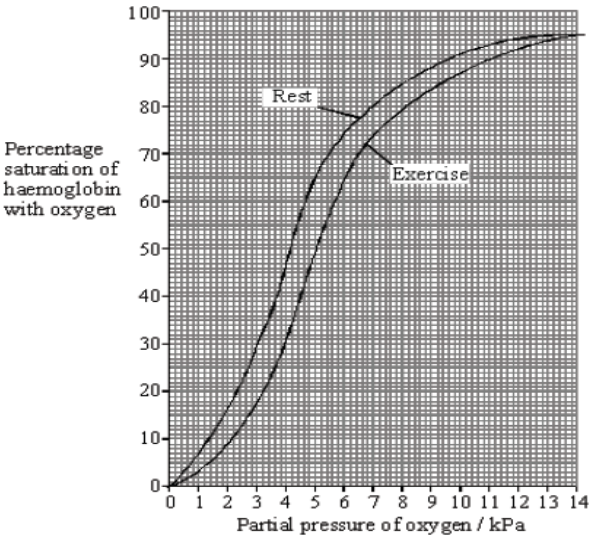
Comparison between the oxygen dissociation curves of different sized mammals

The smaller animal size, the higher the surface area to volume ration. Small animals therefore lose a lot of heat from their surfaces and in order to maintain a constant internal body temperature, they have to produce a lot of heat to compensate for the lost heat. Such animals therefore 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 the curve when at rest.



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

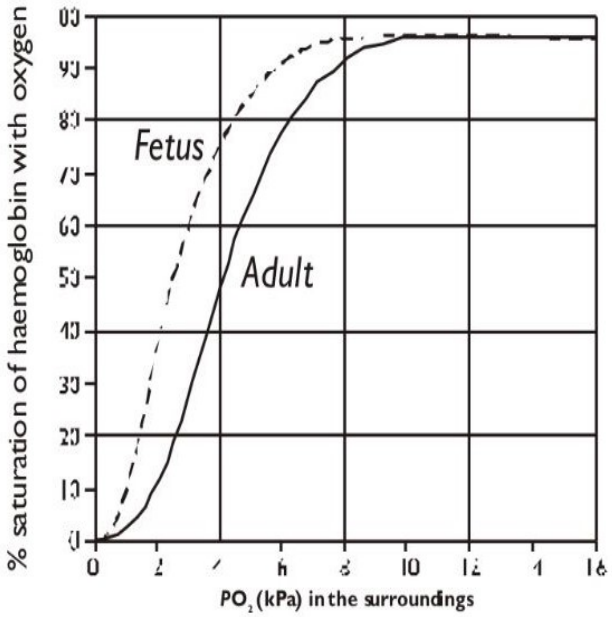
The oxygen dissociation curve of foetal haemoglobin lies to the left of maternal haemoglobin as shown in the diagram besides;

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

This enables the foetal haemoglobin to pick sufficient oxygen from the mother via the placenta and also increases on the oxygen carrying capacity to the tissues, especially when the foetus needs a lot of energy.

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

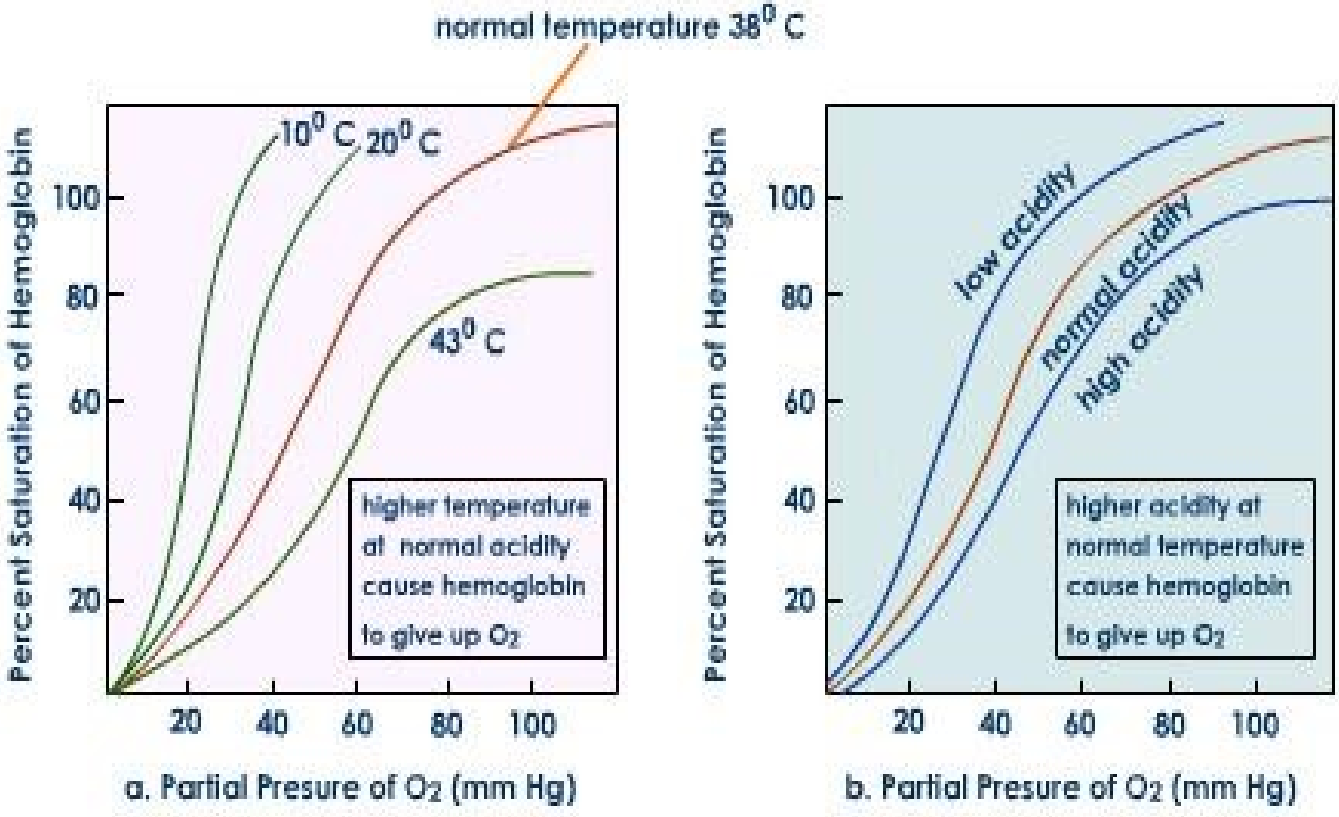
(Clegg fig 17.36 pg 363 OR Toole fig 21.7 pg 416 OR Soper fig 14.32 pg 481)



Effect of 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



Effect of changing altitude on oxygen carriage

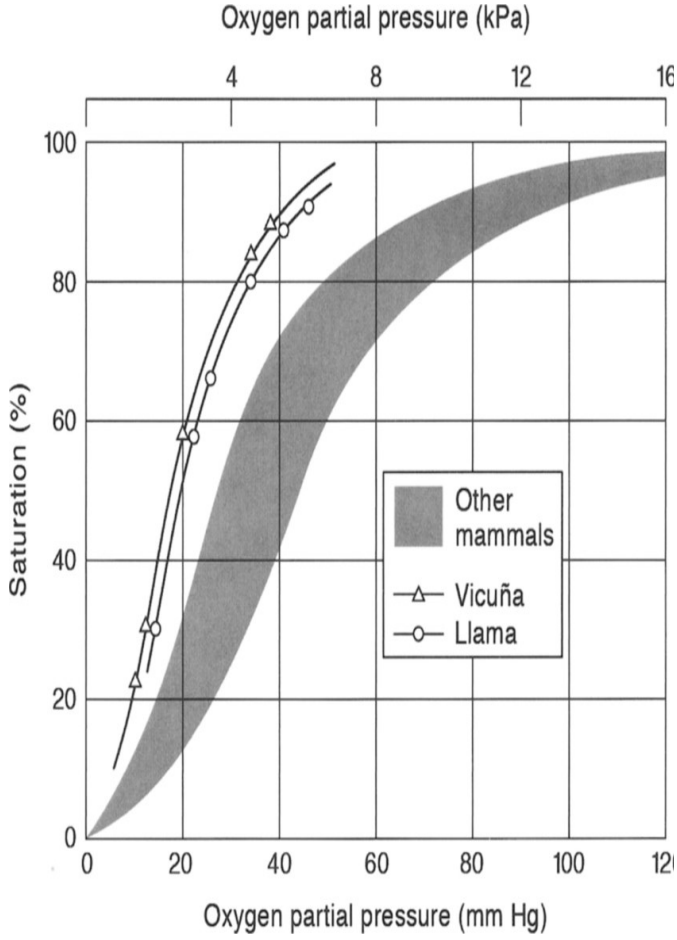
There is a decrease in the partial pressure of oxygen in the atmosphere with increase in altitude from sea level. Therefore the volume of oxygen is less at high altitudes than at sea level. When an organism moves from the sea level to high altitudes, very fast, such an organism tends to develop symptoms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

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

The amount of haemoglobin and the red blood cell count increases together with the rate of breathing and the heart beat. More red blood cell formation occurs in the bone marrow under the control of the hormone called *erythropoietin* secreted by the kidney. Secretion of erythropoietin is stimulated by lower oxygen tension in the tissues. Increase in the amount of haemoglobin and red blood cells together with increase in the breathing rate and heart beat increases the oxygen carrying capacity of the blood to the tissues which leads to the disappearance of the symptoms of anoxia and which also makes the individual organism to be acclimatized.

Acclimatization is therefore a condition whereby an organism carries out a series of physiological adjustments in moving from a low altitude area to a high one to avoid symptoms of anoxia so that such an organism can survive in an environment of low oxygen content.

The graphs below show the oxygen dissociation curves of people living at sea level and at high altitude (Clegg fig 17.37 pg 363 OR Toole fig 21.4 pg 415 OR Soper fig 14.31 pg 481 OR Simpkins fig 8.19 pg 145)



The mammals that live in regions of the world beyond the sea level e.g. mountains solve the problem of lack of enough oxygen in the atmosphere by possessing haemoglobin with a higher affinity for oxygen than that of mammals at sea level. This enables the high altitude mammals to obtain enough oxygen through the oxygen deficient environment e.g. the llama. This explain why the oxygen dissociation curve of the haemoglobin of the llama lies to the left of that of other mammals at sea level. The vicuna long necked member of the camel family that stays in the high alpine areas of the Andes

Mammals living at high altitudes

1. These possess an improved capillary network in the lungs which coupled with their deeper breathing (hyperventilation) insures increased oxygen uptake.
2. They have an increased red blood cell which increases the amount of oxygen transported by blood.
3. Increased haemoglobin concentration in the red blood cells which improves the amount of oxygen transported by the blood.
4. Changes in haemoglobin affinity for oxygen. Here the oxygen dissociation curve is shifted to the right to facilitate release of oxygen to the tissues. This particularly occurs at relatively lower altitudes.

5. Mammals living at altitudes about 3500m have their oxygen dissociation curves shifted to the left this favours their survival by promoting an increased affinity for oxygen by haemoglobin.
6. Increased myoglobin levels in muscles myoglobin has a higher affinity for oxygen than haemoglobin. This facilitates the exchange of oxygen from the blood to the tissues making oxygen available to the tissues.

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

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

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 ion

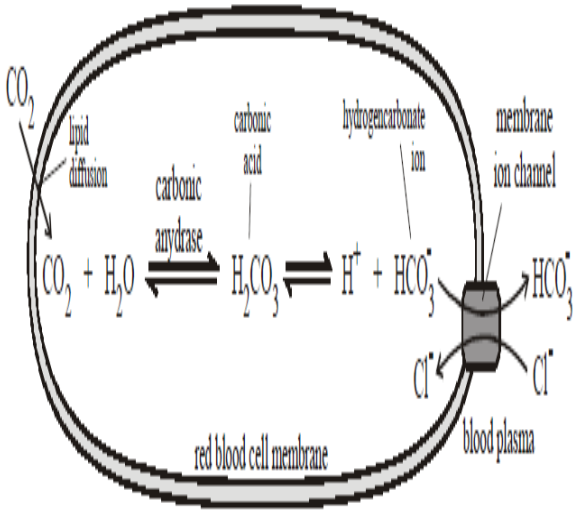
When carbon dioxide is formed during respiration, it diffuses from the tissues into the erythrocytes, via their thin and permeable membrane. Inside the erythrocytes, carbon dioxide reacts with water in the presence of carbonic anhydrase enzyme to form carbonic acid as shown below;

$$H_2O_{(l)} + CO_{2(g)} \xrightarrow{\text{Carbonic anhydrase}} H_2CO_3$$

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

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

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



$$HbO_8 \longrightarrow Hb + 4O_2$$

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

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

In case of excess H^+ plasma proteins are used to buffer them into another weak acid called **proteinic acid.**
The formed hydrogen carbonate ions within the erythrocytes diffuse out into the plasma along the concentration gradient and combine with sodium to form sodium hydrogen carbonate which is then taken to the lungs.
The outward movement of bicarbonate ions from the erythrocytes into the plasma results into an imbalance of positively charged and negatively charged ions within the cytoplasm. In order to maintain electrochemical neutrality, to remove this imbalance in the red blood cells, chloride ions diffuse from the plasma into the red blood cells, a phenomenon known as the **chloride shift**
When the bicarbonate ions reach the lungs, they react with H^+ to form carbonic acid which eventually dissociates into carbon dioxide and water.

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

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.

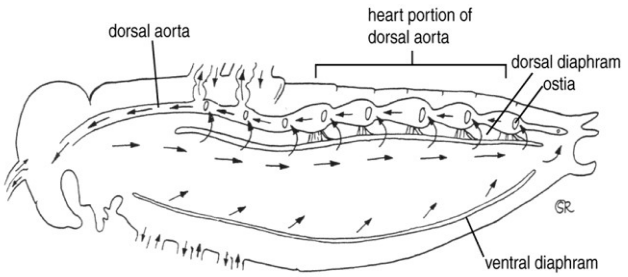
a. It has a circulating fluid e.g. blood
b. It has a pumping device inform of a modified blood vessel or a heart.
c. It has tubes through which the fluid can circulate e.g. blood vessels

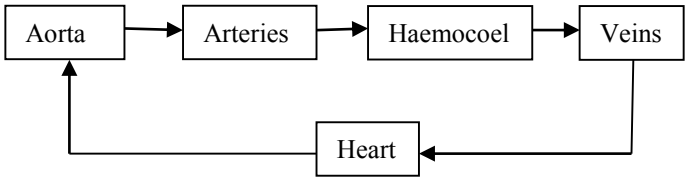
Note; animals require a transport system because of;

1. Surface area of the organism
2. Surface area: volume ratio of the organism
3. Activity of the organism
4. The diffusion distance for the transported substances between the tissues to and from their sources.
5. There are two types of vascular systems, the open vascular system and the closed vascular system.

Open vascular system not on syllabus

Open circulation is the flow of blood through the body cavities called **Haemocoel** instead of flowing in blood vessels. This exists in most arthropods, molluscs and tunicates.
In this system, blood is pumped by an aorta which branches into a number of arteries which open into the haemocoel. From the haemocoel, blood under low pressure moves slowly to the tissues where there's exchange of materials e.g. gases, nutrients e.t.c. from the haemocoel blood percolates back into the heart via the open ended veins.
In insects the haemocoel is divided into two parts by a transverse pericardial membrane forming a pericardial cavity dorsally and the ventral perivisceral cavity.





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

Mechanism of open circulation

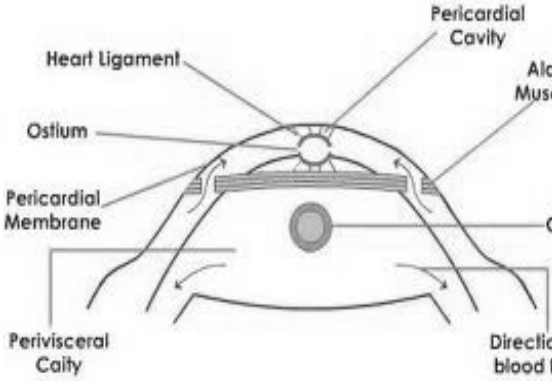
Blood flows through the heart from the posterior end to the anterior end by waves of contractions (systole) which begin from the posterior end and proceed to the anterior end. These waves of contractions enable blood to flow through the heart and then enter the perivisceral cavity.

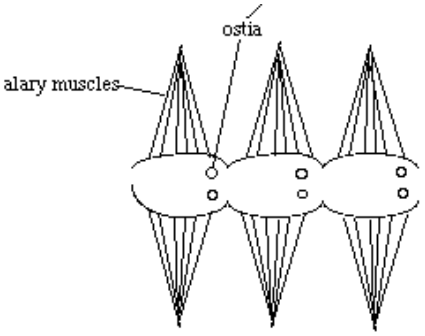
During systole, the heart ligaments are stretched with a result that during diastole they pull the heart walls outwards, thereby decreasing the pressure in the heart and increasing its volume. This results into sucking of blood into the heart via the ostia from the perivisceral cavity which has a higher 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.

Transverse section through the insect's heart

(Clegg fig 17.5b pg 344





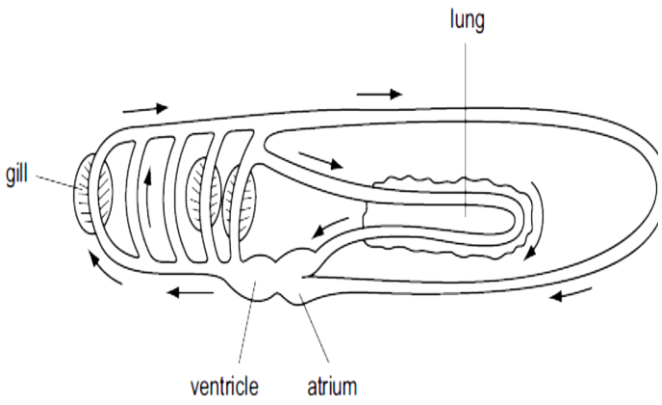
Closed vascular system

In a closed vascular system, blood flows in blood vessels or sinuses. It oc curs 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.

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.

