

## TRANSPORT OF MATERIALS

Movement of materials in and out of the cells is vital in all living organisms. Unicellular organisms and multicellular organisms like hydra have simple methods of transporting materials across the cell. This is mainly by simple diffusion. Such organisms possess a large surface area to volume ratio and each cell can exchange useful materials and waste products directly to the external environment.

In higher organisms, both plants and animal tissues are bulky and the body is complex. Diffusion alone cannot efficiently supply the body's requirements. Such organisms involve a highly vascularized conducting muscular tissue to enable movement of important materials through the body.

The transport system/circulatory system consists of the following:

- ❖ Tubular tissue in which substances move
- ❖ Fluid that dissolves the substance
- ❖ Pumping organ for circulatory of materials

Plants do not have a pumping organ and a vascular tissue is separated by space whereby the xylem tissue which transports water and mineral salts has no direct contact with the phloem tissue which translocate dissolved food substances. In both water is the fluid in which materials are dissolved.

Animals have a pumping organ that enables the circulation of the fluid in the blood vessels so that materials can be supplied to the whole body. Animals therefore have a circulatory system. *There are several functions of the transport system;*

- ❖ Transport of materials from one part of the body to another.
- ❖ Transport of waste products.
- ❖ Movement of important substances i.e. water, hormones, enzymes, etc.
- ❖ Movement of respiratory gases.

The transport system in all higher organisms forms a system of vessels which forms a complex network.

### TRANSPORT OF MATERIALS IN PLANTS

Plants require adequate supply of CO<sub>2</sub>, O<sub>2</sub>, mineral salts and water for normal growth. Lower plants like algae move materials in and out of their bodies by diffusion and active transport because they have a large surface area to volume ratio. Higher plants have a vascular system which helps in translocation.

The vascular tissues have several adaptations to perform their functions.

#### Adaptations of the xylem tissue

- i) Has long cells joined end to end in order to form a continuous column for the flow of water.
- ii) End walls break down to form an uninterrupted structure to ensure smooth flow of water from vessels to leaves in tracheid. Where end walls are not present, large pits are formed to reduce the resistance to flow.
- iii) There are pits at particular places where lignin is deposited. These pits allow natural flow of water where this is necessary to prevent air bubbles from blocking the vessels.
- iv) Deposition of cellulose walls with lignin increases the adhesive forces between water molecules and the tissue wall and it enables water to raise up by capillarity.
- v) The xylem tissue especially the vessels have very narrow lumen of about 0.01-0.02mm in diameter. This increases capillarity forces for the uptake of water.
- vi) Each xylem element has a wall made up cellulose and lignin. Lignin is water proof and a very strong material which helps in maintaining water inside the xylem element.

#### Adaptations of the phloem to its function

The phloem has tissues that are well adapted to movement of materials in the following

ways: i) Possess cytoplasmic strands over which materials can flow.

- ii) Possess end walls called sieve plates which are perforated by numerous pores to allow passage of substances from one sieve element to the next.
- iii) The cytoplasm of the sieve elements is structurally simple with no or few organelles like endoplasmic reticulum. This provides large space for the movement of materials.
- iv) Besides each sieve element is a companion cell which possesses nucleus, mitochondria, endoplasmic reticulum, etc., which is a site for intense metabolism. The mitochondria provide the energy required.
- v) Cells have plasmodesmata pits that allow movement of materials between sieve elements.

- vi) The phloem tissue in leaves have transfer cells responsible for moving products of photosynthesis from the mesophyll cells to the sieve tubes.

### **Absorption of water from the soil by plant roots.**

In plants the principle surface for absorption of water are roots. Not all parts of the root are useful but only the tip between 20 -200mm from the tip. As the root grows older the cells become impermeable to water due to deposition of lignin, suberin and cutin. Root hairs have several adaptations that enables them to absorb water.

- i) They are very small and numerous thus increase surface area to volume ratio.
- ii) They are slender and flexible so they can penetrate through the soil.
- iii) They have large concentrated vacuoles which provide an osmotic gradient.
- iv) The outer cell of the root hairs is fully permeable to water.