Diagram showing single circulation in fish

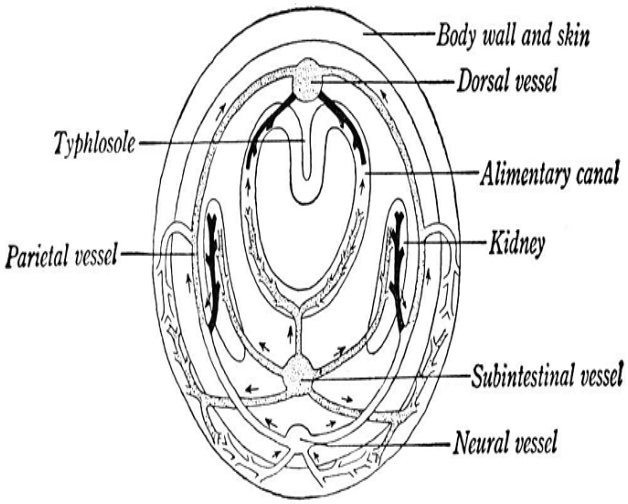


The problem of single circulation is that blood tends to move very slowly at the venous side due to the significant drop in pressure before completing the circulation. The drop in pressure is as a result of capillaries having a considerable resistance to blood flow i.e. capillaries in the gills and body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

Vascular system of the earthworm (annelid) not on syllabus

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

Transverse section of the annelid vascular system
Clegg fig 17.6 pg 344



The largest vessel is the longitudinal muscular-walled dorso vessel and it is above the alimentary canal (gut). The peristaltic contraction from the posterior end of the vessel drives blood forward to the anterior end of the animal. The backflow of blood is prevented by valves. Each valve originates from a fold of an internal membrane or tissue of any blood vessel that is called an endothelium.
The dorso vessel collects and receives blood from the body wall, the gut, the nerve cord and the nephridia via capillaries. The dorso vessel connects with the smaller more contractile ventral vessel via five pairs of contractile pseudo hearts.

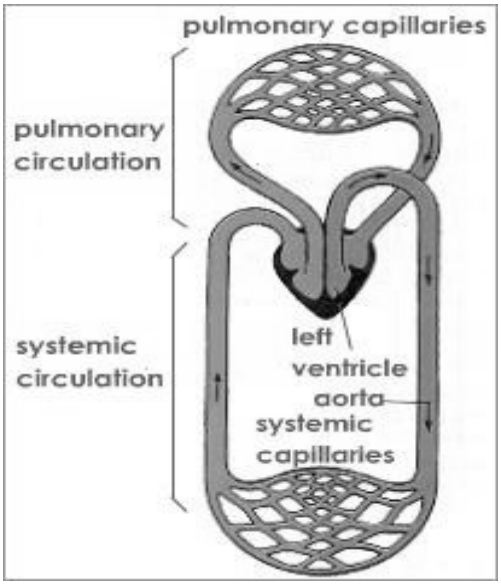
Each pseudo heart has four valves which permit the blood to flow towards only the ventral vessel and back to the posterior end of the animal.
Between the ventral vessel and the organs in the coelom e.g. nephridia and gut, there are a series of segmented blood vessels which run between them and they end up forming capillaries where there is exchange of materials between the organs and the blood in the capillaries. From the capillaries, blood fills its way back to the dorso vessel for its flow to the anterior side due to the peristaltic movement of the dorso vessel.
The blood is red in colour with haemoglobin.

Double circulation

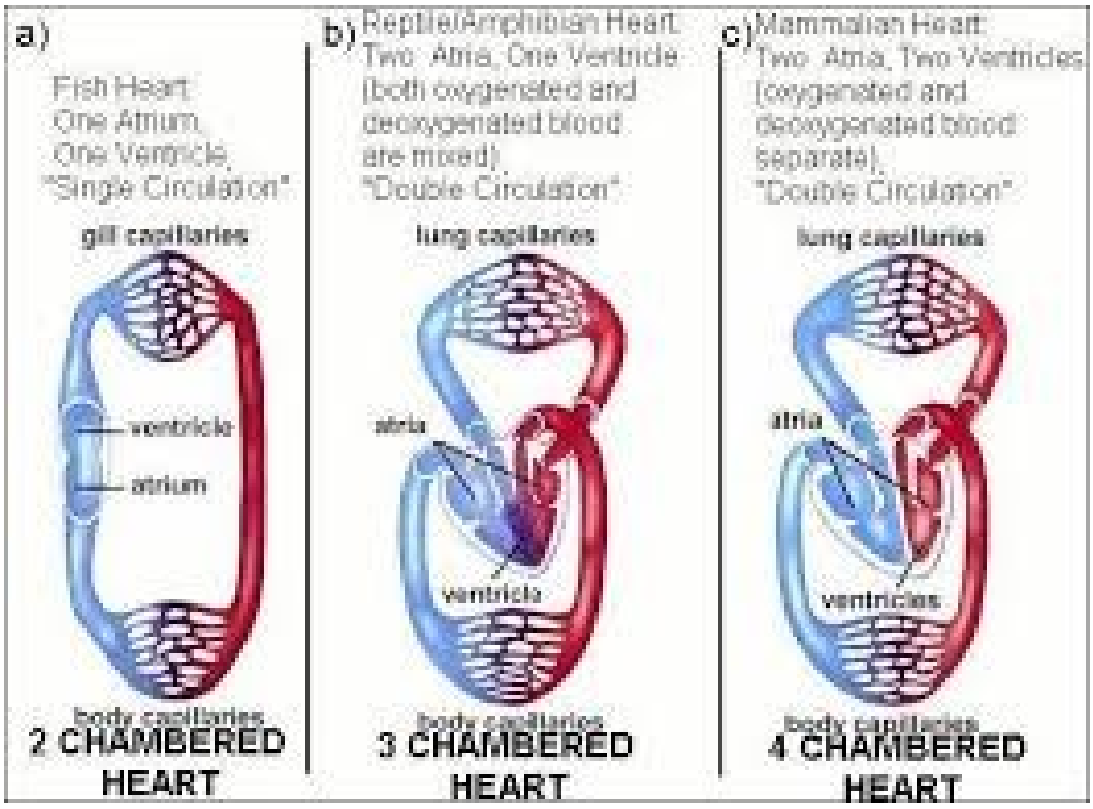
Double circulation is the flow of blood through the heart twice for every complete circulation around the body.

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.

Diagram showing double circulation in a frog and a mammal



Both deoxygenated and oxygenated blood in the frog flow through the same ventricle and conus arteriosus at the same time without mixing. This is achieved due to the folding in the walls of the ventricle which enhances the separation of deoxygenated blood from oxygenated blood and this separation is also facilitated by the spinal valves in the conus arteriosus. Some organisms e.g. the octopus and squids solve the problem of sluggish flow of blood of the venous side by possessing brachial hearts which pump deoxygenated blood from the body tissues of the gills and eventually back to the main heart. The main heart pumps, oxygenated blood to body tissues from the gills.	Roberts fig 11.17 pg 175)



MAMMALIAN BLOOD CIRCULATION

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

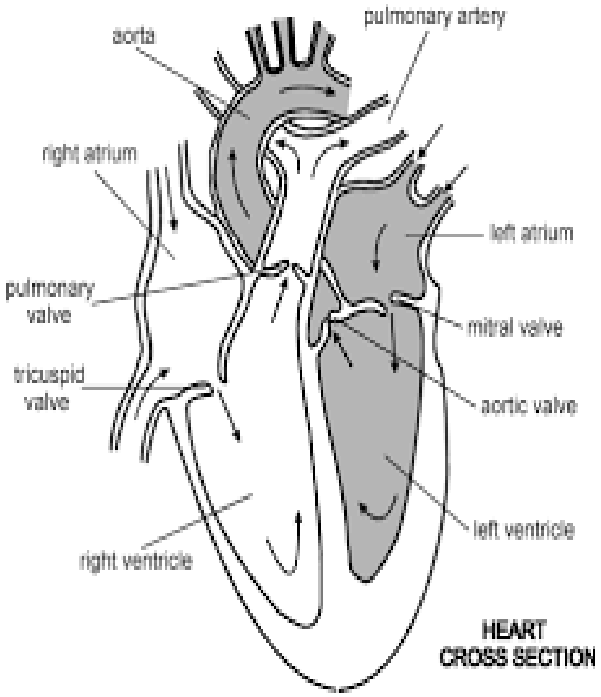
THE MAMMALIAN HEART

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. the deoxygenated blood is separated from oxygenated blood 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;
The three (3) flapped tricuspid valves found between the right atrium and the right ventricle
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;
The venacava which transports deoxygenated blood from body tissues through the right atrium of the heart.
The pulmonary artery which transports deoxygenated blood from the right ventricle of the heart to the lungs.

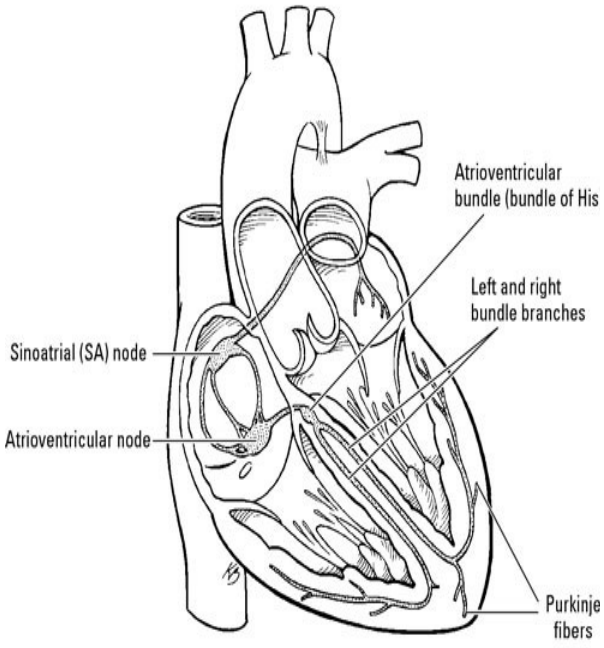


The pulmonary vein which transports oxygenated blood from the lungs into the left atrium of the heart.
The aorta which is the biggest vessel and it transports oxygenated blood from the left ventricle of the heart to the body tissues.
The left ventricle is more muscular (thicker) than the right ventricle 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,

Clegg fig 17.8 pg 347



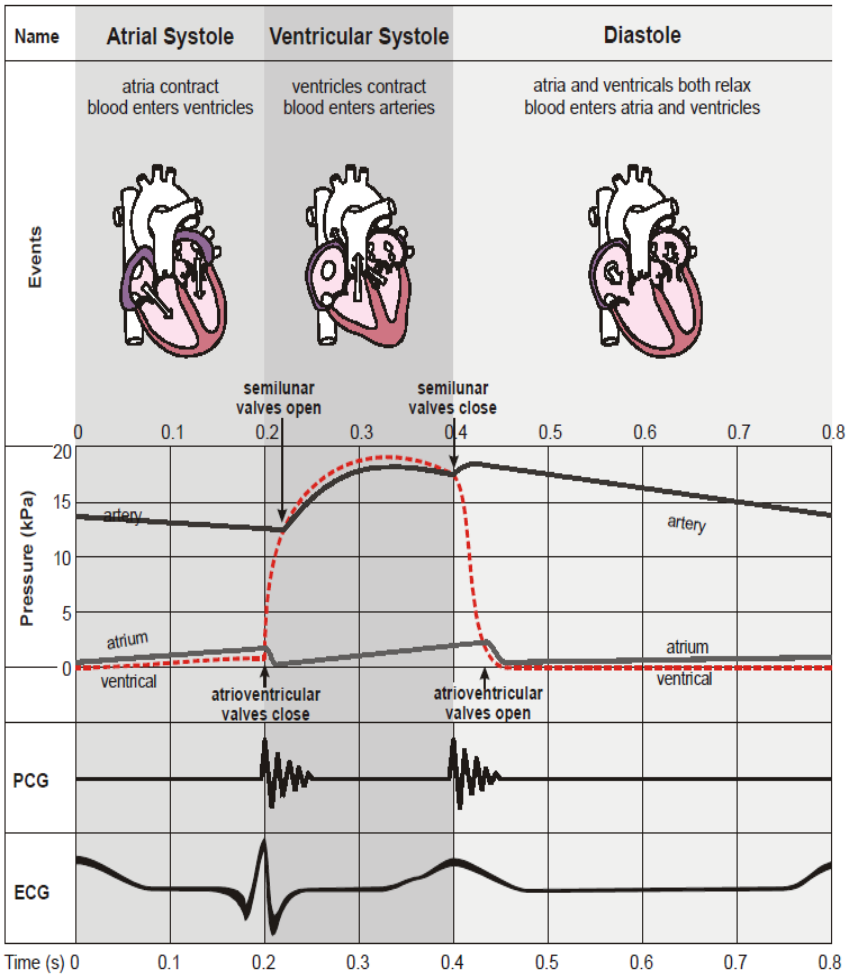
which spread out very rapidly over both atria causing them to contract and force blood into the ventricles via the open atrial ventricular valves. When the electrical excitations reach the junction at the boundary of the atria, they excite another specialised plexus of other cardiac muscle chambers known 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.

NOTE;

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

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

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



The cardiac cycle (Sequence of the heart beat)

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

The cardiac cycle begins with the contractions of the atria i.e. **atrial systole,** which is initiated by SAnode and it which causes the atria volume to decrease and the atrial pressure increases. As the atria contracts, the ventricles relax i.e. undergo ventricular diastole, causing the bicuspid and tricuspid valves to close. The contraction of the

atria due to blood entering the atria forces the bicuspid and tricuspid valves to open so that blood moves from atria into the ventricles.
Contraction of atria walls has an effect of sealing off the venacava and pulmonary veins, thereby preventing the back flow of blood into the vessels as the blood pressure rises within the atria. It takes 0.1 seconds.
When the ventricles are filled with blood from atria, their walls contract simultaneously i.e. **ventricular systole**, and the atria relax i.e. **atrial diastole.** Ventricular systole is initiated by impulses from AVnode to the bundle of His, Purkije fibres and rapidly through the ventricle muscles. The ventricles' volume reduces while the pressure increases, forcing the bicuspid and tricuspid valves to close and prevent the back flow of blood into the atria. The increased pressure in the ventricles also forces blood to be pumped into the pulmonary artery via the open semi lunar valves from the ventricles. This enables the blood to be pumped into the lungs via the pulmonary artery and into the body tissue via the aorta.
The ventricular systole is more powerful than the atrial systole because the ventricles are more muscular than the atria and therefore generate more pressure. The powerful ventricular systole forces blood into the atria and pulmonary artery.
After ventricular systole, there's a short period of simultaneous atrial and ventricular relaxations. In the **ventricular diastole**, the high pressure developed in the ventricles causes a slight back flow of blood which closes the semi lunar valves, thereby reducing blood back flow.
Relaxation of the atrial wall and contraction of the ventricle, initiates the refilling of the atria by blood under relatively low pressure i.e. deoxygenated blood in the venacava flows into the right atrium and oxygenated blood from the lungs flows into the left atrium via the pulmonary vein.
Intrinsic control of the heart beat
The cardiac muscle in the heart is myogenic. It contracts and relaxes automatically and does not depend on stimulation by nerves. The initial stimulus originates from the sino-atrial node (SAN), often called the pacemaker. The pacemaker is found in the right atrium wall at the entrance of the superior venacava. The membranes of the cells of the SAnode are permeable to sodium ions. Sodium ions enter into these cells and the cell membranes are depolarized.
An excitatory wave of depolarization is generated which spreads rapidly from the SA node across the two atria causing them to contract simultaneously. A slowing down occurs as depolarization of the atrio-ventricular node (AVN) is delayed for about 0.1s to allow the atria to complete their contraction and empty the blood into the ventricles. Impulses from the AV node are conducted by specialized muscle fibres called bundle of His in the inter-ventricular septum towards the heart apex. Impulses are conducted by Purkinje fibres (Purkyne tissue) throughout the ventricular walls. This causes the contraction of both ventricles forcing blood into the pulmonary arteries and the aorta.
Characteristics of the cardiac muscle in relation to excitation and contraction

1. The absolute relative refractory period is longer than that of other muscles i.e. the heart cannot be fatigued easily
2. 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.

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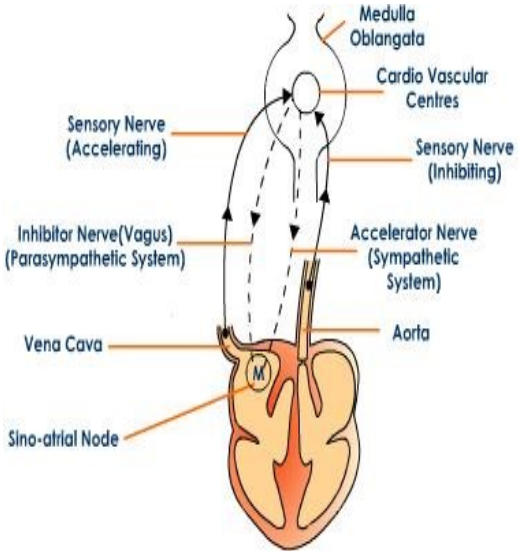
Control of the rate of the heart beat

Through 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.

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



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.

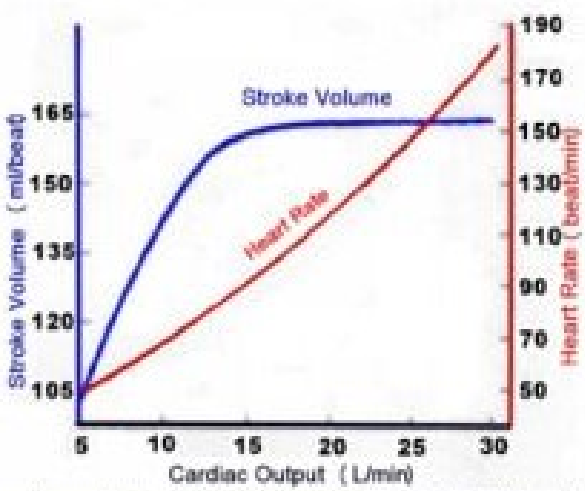
Cardiac output (volume of blood going out of the heart) = **Rate of heart beat X Cardiac frequency**

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

QN. Explain how change in each of the above factors may affect the heart beat ; **20**

Soper fig 14.25 pg 476



Approximate stroke volume and heart rate at different levels of cardiac output in a marathon athlete.

Explain the relationship between;

- Stroke volume and heart beats
- Cardiac output and heart beats

BLOOD VESSELS

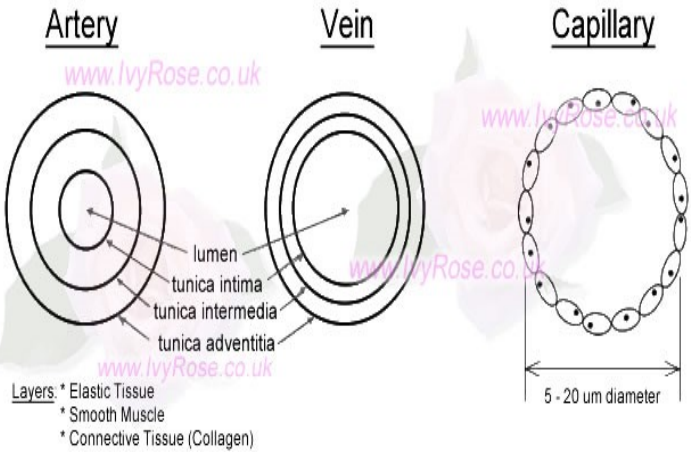
There are three main types of blood vessels; arteries, veins and capillaries. The walls of these blood vessels occur in three layers, namely;

1. Tunica externa (outer most layer)
2. Tunica media (middle layer)
3. 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.

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



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.

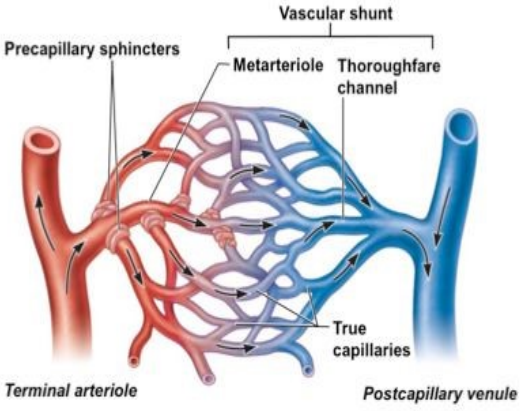
Arteries transport oxygenated blood from the heart to the tissues except the pulmonary artery which transports deoxygenated blood from the heart to the lungs while veins transport deoxygenated blood from tissues to the heart except the pulmonary vein which transports oxygenated blood from the lungs to 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.

Comparison between arteries and veins

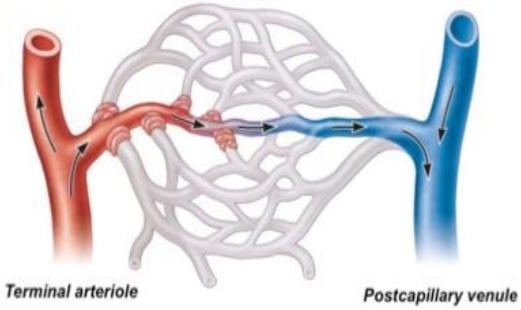
1. Both tunica media and tunica externa are more developed in arteries than veins and therefore arteries have thicker walls than those of veins. Arteries have thicker walls than veins because blood flows through them at a higher pressure than in the veins, due to the pumping action of blood by the heart. 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.
2. 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.
3. Also arteries have a narrower rumen than veins, which increases the pressure of the blood flowing through them.
4. 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

Diagram showing the capillary network

Clegg fig 17.18 pg 353



(a) Sphincters open—blood flows through true capillaries.



(b) Sphincters closed—blood flows through metarteriole – thoroughfare channel and bypasses true capillaries.

Adaptations of blood capillaries

1. They possess the capillary sphincter muscles which contract and relax so as to regulate the amount of blood entering into the capillary network.
2. Some capillaries have a bypass arterio-venous shunt vessel which links the arterioles and venules directly so as to regulate the amount of blood which flows through the capillary network e.g. in the capillaries of the feet, hands, stomach e.t.c.
3. 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. 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.
4. 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.
5. 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.

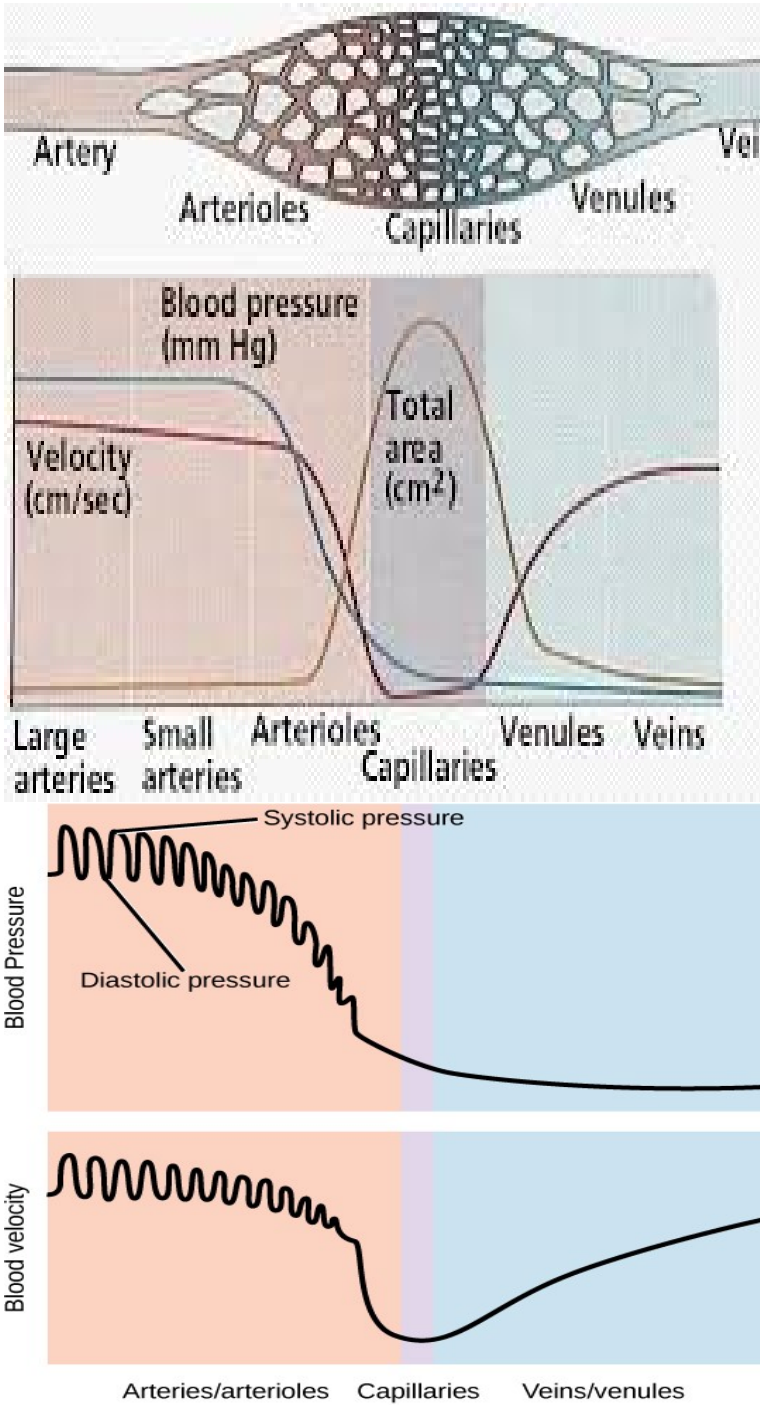
Blood flow velocity

The speed of blood flow reduces as it moves from arteries to arterioles to capillaries. Each artery conveys blood to so many capillaries that the total cross-sectional area is much greater in capillary beds than in the arteries or any part of the circulatory system. The result is an increase in velocity from the arteries to capillaries than in the aorta.

The reduced velocity of blood flow in capillaries is critical to the function of the circulatory system. Capillaries are the only vessels with walls thin enough to permit the transfer of substances between the blood and interstitial fluid. The slower flow of blood through these tiny vessels allows time for exchange to occur. After passing through the capillaries, the blood speeds up as it enters the venules and veins, which have smaller total-sectional areas

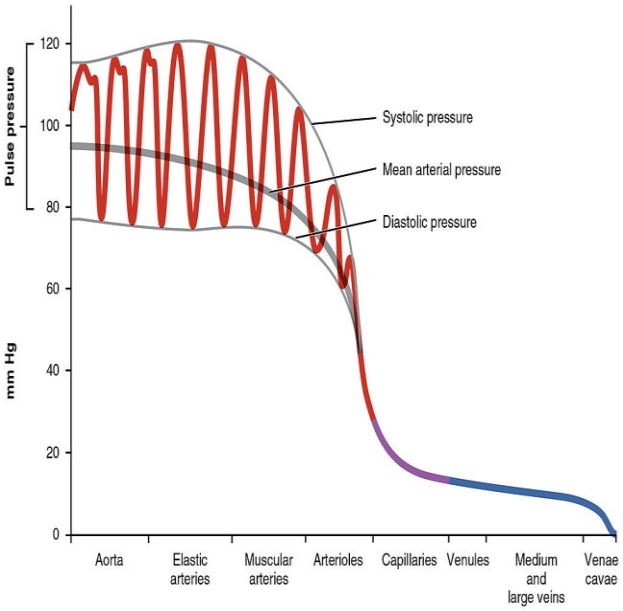
Blood pressure

Contraction of the heart ventricle generates blood pressure, which exerts a force in all directions. The force directed lengthwise in artery causes the blood to flow away from the heart, the site of highest pressure. The force exerted against the elastic wall of an artery stretches the wall, and the recoil of the arterial wall plays a critical role in maintaining blood pressure, and hence blood flow, throughout the cardiac cycle. The numerous arterioles and capillaries offer resistance to blood flow hence reducing the blood pressure.



Changes in blood pressure during the cardiac cycle

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. Arterial blood pressure is highest when the heart contracts during ventricular systole, this is systolic pressure. This is also due to the narrow openings of arterioles impeding the exit of blood from arteries. Hence, when the heart contracts, blood enters the arteries faster than it can leave, and the vessels stretch from the rise in pressure.



During diastole, the elastic walls of the arteries snap back. As consequence, there's a lower but still substantial blood pressure when ventricles are relaxed (diastolic pressure). Before enough blood has flowed into the arteries to completely relieve pressure in the arteries, the heart contracts again. Because the arteries remain pressurized throughout the cardiac cycle blood continuously flows into arterioles and capillaries.

NOTE:

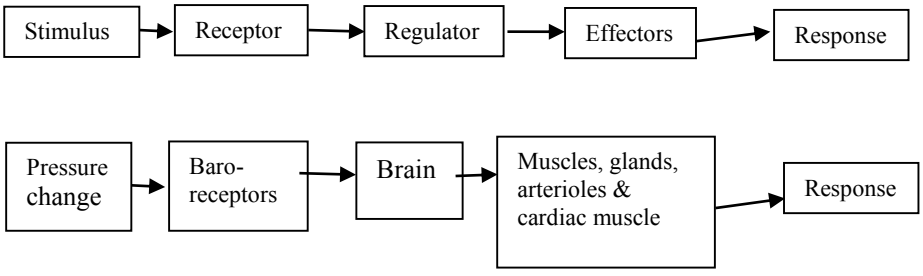
Blood is expelled from the heart only when it contracts. Blood flow through the arteries is therefore *intermittent,* the blood flowing rapidly during systole and slowly during diastole. However, by the time the blood reaches the capillaries it is flowing evenly. The gradual change from intermittent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

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;

1. Blood volume
2. Force of the heart
3. Blood vessel radius/ diameter of the lumen
4. 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 α $\frac{1}{r^4}$).** 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.

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

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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;

1. Clotting of blood
2. Phagocytosis
3. 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

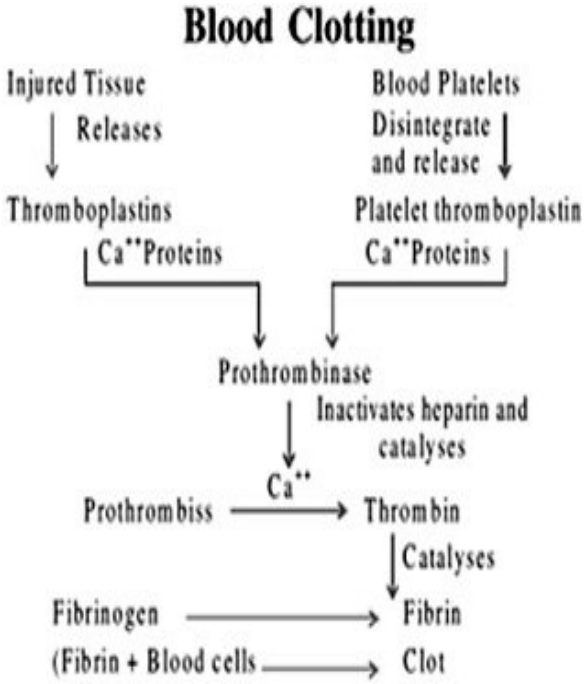
Thrombin is a proteolytic enzyme that hydrolyses a plasma protein called **fibrinogen** into an insoluble protein called Fibrin forms fibres at the wounded area. Within the fibrous network of fibrin blood cells become

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:
Heparin is an anticoagulant which inhibits the conversion of prothrombin to thrombin thereby preventing blood clotting.
Apart from blood clotting, the entry of microbes into the body can be prevented by the following;

1. Using impermeable skin and its protective fluid called sebum (oily secretion in the skin)
2. Using mucus and cilia to trap the microbes and then remove them
3. By using hydrochloric acid in the stomach
4. By using lysozyme enzyme in the tears and nasal fluids
5. By vomiting and sneezing

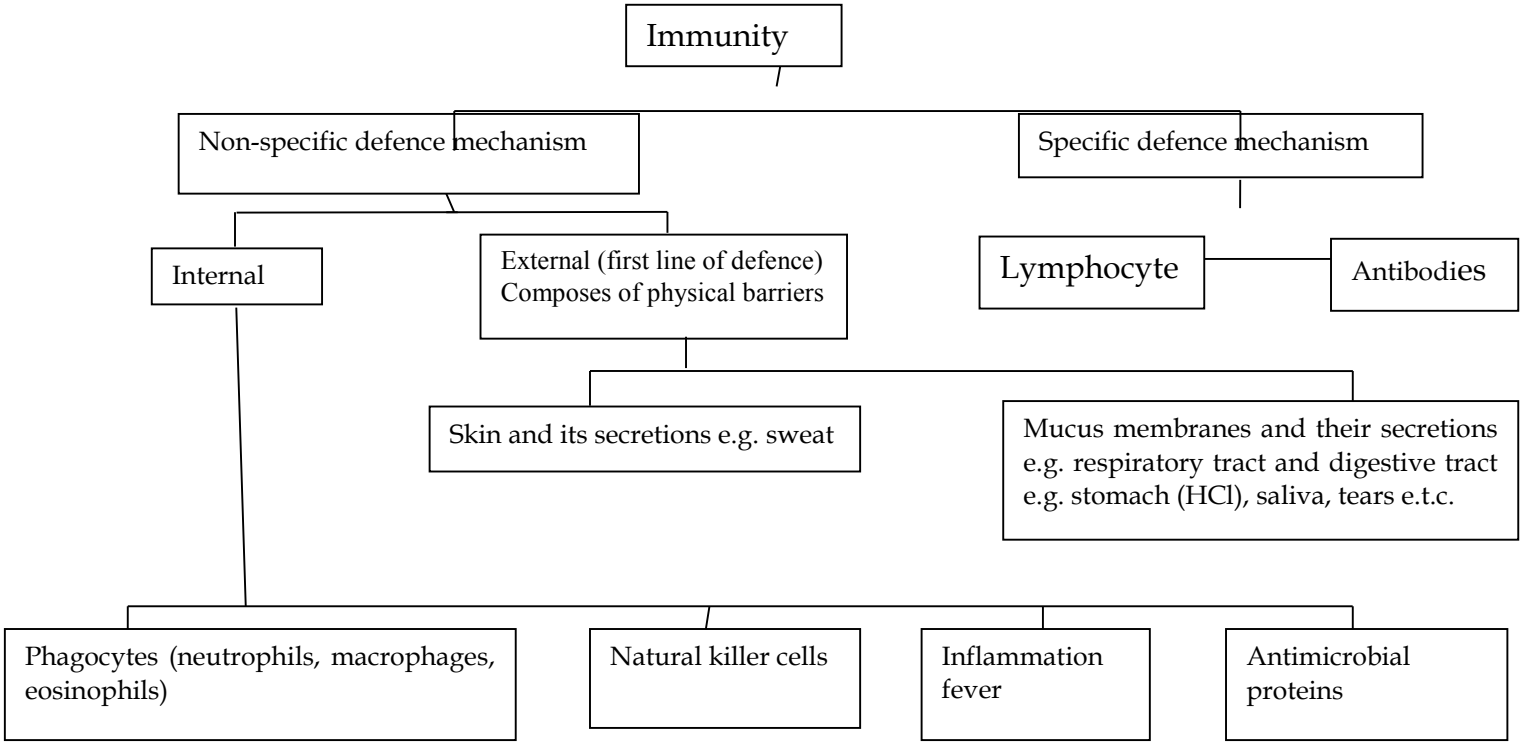
(Clegg fig 17.41 pg 365)



Why blood does not clot in the vessels
Connective tissue plus the liver produce chemical, heparin, which prevents the conversion of prothrombin to thrombin, and fibrinogen to fibrin. Blood vessels are smooth to the flow of blood. Damage to the vessel's endothelium can lead to platelets breakdown which leads to clotting of blood.

BODY DEFENCE SYSTEM AND MECHANISM IN MAMMALS (HUMANS)
An animal must defend itself against unwelcome intruders e.g. dangerous viruses and other pathogens it encounters in the air, water and food. The body also deals with abnormal cells (cancer cells) that develop periodically in the animal's body.

A summary of defence mechanisms in an animal's body



Two comparative defensive systems are used to fight pathogenic and abnormal cells in the body. One of the system is **non-specific** in nature i.e. it does not distinguish ones infections agent from another. The other defence system is **specific** in nature and constitutes the **immune system**. The non-specific system includes two lines of defence which an invader encounters in sequence. The first line of defence is external comprising of epithelial tissues that cover and line our bodies (skin and mucus membranes) and other secretions these tissues produce. The second line of non-specific defence is internal. It is triggered by chemical signals and uses antimicrobial proteins and phagocytic cells that indiscriminately attack any invader that penetrates the body's outer barrier (inflammation is a sign that tins second line of defence has been deployed.
The immune system constitutes a third line of defence which comes into place simultaneously with the second line of specific defence. However, the immune system responds specifically to a particular type of invader. This immune response includes the production of specific defence proteins called **antibodies**. It also involves participation of several different types of cells that are derived from the white blood cells called **lymphocytes**.

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

NON SPECIFIC DEFENCE MECHANISM

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

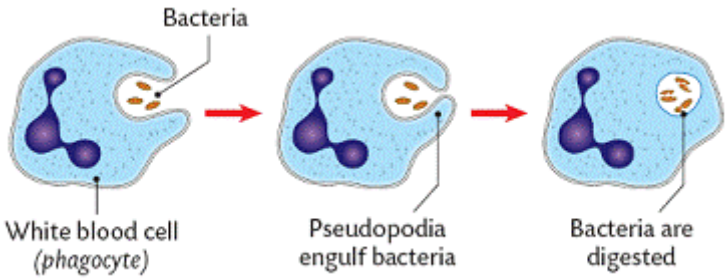
1. Through physical barriers e.g. skin.
2. Phagocytosis.
3. Natural killer cell.
4. Anti-microbial proteins.
5. Inflammation.
6. Fever

PHAGOCYTIC DEFENCE MECHANISM

Certain white blood cells particularly neutrophils and monocytes are attracted by chemicals released by body cells which have been damaged by invading pathogens. These white blood cells show amoeboid movements which engulf, ingest and destroy pathogens.
Neutrophils can squeeze through blood capillary walls a process called diapedesis and move about in tissue spaces. The monocytes migrate out of blood stream then become larger white blood cells (leucocytes) called macrophages.

Some macrophages are permanently located in tissues and organs such as the liver, spleen, kidney and lymph nodes while other circulate throughout the body. The term macrophage means "**big eater**" and these cells are long lived phagocytes which even engulf much larger particles like old red blood cells and protozoan parasites.

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



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

THE SKIN AND MEMBRANES

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

Mucus, which is a viscous secreted by cells of the mucus membranes also traps particles that contact it. Microbes entering the upper respiratory system are caught in the mucus and are the swallowed or expelled. The lining of the trachea has specialized epithelial cells equipped with cilia which sweep out microbes and other particles trapped by mucus, preventing them from entering the lungs.
Microbes prevent in food or trapped in swallowed mucus from the upper respiratory system pass through the highly acidic gastric juice produced by the stomach lining which destroys most of the macrobes before enter the intestinal tract.

NATURAL KILLER (NK) CELLS	**INFLAMMATION**
This is a class of white blood cells which attack virus injected body cells and abnormal cells that could form tumours. The virus infected cells have viral proteins displayed on their surfaces and these are recognized by the natural killer cells contains perforin – filled vesicle. When an N.K encounters a virus infected cell, perforin molecules are released by exocytosis. Perforin molecules make large holes of pores in the turgid cells plasma membrane, causing leakage of the cytoplasmic contents. This results into cell death. The membrane of NK cell is not affected by these membranes dissolving molecules.	This is a localized non-specific response initiated by the defence system of the body, in which the part of the body infected by a micro – organism has its blood vessels dilated, more permeable to blood components, having increased blood flow swells up, becomes warm and red as the phagocytes destroy the invading pathogens. An inflammation is usually by physical damage to the skin or mucus membranes by bacteria. This physical damage causes release of chemical signals such as histamine and prostaglandins. The chemical signals induce increased permeability of the blood capillaries and the flow of blood to the affected area respectively. They also attract phagocytic cells and lymphocytes which on arrival at the site of injury, the phagocytes consume pathogen and the cells debris and consequently the tissue heals. N.B. it is the damaged cells and certain leucocytes that produce histamine and Prostaglandins. The histamine cause vasodilatation i.e. the capillaries dilate and the walls become leaky. As more fluid collects around the wound, the site becomes red, swollen and warm. The localized swelling is called **oedema**. The prostaglandins are the ones that promote blood flow to the site of injury and increase the sensation of pain.

FEVER

Fever refers to increase in body temperature. It is triggered if microbes infect larger areas of the body in response to infection, certain leucocytes releases pyrogens which are also anti-microbial protein of the complement system. The pyrogen stimulate the hypothalamus to rise the body temperature set point from its normal value about 39^0C hence casing a fever. The fever has several beneficial effects;
It increases the activity of phagocytes which then attack the invading microbes more efficiently.
It increases the production of interferon in virus infected cells. Interferons are proteins which inhibit viral replication, activate natural killer and stimulate macrophages to destroy tumour cells and virus infected cell

ANTIMICROBIAL PROTEINS

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

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

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

SPECIFIC DEFENCE SYSTEM /IMMUNE SYSTEM/ACQUIRED IMMUNITY

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

MAJOR CELLS IN THE IMMUNE SYSTEM.

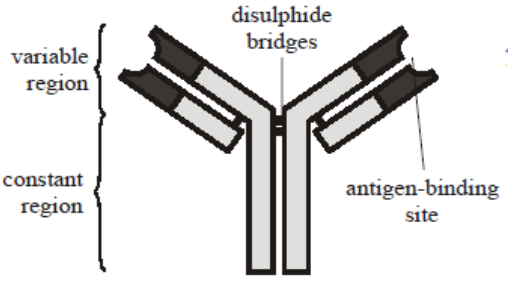
1. B-CELLS (B-LYMPHOCYTES) These are lymphocytes that produce antibodies when stimulated. They are produced and mature in the bone marrows from the **stem cells**. They have glycoprotein receptors on their cell surface membranes which bind specific antigens. Mature B-cells become plasma cells and memory cells produce much more antibodies in terms of quantity and effectiveness than plasma cells. 2. **T-CELLS** (**T-LYMPOCYTES**) The T-lymphocytes regulate the immune response (in case of T_H-cells) or kill certain types of cells (Tc-cells) the T cells are produced in the bone marrow but mature in the thymus gland where they develop specific receptors which recognise specific antigens. These are two main categories of T cell namely a. T_4 cell which have the CD4 receptor cites b. T-helper cells.	a. TC/T.cytotic cells recognize and destroy cells with foreign antigens on their surface. They mainly attack virus infected cells, cancerous body cells and foreign grafted tissues T_4 cells recognize and destroy cells with foreign antigens on their surface. They mainly attract virus infected cells, cancerous body cells and foreign grafted tissues. T_4 cells stimulates and enhance the immune responses by both B and Tc cells. T cells include the following; **i. 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. ii. **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. **iii. Suppressor T-cells** These suppress the activity of the killer T-cells and B-cells after the microbes have been cleared out of the body to prevent these cells from attacking and destroying the body cells. Suppressor T-cells therefore regulate the immune response and prevents antibodies from being produced by the B-cells.

MEMORY CELLS

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

MOLECULES OF THE IMMUNE SYSTEM

Antibody
This is a specific protein (immunoglobin) which recognizes and binds to specific antigens. Antibodies either neutralise antigens or tag cells that are antigens for easy attack by macrophages.
N.B. Macrophages are also taken to be part of the immune response i.e. involved in specific defence mechanism through indirectly since they are phagocytes which destroy microbes and alert other immune cells the infection.



stylised diagram

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

Cytokines (lymphokines)
These are peptides and proteins that regulate many cell activities (growth and repair) and act as signal in both the specific and non-specific immune responses
Examples of cytokines include
Interferons Interleukin

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

CHARACTERISTICS OF THE IMMUNE SYSTEM
The immune system develops specific response against each type of foreign microbes, toxin or transplanted tissues.
The immune system has 4 features i.e.

a. Specificity.
b. Diversity
c. Memory
d. Self/non self-recognition.

a. **Specificity**
The immune system has the ability to recognize and eliminate particular microorganism, and foreign molecules. The immune system responds to an antigen by activating specialized lymphocytes and producing specific proteins called antibodies.
Antigens that trigger an immune response include molecules belonging to viruses, bacteria, fungi, protozoa and parasitic worms.
Anti-bodes recognize antigens using epitopes which are antigenic determinants on the surfaces of the antigens. If an antigen has several epitopes, it stimulates several different B cells which secrete specific distinct antibodies against it. Therefore each antigen has a unique molecular shape and stimulate the production of the very type of antibody that defends against that specific defences, each response the immune system targets a specific invader distinguishing it from other foreign molecules that may be very similar.

b. **Diversity**
The immune system has the ability to respond to very many kids of invaders each recognized by its antigenic markers. This diversity of response is possible because the immune system is equipped with an enormous variety of lymphocyte population among the antibody producing lymphocytes (B-lymphocytes) each

population is stimulated by a specific antigen and response synthesizing and secreting the appropriate type of antibody.

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

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

.**TYPES OF ACQUIRED IMMUNITY**
There are two types of acquired immunity namely:

a. Active acquired immunity.
b. Passive acquired immunity.

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

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

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

TYPES OF NATURAL IMMUNITY

a. 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.

b. Natural active immunity
This is the immunity that involves formation of antibodies by the body of an organism in the presence of certain antigens.
This type of immunity is permanent because during the immune response, memory B-cells are produced which recognize the microbes on reinfection (second infection) and then stimulate the rapid production of large amounts of antibodies to curb down the microbes before causing significant damage. Memory B-cells stay for long in blood.

MECHANISM OF IMMUNE RESPONSES
The immune system mounts two different types of responses to antigens namely;
Cell-mediated response.
Humoral response.

HUMORAL RESPONSE

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

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

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

HOW ANTIBODIES WORK

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

a. Neutralisation

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

b. Agglutination (**clumping**)

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

c. Precipitation

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

d. Opsonisation

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

e. Complement fixation

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

CELL MEDIATED IMMUNE RESPONSE.

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

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

IL-2 also stimulates the development of natural killer cell and B-cells. Interlenkin-2 also stimulates cytotoxic T-cell which generally have the CD8 receptors on their cell membranes. These receptors enable the TC cells to interact with the class I MHC molecule. If these cells are infected by viruses, the fragments of virus are displayed on the membrane with the aid of MHC protein. The T cell is also activated when it is in contact with

the class I MHC antigen complex on an infected cell. The stimulated TC cell release perforins a protein that forms pores in the infected cell membrane. This results in the lysis of the infected cell. The pathogen e.g. a virus becomes exposed and it is destroyed by the circulating antibodies.

NB. In the same way, the T-cells attack tumour cells which display fragments of tumour antigen.
The Major Histocompatibility Complex (MHC) is a set of closely linked genes which code for a set of proteins (antigen marker) found on the surface of cells.

It is divided into two main classes i.e.

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

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

SPECIFITY AND DIVERSITY

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

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

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

Memory and secondary immune response

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

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

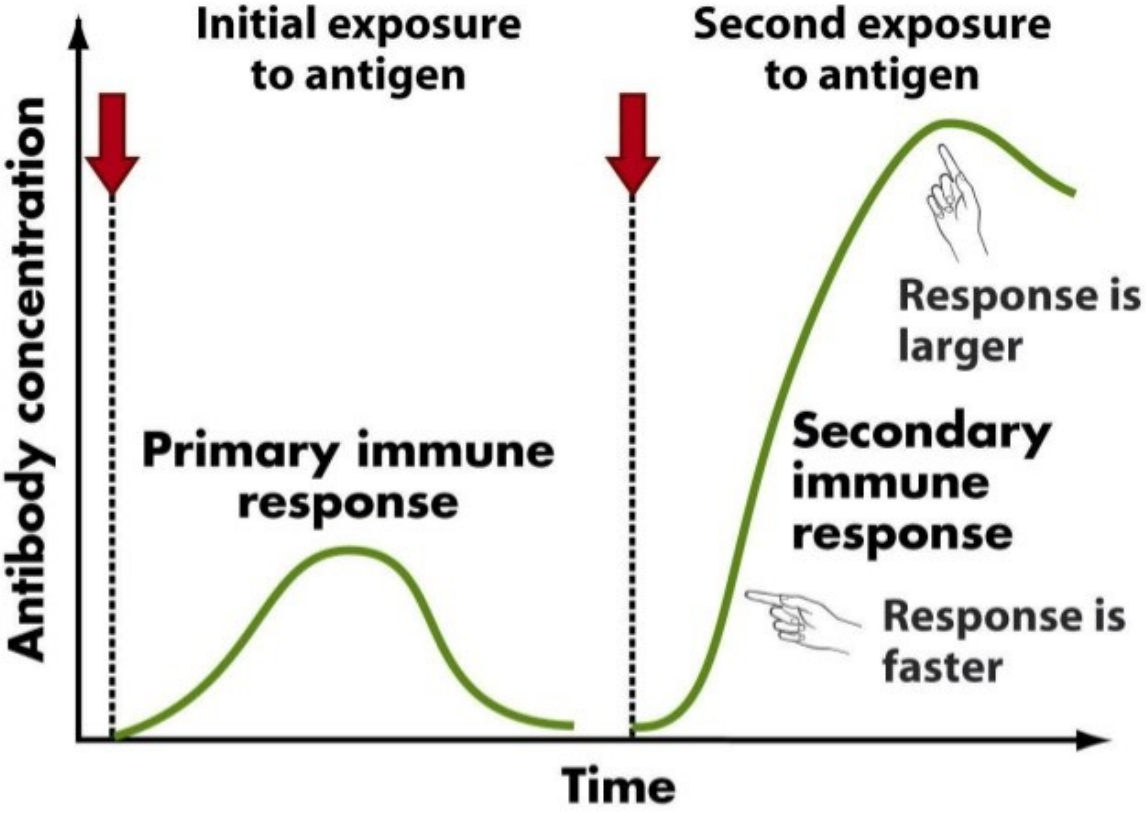
If the body is exposed to the same antigen at a later time, the response is faster one/more prolonged than the primary immune response. This is the secondary immune response.

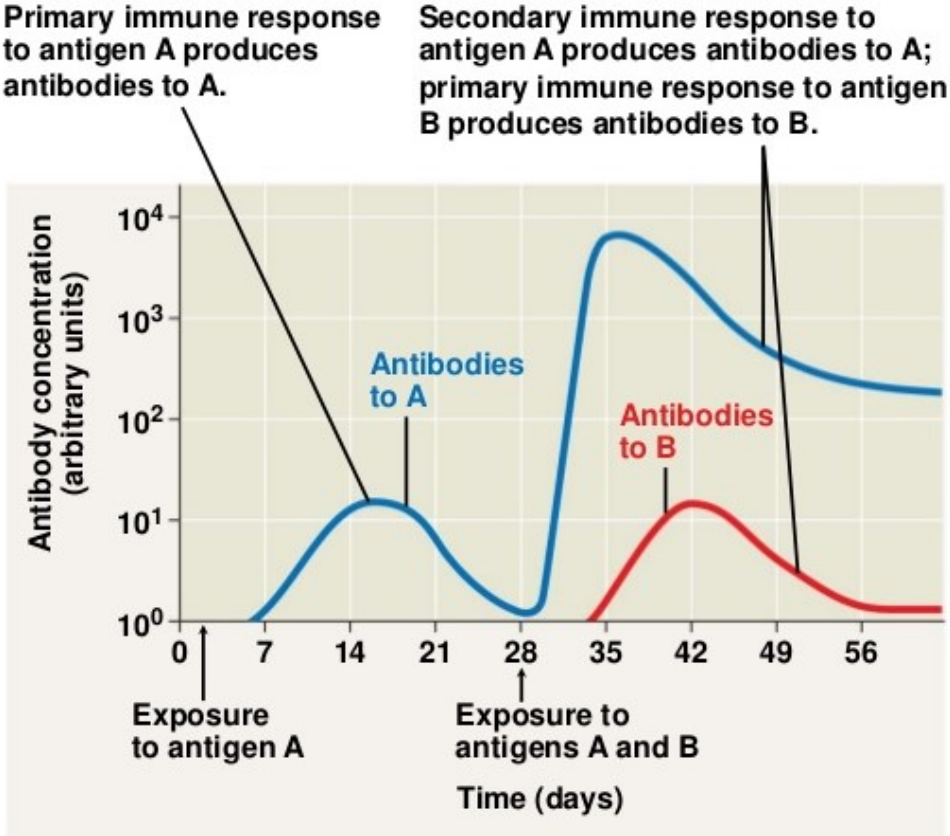
Secondary immune response is the rapid response that results in faster production of effector Tcells and antibody molecules when the body is exposed to subsequent infection of the same antigen that has ever invaded the body.
Antibodies produced during the secondary immune response are more effective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

The immune systems' ability to recognize an antigen as previously encountered is called immunological memory. The ability is based on long lived effector cells of the immune response, memory cells are not

active- memory cells survive for long periods and proliferate rapidly when expose to the same antigen that caused their formation secondary immune gives rise to new clone to memory cells as well as effector cells.

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





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

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

1. Auto immune disease.
2. Allergy.
3. Immune deficiency.

THE LYMPHATIC SYSTEM

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

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

N.**B** the lymphatic system serves to;
a) Defend the body against infection.
b) Maintains the level of interstitial fluid (tissue fluid).
c) Transports fats from the digestive tract to the circulatory system (the lymph capillaries called lacteals) penetrate the villi of the small intestine which absorb the fatty acids and glycerol.

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

VACCINES

Vaccines are toxic chemicals or killed or attenuated (weakened) microbes introduced into the body of an organism to make it produce very many antibodies against a certain pathogen.
The killed microbes are usually viruses and bacteria. The attenuated microbes are living microbes which are inactivated and they lack powers to infect the body due to the chemical or temperature treatment given to them.
Note; toxins are toxic chemicals produced by microbes and therefore can work as antigens

BLOOD TRANSFUSION

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

Blood transfusion based on the ABO system of grouping blood

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

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

Blood plasma permanently contains antibodies depending on a particular blood group. However these antibodies do not correspond to a specific antigen, if they correspond then agglutination occurs (precipitation of blood). That is why an individual with blood A having antigen A cannot donate blood to an individual with blood group B having antibody a in the plasma which corresponds to antigen A to cause agglutination.
Similarly, blood groups A and B cannot donate blood to an individual of blood group O because antigen A will be attacked by antibody a in blood group O and antigenB will be attacked by antibody b in blood group O to precipitate the recipient's blood. The table below summarizes the possible blood transfusions and the impossible ones.
Individuals with blood group AB posses antigen B which stimulates blood group B of the recipient to produce antibody a that reacts with antigen A in the donor's blood to cause agglutination and therefore this transfusion from AB to B is impossible. Similarly blood group O individuals can donate blood to blood group A because the donor's blood has no antigens which would react with antigen A in the recipient's blood and therefore agglutination is impossible.

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

UPTAKE AND TRANSPORT IN PLANTS

Water and mineral salts are necessary for photosynthetic reactions and other metabolic processes; hence they must be absorbed in sufficient quantities by using the root system and transporting them through the xylem to the mesophyll cells of leaves where photosynthesis takes place.
Water however can be lost from the mesophyll cells into sub-stomatal air chambers and then eventually lost into the atmosphere of water vapour through tiny pores called “stomata” by a process known as transpiration.

TRANSPIRATION

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

Types of transpiration

There are three types of transpiration which include the following;

a. Stomatal transpiration
b. Cuticular transpiration
c. 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

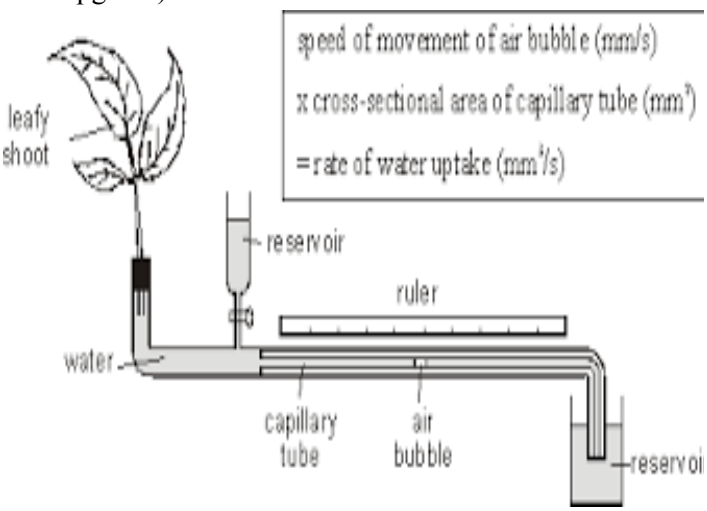
a. the weighing method

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.

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



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

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

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 above.

Precautions taken when using a potometer

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

How to use a potometer

a. 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.

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

a. 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.
b. It facilitates the uptake of the absorbed mineral salts within the xylem vessels from roots to leaves
c. 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
d. 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
e. It is important for cloud formation via evapotranspiration hence resulting into rainfall

Disadvantages of transpiration

a. It causes wilting of plants in case of excessive transpiration
b. It may eventually cause death of the plant, when the plant loses water excessively due to excessive transpiration

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

FACTORS AFFECTING TRANSPIRATION

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

ENVIRONMENTAL FACTORS

1. Humidity

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

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

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

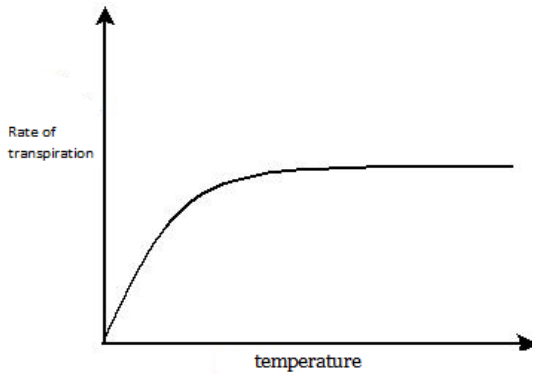
In areas where humidity is too high, plants loose liquid water from their leaves via structures/glands on their leaf margins known as hydathodes, a process known as guttation. Guttation is the loss of liquid water from plant leaves through hydathodes due to excessive humidity in the atmosphere.

2. Temperature

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

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

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



3. Air movements

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

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

(Soper fig 13.9 pg 439)

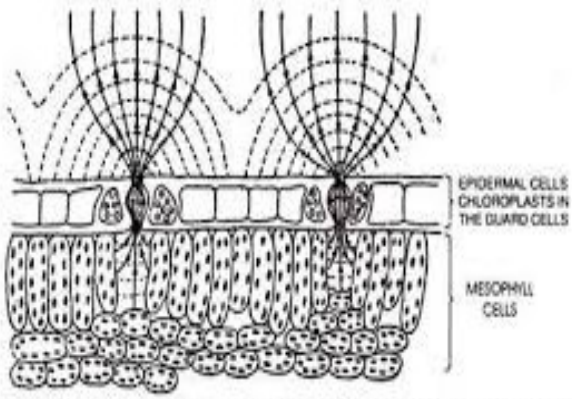


Fig. 8-3. Diffusion pathway of water vapor in stomatal transpiration from a leaf. Arrows indicate path water vapor diffusion. The dotted lines indicate surfaces of equal water vapor concentration.

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

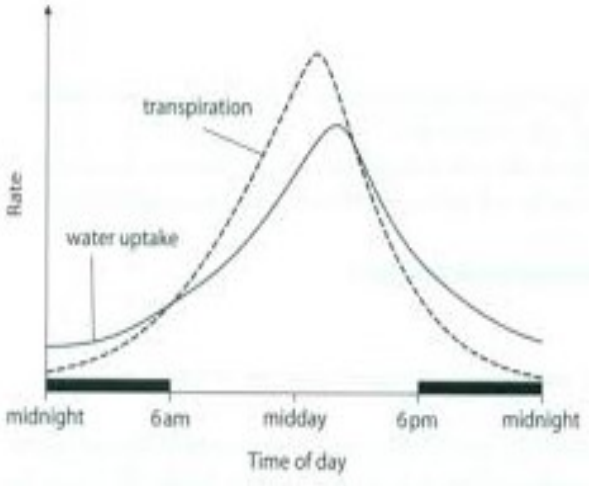
For water vapour to diffuse out of the sub-stomatal air chamber to the atmosphere, the mesophyll cells must be thoroughly wet. Shortage of water in the soil or any mechanism which hinders the uptake of water by the plant leads to wilting of the plant hence the closure of the stomata.

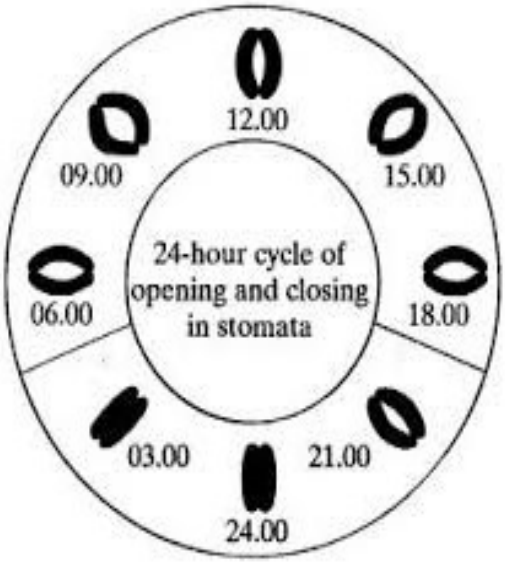
When water is supplied in large amounts, too much water evaporates to the atmosphere and therefore a high rate of transpiration. However, when the water supply to the mesophyll cells is low, less water evaporates from the sub-stomatal to the atmosphere, hence a low rate of evaporation.

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.





QN. What is the relationship between transpiration and water up take?

NON-ENVIRONMENTAL FACTORS

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.

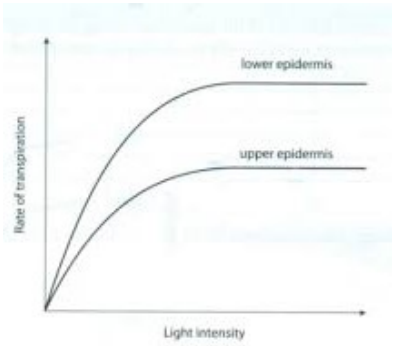
Number of stomata

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.

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.



STOMATA

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

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

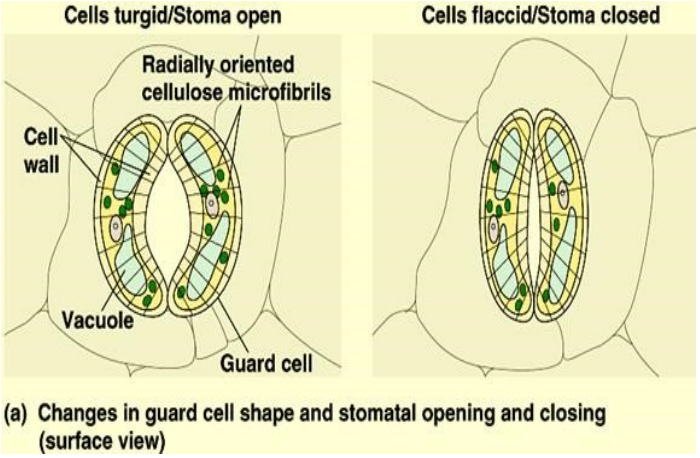
In most terrestrial plants, stomata are more abundant on the lower side than the upper surface of the leaf. This reduces water loss through transpiration since the upper surface is exposed to direct sunlight.

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

Structure of the stoma

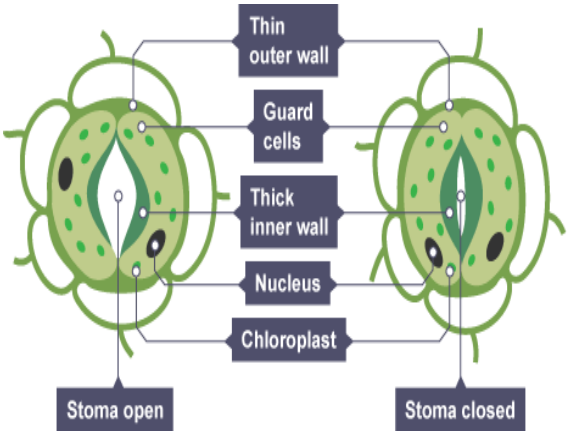
Each stoma consists of a stomatal pore is bordered by a pair of crescent or bean-shaped cells called guard cells. Unlike epidermal cells, guard cells contain chlorophyll. The inner cell wall of guard cells is thicker and less elastic than the outer wall. Microfibrils are radially orientated in the cell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

(Toole fig 22.7a pg 452)



(a) Changes in guard cell shape and stomatal opening and closing (surface view)

(Toole fig 22.7b pg 452)



(Soper fig 13.15 pg 444)

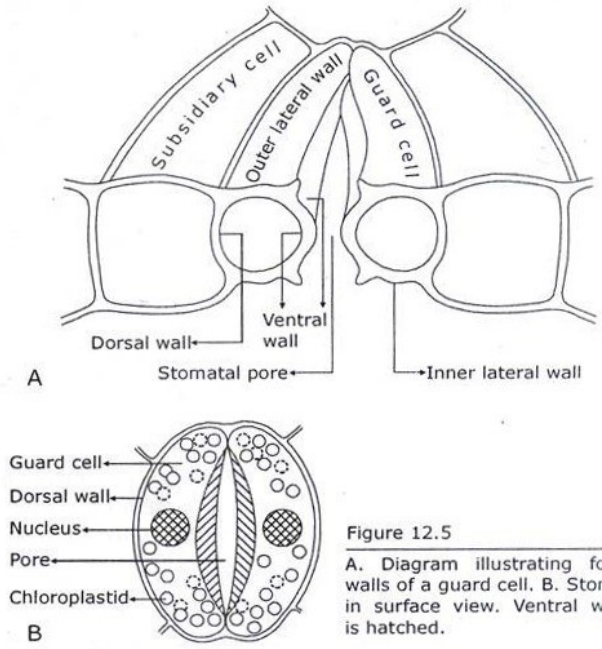


Figure 12.5
A. Diagram illustrating four walls of a guard cell. B. Stoma in surface view. Ventral wall is hatched.

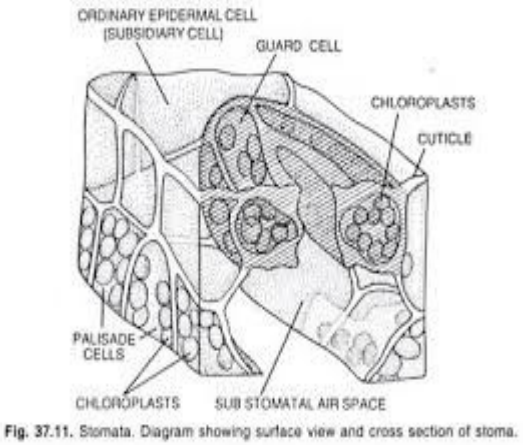


Fig. 37.11. Stomata. Diagram showing surface view and cross section of stoma.

Ventilation (opening and closing of stomata)

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

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

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

a. Photosynthetic product theory

- Guard cells have chloroplast.
- During day light, they carry out photosynthesis producing sugar.
- The sugar increases the osmotic pressure of the cell sap. This causes water to move into the guard cells from neighbouring epidermal cells by osmosis. The result is an expansion and increase in turgidity of the guard cells containing the stomata to open.
- In darkness, photosynthesis stops and the sugar in the guard cells is converted to starch. This lowers the osmotic pressure of guard cells causing them to lose water to neighboring cells by osmosis.
- The guard cells become flaccid and the stomata close.

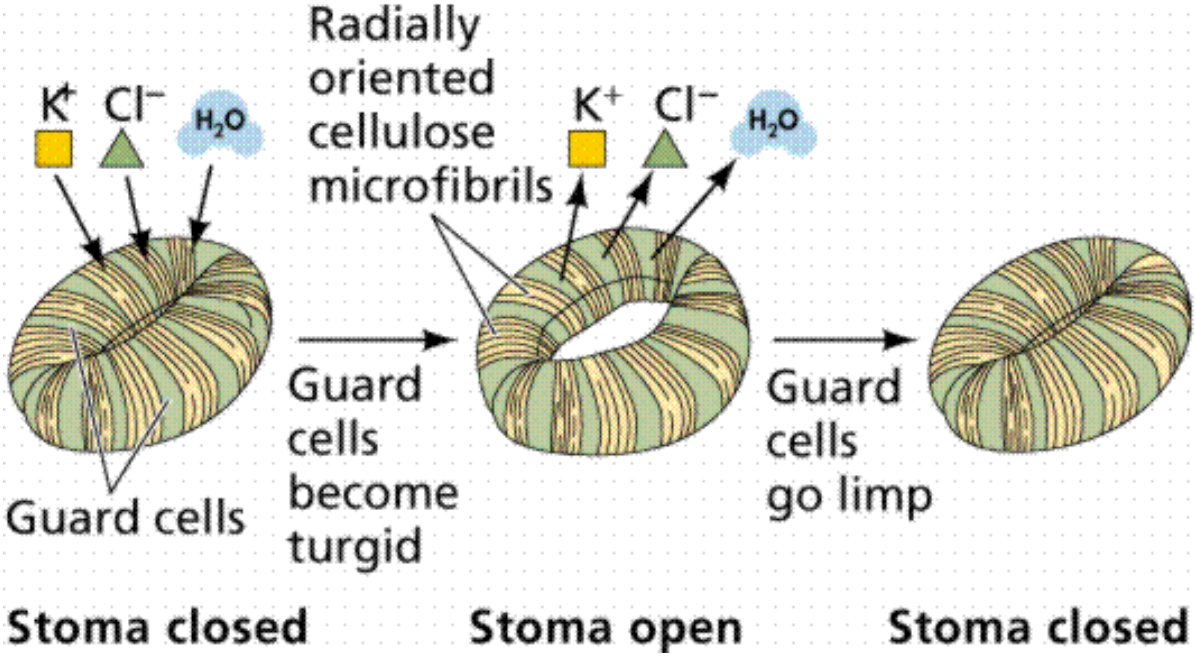
Note; this theory does not explain how the low rate of glucose formation can account for the rapid opening of stomata

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

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

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

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



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

Stomata opening

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

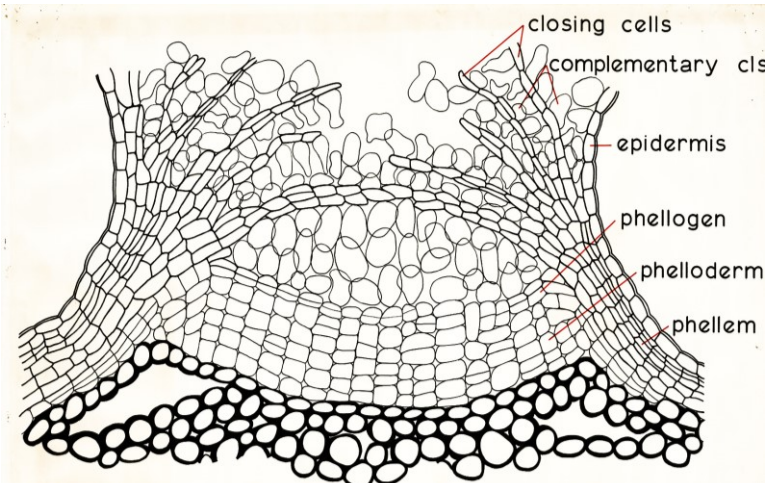
Stomata closure

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

LENTICELS

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

Structure of the lenticel



ROOT EPIDERMAL CELLS

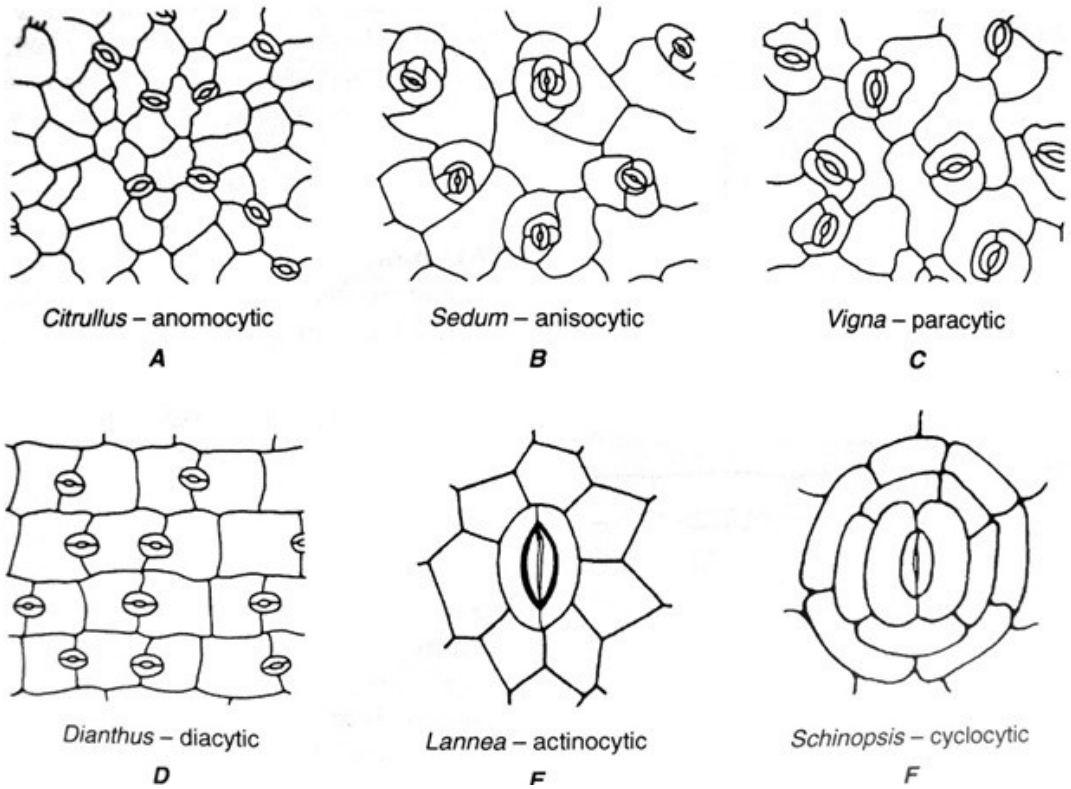
Root cells can also take in oxygen for respiration and give out carbon dioxide. Gaseous exchange takes place by diffusion between the epidermal cells of roots and the air spaces in the soil. Most of the exchange takes place at the root hairs which provide a large surface area.
Water logged soils have their air spaces occupied by water, thereby reducing respiration in the roots which may subsequently die. This would obviously kill the whole plant.

Some aquatic plants, like pond weeks and multi cellular algae are completely submerged in water. These obtain their gaseous requirements by diffusion from the surrounding water. Epidermal cells of such plants have no cuticle and gasses diffuse directly across it.
Others like rice and water lilies are partially submerged in water. Their aerial parts obtain carbon dioxide and oxygen in the same manner as terrestrial plants. The submerged parts may face the problems of obtaining adequate oxygen for their respiratory requirement. However such plants have large air spaces in their stems and roots which store oxygen obtained from the aerial parts and that formed during photosynthesis. Floating leaves of such plants have stomata on the upper surfaces only.

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

EXPERIMENT TO OBSERVE STOMATA

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



WATER UPTAKE BY THE ROOTS

Internal structure of the root

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

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

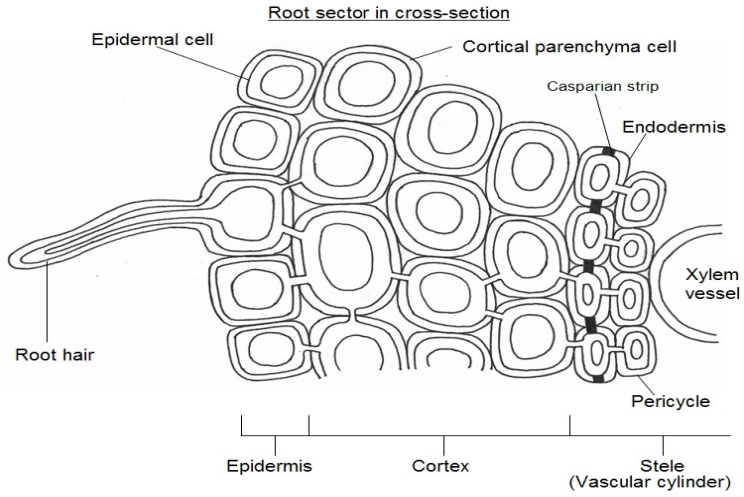
The endodermal cells have their radial and horizontal walls coated with a corky band called casparian strip. This strip is made up of a substance called suberin. The Casparian strip is impermeable to water and solutes due to the suberin that it contains and therefore prevents water and solutes to pass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

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

Diagram showing the internal structure of the root

(Toole fig 22.13a pg 462) (Toole fig 22.13b pg 462)

Longitudinal section through a root



Mechanism of water uptake by the roots

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

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

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

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

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

Apoplast pathway

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

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

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

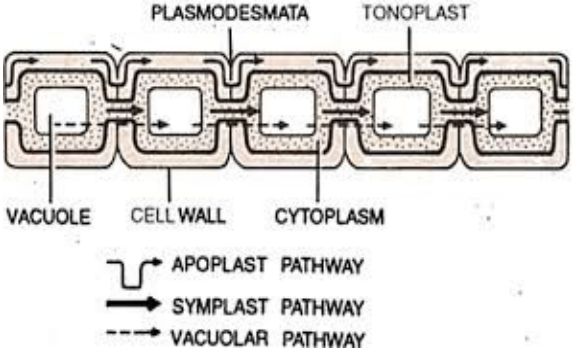
The casparian strip facilitates the pushing of water upwards through the xylem vessels by root pressure up to the leaves due to its active pumping of the salts. In addition, this active pumping of the salts into the xylem vessels prevents leakage of slats (ions) out of the xylem vessels so as to maintain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

Symplast pathway

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

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

Diagram showing the three pathways of water in the root
(Soper fig 13.18a pg 448)

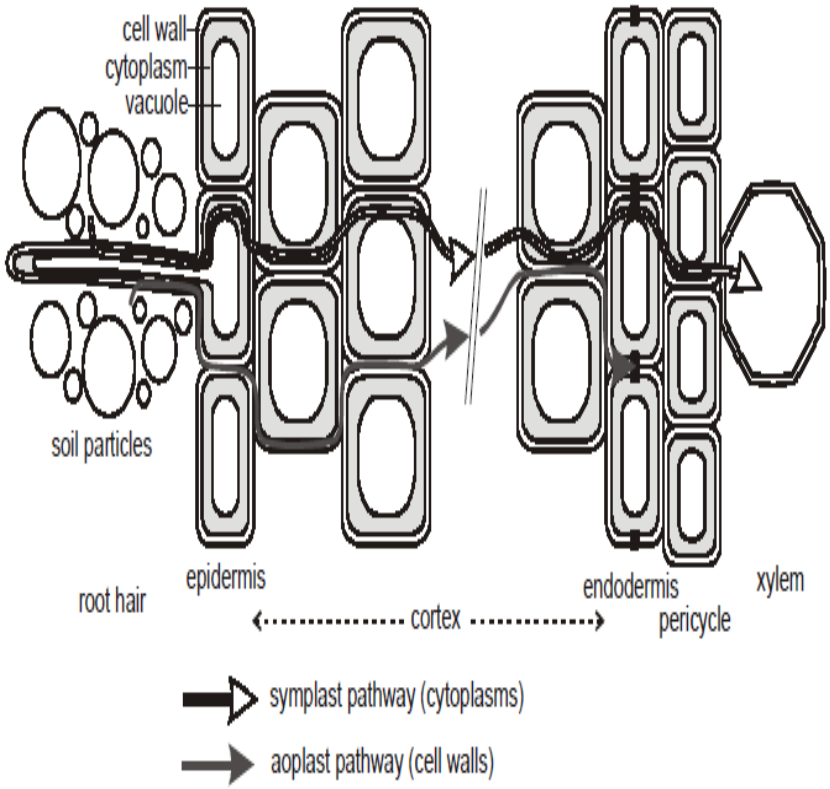


Vacuolar pathway

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.



To ensure maximum absorption of water, the root hairs have the following <u>adaptations</u>

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

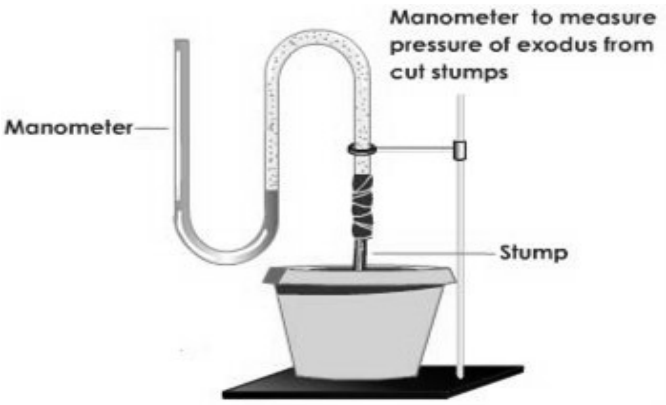
a. There are numerous starch grains in endodermal cells which could act as an energy source for active transport.
b. Lowering the temperature reduces the rate of water exudation (given out) from the cut stem as it prevents root pressure, an active process.
c. Treating the roots with metabolic poisons 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.

a. 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

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.



Experiment to demonstrate root pressure-B

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;

1. Root pressure
2. Transpiration pull(cohesion force)
3. Capillarity

Root pressure

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

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

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

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

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

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

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

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

Capillarity

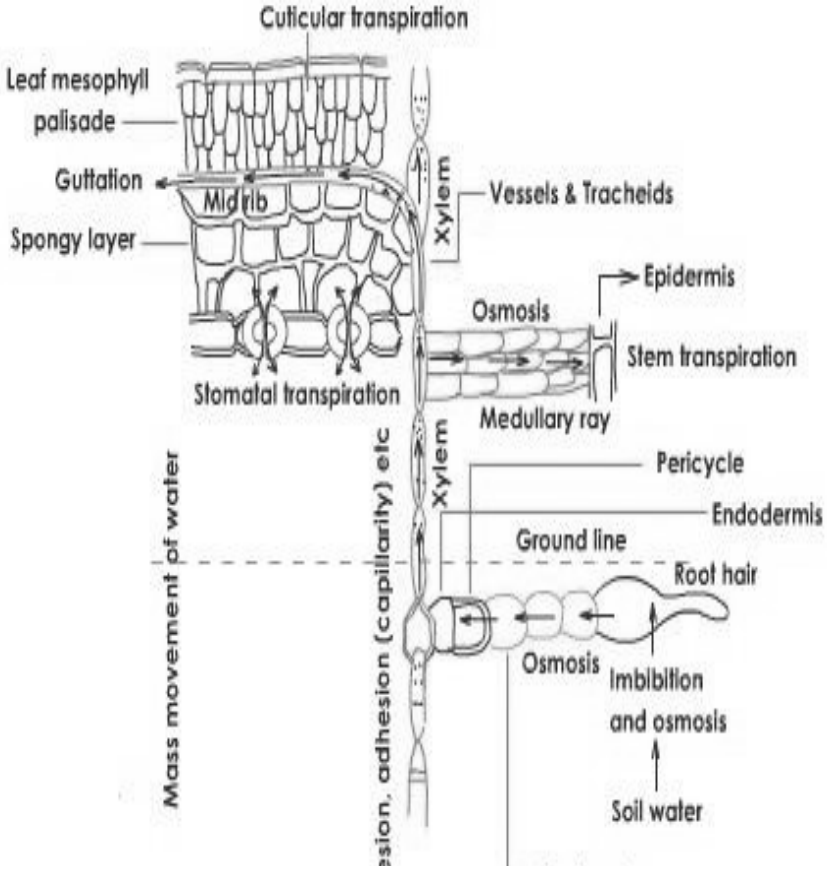
Since the water rises upwards through narrow leaves, it is also facilitated by capillarity through the stem. This is because the xylem vessels are too narrow and the flow of water is maintained without breaking by both the cohesive and adhesive forces.

NOTE

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

Adhesion is the force of attraction between molecules of different substances while cohesion is the force of attraction between molecules of the same substance

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



UPTAKE AND TRANSLOCATION OF MINERAL IONS

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

There are two main processes of translocation which include;

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

Mechanism of mineral ion uptake

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

Active absorption of minerals

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

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

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

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.

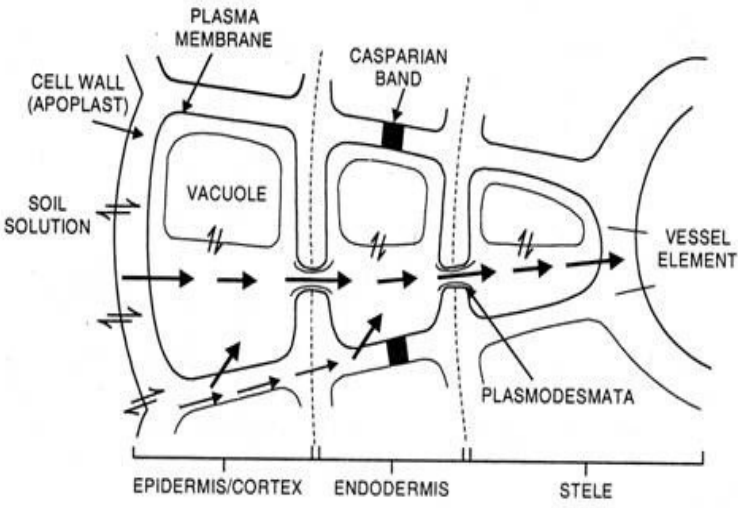


Fig. 7.5. Radial paths of movement of mineral nutrient ions in root

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.

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

1. 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
2. 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.
3. 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.

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

1. The presence of mineral ions in the xylem sap i.e. many mineral ions have been found to be present in the xylem sap.
2. 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.
3. There's evidence that other solutes e.g. the dye, eosin, when applied to the plant roots, it is carried in the xylem vessels
4. 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 **mycorrhiza**.

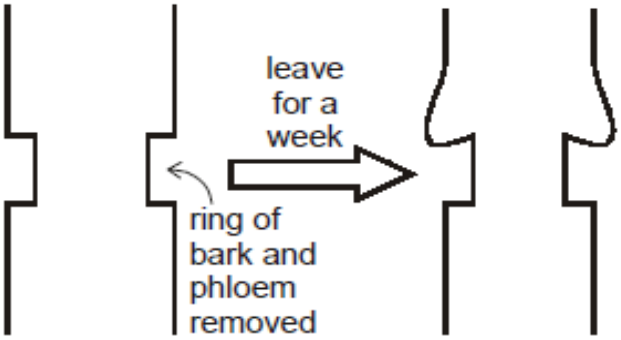
TRASLOCATION OF ORGANIC MOLECULES

(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

1. 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.**



2. When the phloem is cut, the sap which exudes out of it is rich in organic food materials especially sucrose and amino acids.
3. 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

4. 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.
5. 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
6. 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
7. 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.

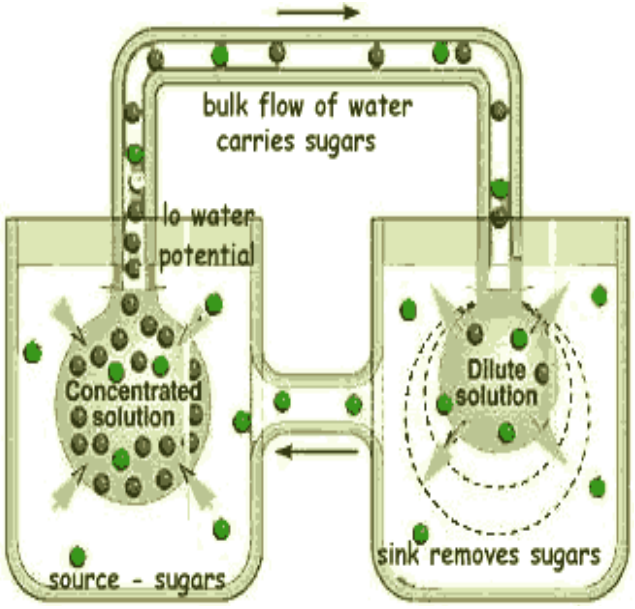
a. The mass flow or pressure flow hypothesis (i.e. Much's hypothesis)
b. Electro-osmosis
c. Cytoplasmic streaming

Mass flow or pressure flow hypothesis

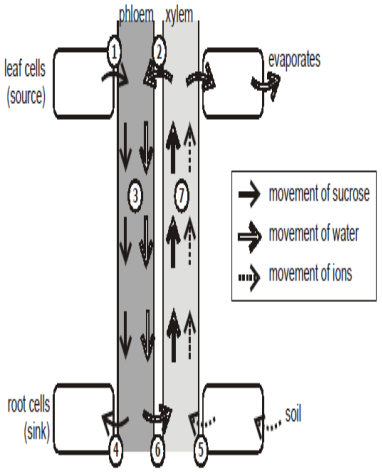
Mass flow is the movement of large quantities of water and solutes in the same directions.
According to this theory, photosynthesis forms soluble carbohydrates like sucrose in the leaves. The photosynthesizing cells in the leaf therefore have their water potential lowered due to the accumulation of this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

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

A diagram showing movement of the products of photosynthesis by mass flow
(Toole fig 22.23 pg 470, Kent fig 2 pg 286)



Evidence supporting the mass flow theory



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

Criticism of mass flow

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

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

Electro-Osmosis

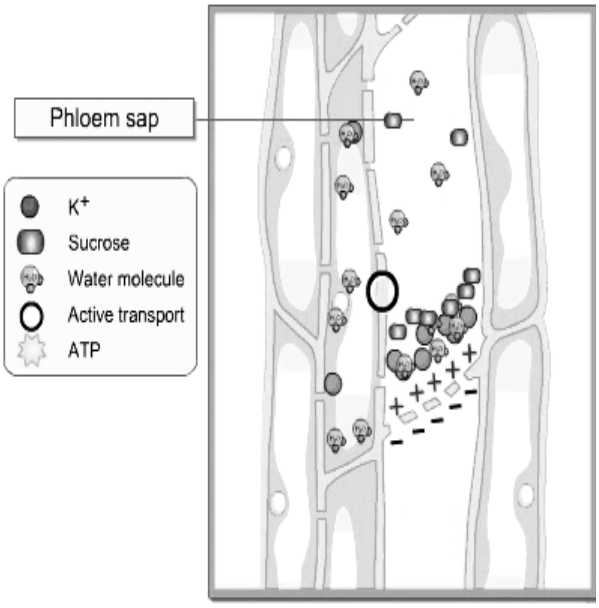
This is the passage of water across a charged membrane.

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.

(Clegg fig 16.39b pg 341)



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.

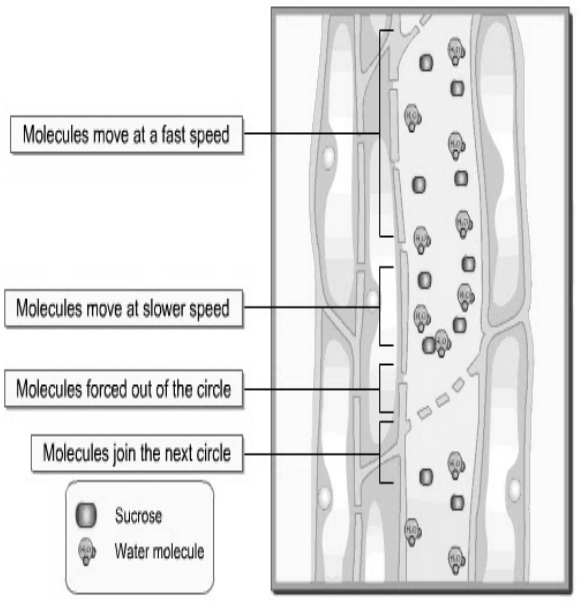
Cytoplasmic streaming theory

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.

Evidence supporting the cytoplasmic streaming theory

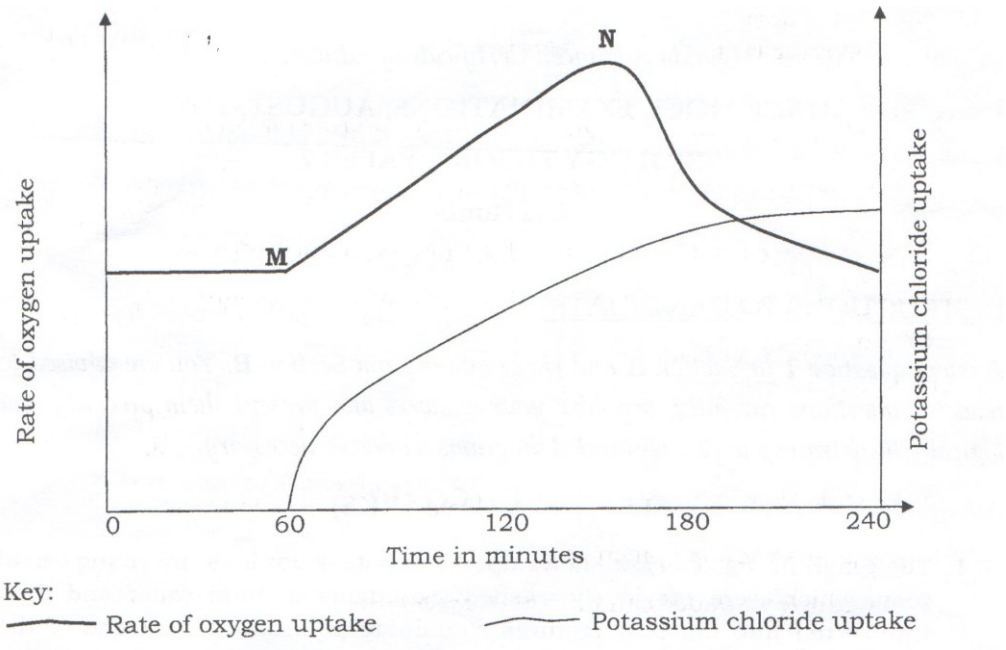
1. It has been found that the solute materials move in both directions in the phloem tissue
2. The theory explains the existence of the trans-cellular strands in the phloem tissue as well as many mitochondria in the companion cells
3. Presence of a sieve plate where a potential difference can be developed across the plate
4. Criticism of the Cytoplasmic Streaming Theory
5. Cytoplasmic streaming has not been reported in mature sieve tube elements but only in young sieve tubes.
6. The rate at which the protoplasm streams is far slower than the rate of translocation

Diagram showing Cytoplasmic streaming
(Kent fig 3 pg 287)



SAMPLE QUESTIONS

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



a) Compare the rate of oxygen uptake with the rate of chloride uptake between 60 and 240 minutes. (04 marks)

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

2. a) State the **physiological importance** of the following structural components of the plasma membrane.

i. Proteins (03 marks)

ii. Carbohydrates (02 marks)

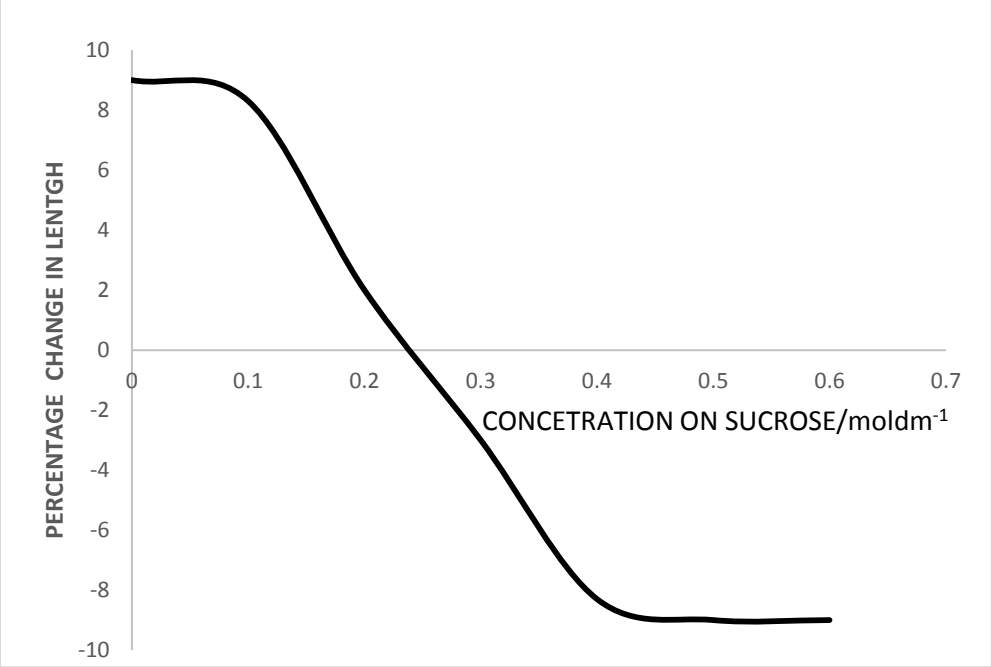
iii. Cholesterol (03 marks)

b) Explain why non polar (lipid soluble) molecules diffuse more rapidly through membranes than polar (lipid insoluble) molecules. (02 marks)

3. (a) Describe the formation of Golgi bodies in the cell (06 marks)

(b) What are the functions of this organelle to the cell? (04 marks)

4. The graph below shows the percentage change in length of cylinders of potato which had been placed in sucrose solutions of different concentrations for 12 hours.



a) What is meant by the term **water potential**? (02 marks)

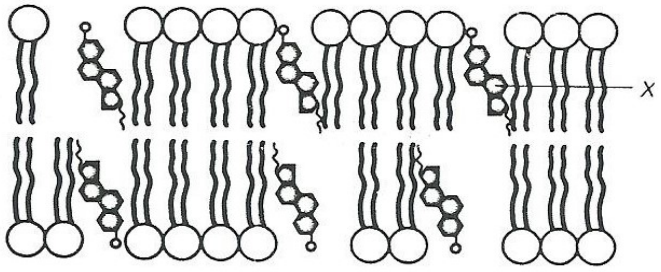
b) In terms of water potential, explain the change in length which occurred when the cylinder of potato was placed in a sucrose solution of concentration of 0.3mol dm^{-1}

c) With a reason, state the concentration of sucrose in the potato tubers used in the experiment above (03 marks)

Potato tubers store starch. As they start to grow or sprout, some of this starch is converted to sugars. Sketch a graph on the one plotted above to represent the changes in length you would expect if the investigation had been carried out with sprouting potatoes

5. a) State the components of the **cell theory**? (04 marks)

(b) The figure below shows part of a membrane



(i) Name the structure labelled **X** (01 mark)

(ii) Explain briefly the role of **X** in the membrane when the surrounding temperature is low or at moderately warm conditions (05 marks)

6. In an investigation pea plants were dug up from the field and washed thoroughly. The nodules were removed surface sterilized and transferred aseptically to a sterile liquid culture medium. After two weeks incubation, small samples of culture media were removed and added to trays each containing a batch of pea plants growing in an inert medium. Each batch was watered regularly with a nutrient

solution containing a particular concentration of sodium nitrate for four weeks, at the end of four weeks the mean number of root nodules and biomass were obtained from the investigation are shown in the table below.

Nitrate concentration of nutrient solution (arbitrary units)	**Mean number of nodules per plant**	**Biomass of pea plants /gm^{-2}**
0	82	140
1	70	200
2	68	230
3	40	350
3.5	20	400
4	10	460
5	0	440
5.5	0	400
6	0	350

(a) Represent the results of the table above graphically (**08 marks**)

(b) Explain the changes in mean number of nodules per plant and changes in the biomass of pea plants with increasing nitrate concentration of nutrient solution (**20 marks**)

(c) How was accuracy of results to be obtained ensured throughout the experiment (**05 marks**)

(d) (i) on the graph draw a graph to represent the plot for biomass you would expect if the experiment was repeated and in this case the sample culture medium was not added to the trays containing pea plants (**02 marks**)

(ii) Suggest reason(s) for the appearance of the graph drawn in d (i) above (**03 marks**)

(e) How can the information from the investigation be beneficial in crop production? (**02 marks**

7. Differentiate between natural active immunity and artificial active immunity. (02 mark)

(b) What are the different ways in which the mammalian body naturally defends itself against pathogens? [12 marks]

(c) Explain how artificial active immunity occurs. [06 marks]

8. In an experiment to investigate the effect of light intensity on the rate of transpiration and stomatal opening a leafy herbaceous plant was used. A potometer with the stem of a herbaceous plant was placed in an open grassland, the following results were obtained.

Light intensity in µm	Number of open stomata per branch	Rate of transpiration in mgm^{-2}h^{-1}
10	30	28
30	50	36
40	62	41
60	90	50
80	51	33
90	28	20
100	0	7

(a) Represent the above results graphically on the same axes (09 marks)

(b) Compare the effect of light intensity on the rate of transpiration and the number of open stomata (06 marks)

(c) Explain the effect of light intensity on the number of open stomata (14

(d) (i) State the relationship between the number of open stomata and the rate of transpiration *(02 marks)*

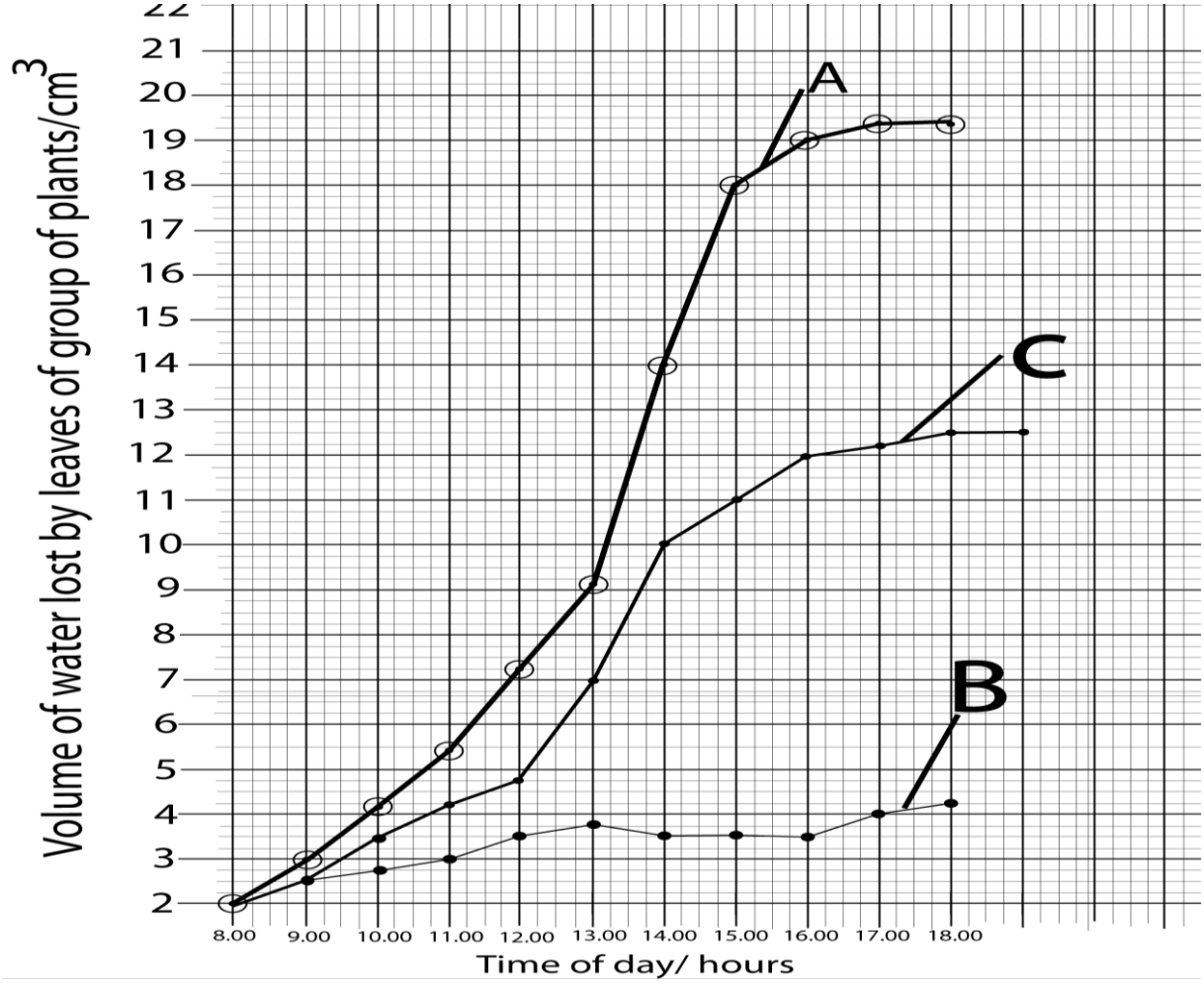
(ii) Explain the relationship stated in (c) (i) above (06 marks)

(e) Explain the results obtained at 100µm of light intensity (03 marks)

9. An experiment was carried out to investigate the rate of water loss by three groups of leafy plants under different conditions. Twelve leafy plants of approximately the same age, leaf surface area and of the same species were used in the experiment. Four plants were placed in each group and treated simultaneously as follows:

Group 1: Plants completely covered with transparent polythene bags.
Group 2: Plants fanned with an electric fan.
Group 3: Plants placed in still air in the open

The figure below shows the results of the experiments and the mean volume in cubic centimetres of water lost through evaporation over the leaf surfaces of groups of plants recorded. Each group of plants is represented as A, B and C in the figure 1 below



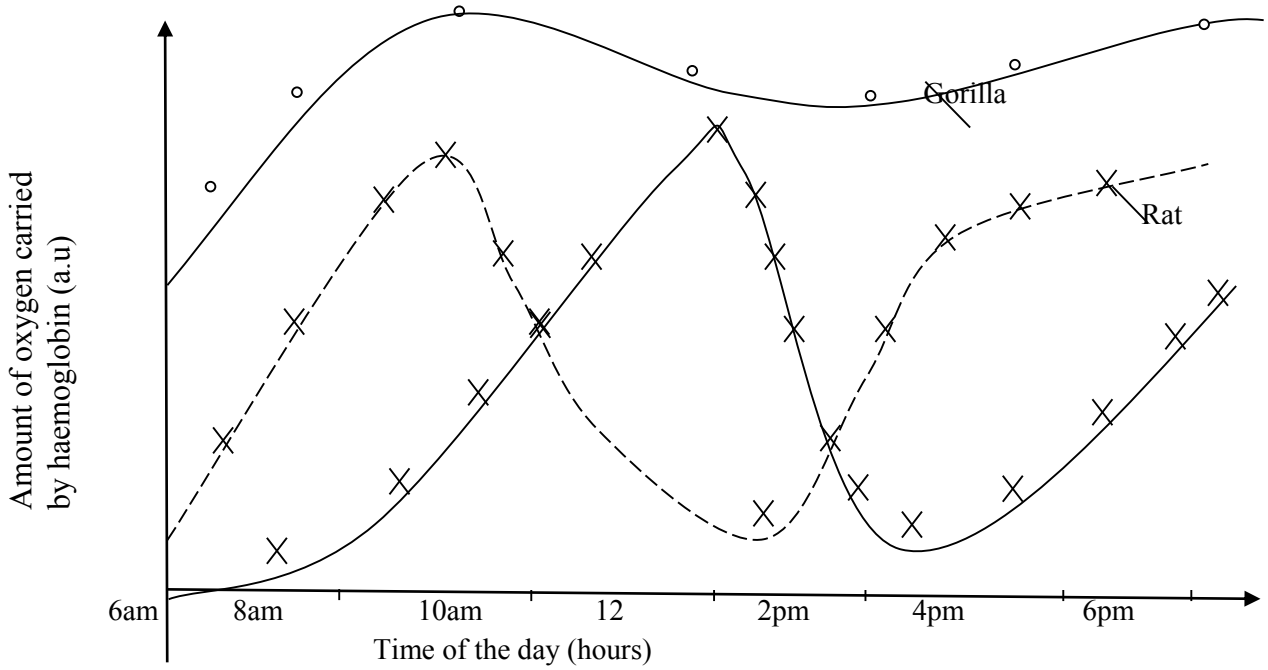
(a) Compare the volume of water lost by the leaves of different groups of plants shown in figure 1 above. (12 m)
(b) (i) From the curves drawn, identify the experimental conditions to which each group of plants **A**, **B** and **C** were placed. (03 marks)
(ii) With respect to group of plants **A** and **B**, suggest reasons for the observed difference in the two curves drawn. (07 marks)
(c) Why were the plants of the same age, leaf surface area and same species used in the experiment? (05 marks)
Suggest
(i) a hypothesis which this experiment was designed to test. (01 mark)
(ii) the name of the apparatus commonly used in this type of experiment. (01 mark)
(d) (i) Calculate the rate of water loss over the leaf surfaces by evaporation in group **C** between the time of the day 12:00 – 14:00 hours and 16:00 – 18 hour (03 marks)
(ii) Explain the difference in the rate of water loss by the same group of plants at various times of the day. (08 marks)

10. a) Discuss the advantages of possessing membrane bound organelles in an eukaryotic cell (04 marks)

b) Briefly describe the structure of the nucleus (08 marks)

c) How does the structure of a nucleus compare with that of a mitochondrion? (08 marks)

11. (a) Figure 1 below shows the amount of oxygen carried by haemoglobin in three different mammals during the course of the day.



(i) Outline the differences in the amount of oxygen carried by haemoglobin of a rat with that of a human. (04marks)

(ii) Explain the trend of oxygen carried by haemoglobin for the;

- Gorilla (05 marks)
- Human (06 marks)
- Rat (06 marks)

b) Table 1 below shows the data obtained during an investigation on the effect of altitude on the amount of oxygen carried by haemoglobin and the rate of oxygen delivery to body tissues, for a person with sickle cell trait.

Altitude (metres)	Amount of oxygen carried by haemoglobin/cm^3	Rate of oxygen delivery to blood tissues (cm^3/minute)
0	85	20
100	80	5
200	73	11
300	48	20
400	32	45
500	20	60
600	15	75
700	13	85
800	11	88
900	8	90
1000	7	93

(i) Represent the above information on the graph paper. (06 marks)

(ii) Explain the relationship between altitude and the;

- the rate of oxygen delivery to body tissues. (05 marks)
- amount of oxygen carried by haemoglobin (06 marks)

c) What possible conclusion can be made from figure 1 and the graph plotted? (02 marks)

12. (a) What is meant by the term **human specific defence system**? (02 marks)
(b) Describe the role played by the thymus glands in the human specific defence system (12 m
(c) Of what importance is memory and diversity to a defence system? (06 marks)

13. Differentiate between Natural active immunity and Artificial active immunity (02 marks)
b) State the different ways in which the mammalian body naturally prevents pathogens from accessing its internal environment (11 marks)
c) What is the significance of the high body temperature experienced when the mammalian body is attacked by *Plasmodium Spp?* (07 marks)
a) What is meant by the term chloride shift? (03 marks)

14. Account for the relative position of the oxygen dissociation curves of the human and rat haemoglobin
(b)Explain the rapid dissociation of oxyhaemoglobin of a rat during a vigorous activity (07 marks)
(c) Describe the events which occur during the heart beat (16 marks)
(d)Outline the features which ensure efficient flow of blood within the mammalian body (04 marks)

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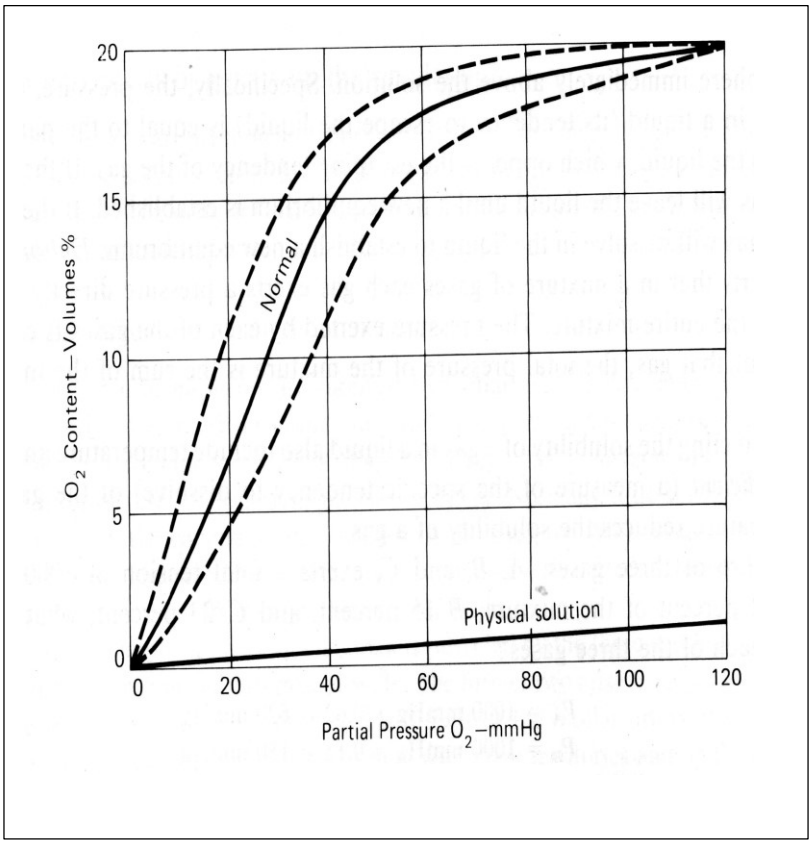
15. (a) What is the physiological significance of the Bohr effect in animals? (08 marks)
(b) Discuss the factors that may alter the rate of heart beat in mammals (12 marks)

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



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

(a) Label the curves of blood in
(i) veins and muscles and
(ii) arteries and lungs (02 marks).

(b) Explain the importance of the positions suggested above in the physiology of the animal (04 marks).
(c) Explain the difference in the variation of the oxygen content of normal and physiological solutions(03 ma

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

18. Define the term **facilitated diffusion**
c) State **three** ways how facilitated diffusion differs from simple diffusion

d) Describe **one** way how facilitated diffusion occurs across membranes
e) State **two** ways how the action of carrier proteins is similar to that of enzymes

19. 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.

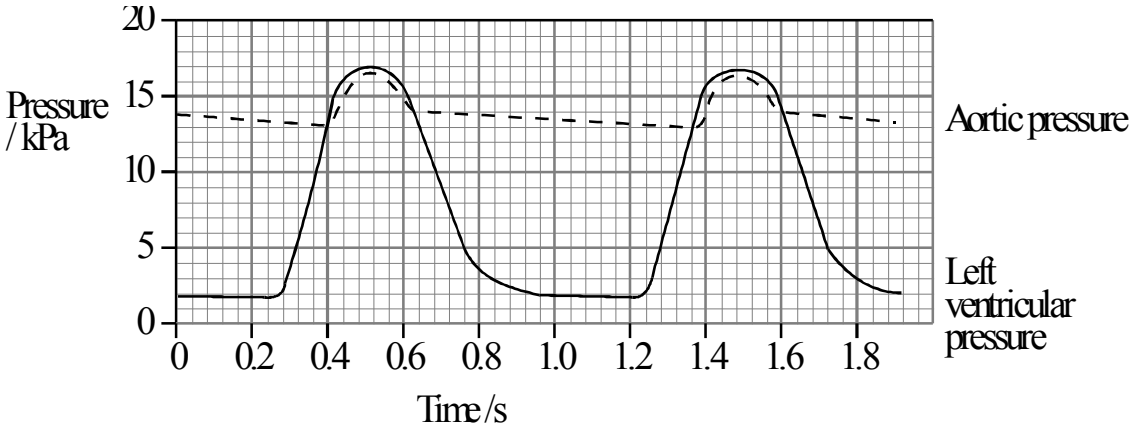
Partial pressure of oxygen in Pa	Percentage saturation of blood with oxygen	
	Partial pressure of carbon dioxide at 500 Pa	Partial pressure of carbon dioxide at 2600 Pa
500	30	5
1000	70	13
2000	90	24
3000	96	33
4000	98	41
5000	99	48
7000	100	60
9000	100	69
11000	100	76
13000	100	81

(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.

20. 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.

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

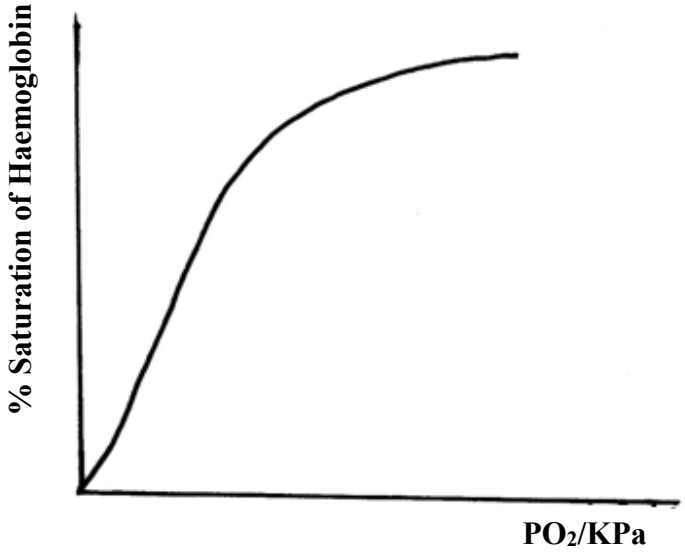
21. Figure below shows changes in the blood pressure in the aorta and the left ventricle during two complete cardiac cycles.



(a) On the graph, draw an arrow to show when the left atrioventricular (mitral) valve closes.(01 mark
(b) Use the information in the graph to calculate the heart rate. Show your working. (02 marks
(c) During the cardiac cycle, the pressure in the left ventricle falls to a much lower level than in the aorta. Suggest an explanation for this difference. (03 marks)
(d) During the cardiac cycle, the pressure in the right ventricle rises to a maximum of about 3.3 KPa. Suggest reasons for the difference between this pressure and the maximum pressure in the left ventricle.(03 marks)

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

The figure below shows the oxygen dissociation curve of hemoglobin from a mammal at 38^{0}C.



(b) Draw the curve of hemoglobin when the body temperature is raised to 43^{0}C(01 mark)
(c) Name one change in the conditions in the tissues which has the same effect on the oxygen dissociation curve as change in temperature (01 mark)
(d) Explain the effect of increased body temperature on the oxygen dissociation curve for hemoglobin in mammals(03 marks)
(e) State how this effect of temperature on the oxygen dissociation curve of hemoglobin might be advantageous to the mammal (03 marks)

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

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

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

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

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

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

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

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

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

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

24. (a) What is meant by the term **Bohr's effect**? (02 marks)

(b) Briefly explain the following observations;

The oxygen dissociation curve of,

i. man shifts to the right during exercise (03 marks)

ii. the elephant is on th e left of the oxygen dissociation curve of a mouse? (03 marks)

iii. thelungworm is on the left of that of man? (03 marks)

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

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

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

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

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

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

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

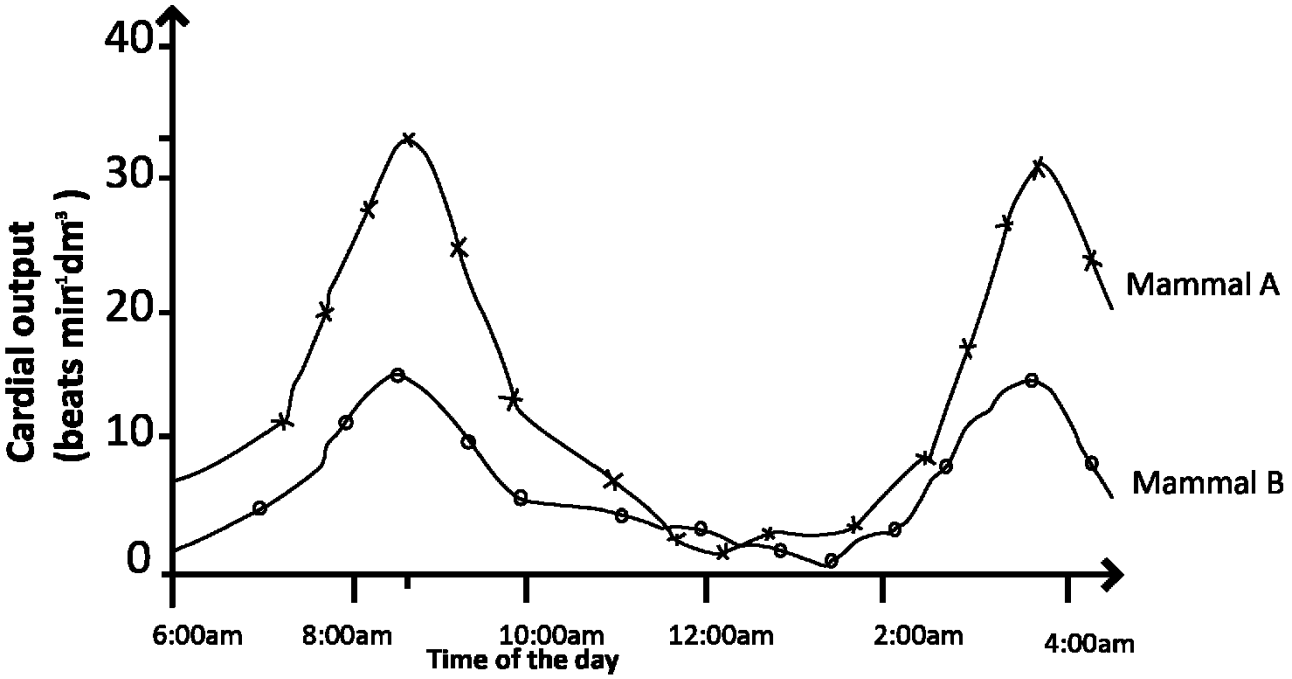
i) Bohr's effect

ii) Loading tension

iii) Un loading tension

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

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



i. Compare the cardiac output of both mammals. (04marks)
ii. Explain the effect of day time on the cardiac output of both mammals. (08marks)
iii. Comment on the difference in the cardiac output both mammals. (04marks)
iv. Suggest factors that are likely to affect the cardiac output of a mammal. (03marks)

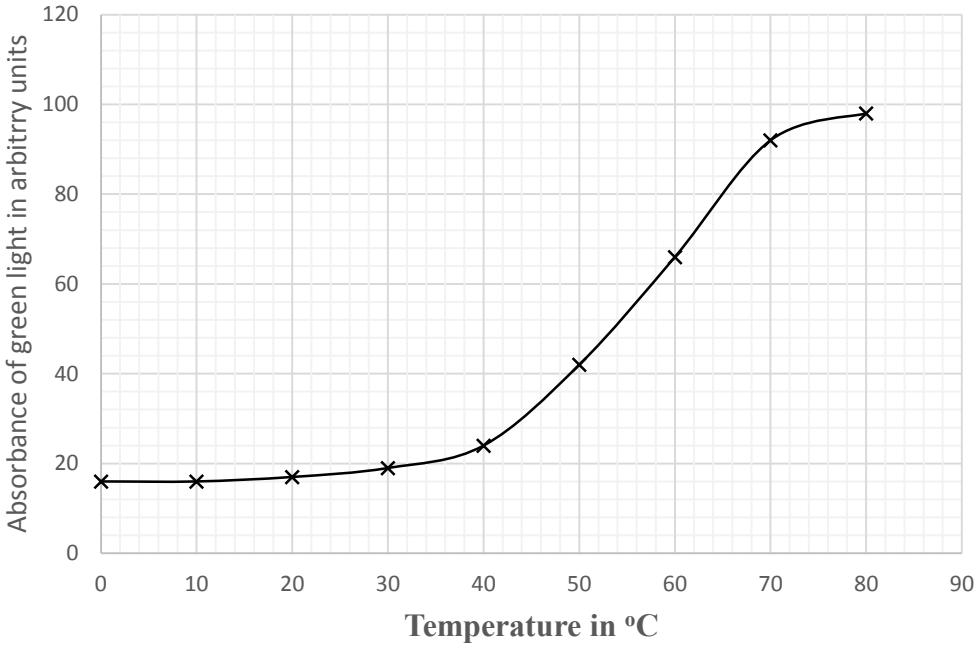
b) The table below shows the volume of blood flowing from the left vertical side of the heart of various parts of the body in one minute at rest and during a heavy exercise.

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

i. Calculate the percentage increase in blood flow from rest to exercise in skeletal muscle. (03 marks)
ii. Give three ways in which the increase in b(i) is achieved. (03 marks)
iii. Explain the changes in volume of blood flow rest to exercise to various parts of the body. (11 marks)
iv. Suggest with reasons the likely changes in composition of blood as it flows through the kidney.(04

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

had been immersed. The greater the absorbance, the more red pigment had leaved out of the beet root cells.



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

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

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

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

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

Sugar	Without cyanide	With cyanide
Glucose	100	28
xylose	18	18

a) Represent graphically the results in table 1 using a single set of axes (06 marks)
bi) Explain the effects of dilutions on the activity of the contractile vacuole(04 arks)
ii) what do changes in relative body volume indicate about the effect of the contractile vacuole activity?
c) Some species of marine protozoa form contractile vacuoles only the protozoan begins to feed . Suggest an explanation for this observation. (03 marks)
d) How is active transport:
i) similar to facilitated diffusion (02 marks)
ii) different from facilitated diffusion (03 marks)
e) Explain the relative uptake of the sugars by the intestines (05 marks)

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

i) concentration difference, (02 marks)

ii) the size of the molecules(02 marks)

iii) temperature (02 marks)

iv) polarity of the molecules(02 marks)

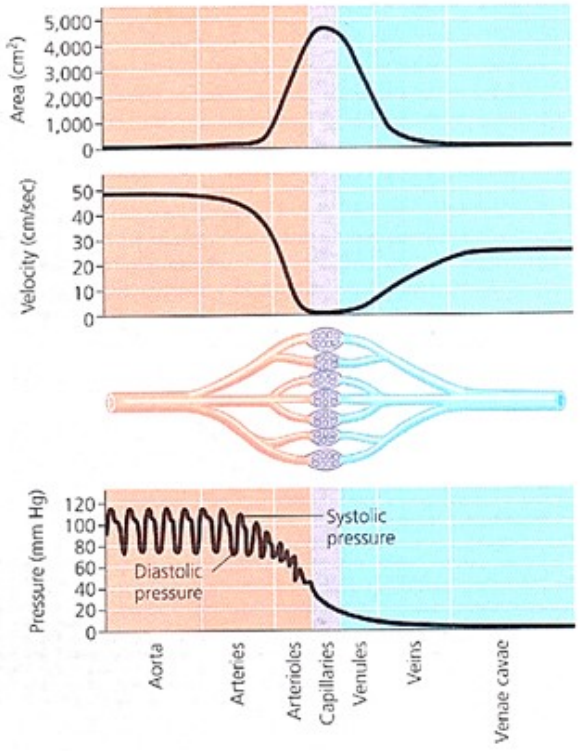
g) state the composition and major function of the animal's cell surface.(03 marks)

29. What fundamental physical constraints necessitate a circulatory system in large organisms? *(02*

b) State **one** advantage and **one** disadvantage of a closed circulatory systems *(02 marks)*

c) State **two** physiological advantages of separate pulmonary and systemic circuits in a mammalian circulatory system *(02 marks)*

d) Figure 6 shows the interrelationship of blood flow velocity, cross sectional area of



Explain the relationship between **area** and **velocity** in the arteries

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7. J.SIMPKINS & J.I.WILLIAMS. ADVANCED BIOLOGY

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