Root hairs absorb water from the soil by osmosis and thus water moves from the root hair cells to xylem by osmosis. The cortex cells neighboring the root hair cells have a high osmotic pressure therefore water moves the root hair cell to the cortex cells by osmosis.

As water flows from one cell to another it moves along 3 major routes:

#### **Apoplast pathway:**

The main route of water flow in plants (90%) This is where water flows along the air spaces in cell walls between the different cortex cells. Along this route, there is less resistance to water flow.

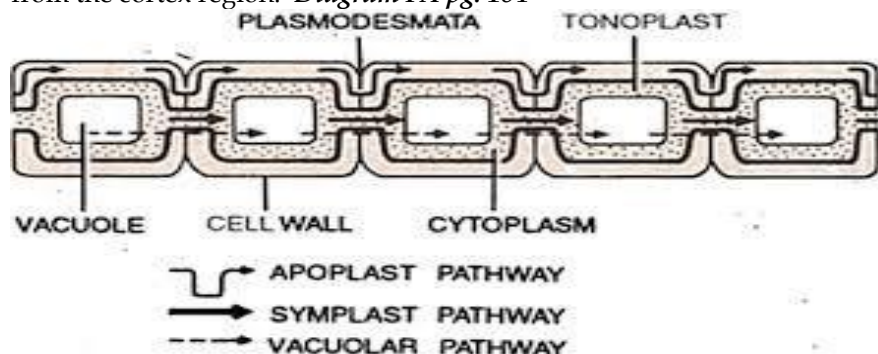
#### **Symplast pathway:**

Here water moves from cytoplasm to cytoplasm through plasmodesmata that crosses cell walls. 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. There is some resistance along this route.

#### **Vacuolar pathway:**

Water moves from vacuole to vacuole. The resistance to water flow is too high due to high concentration of the vacuole. A limited amount of water moves to the xylem through this route.

Towards the xylem tissue, there is an epidermal layer with casparian strip. The strip is made of suberin which impermeable to water. The strip prevents flow of water through the Apoplast pathway. Water is therefore forced to pass through the cytoplasm of endodermal cells. Some endodermal cells secret materials close and into the xylem tissue which increases the osmotic pressure along the region. This increases the flow of water into the xylem tissue from the cortex region. *Diagram FA pg. 184*



### **Water uptake by roots. FA pg. 180**

#### **Uptake of water in the xylem tissue (from roots to leaves.)**

As water is absorbed from the soil, it accumulates in the xylem. There are several forces that ensure its movement upwards. These include; cohesion, tension, root pressure, adhesion, transpiration pull and capillarity.

1. Movement of water up the plant may be due to **capillary forces** because of the narrow xylem vessels and tracheid. These provide capillary forces to raise water up the stem. The level at which the water raises depends on the height of the plant. In very tall trees, capillary may not be enough to raise water to the leaves.
2. **Cohesion-tension forces**; as water molecules raise, they attract and pull other water molecules to cause an upward movement of water in a continuous column. This is mainly due to high cohesion forces between the water

molecules, in case of any blockage of water column, lateral flow of water between xylem and tracheid through pits will prevent creation of bubbles to ensure that the continuous water column is maintained.

3. **Adhesion forces;** forces of attraction between water molecules and walls of the xylem tissues enables water to raise up the stem.

#### 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

4. **Root pressure;** continuous absorption of water from the soil by the root cortex creates a pushing force in the xylem tissue as more water enters the xylem. This makes a considerable contribution of the movement of water upwards especially in herbaceous plants but its effects are less significant especially in tall woody plants.
5. **Transpiration pull;** this is the most important force responsible for the uptake of water in tall woody plants. As water is lost by evaporation from the mesophyll cells in the leaves, such cells become concentrated and absorb more water from the leaf veins due to high osmotic gradient by transpiration. More water moves up from the stem to the leaf veins to replace lost water. This would eventually create a continuous flow of water moving up the plant called the transpiration stream. The pulling force generated in the leaves is called the transpiration pull and is the one responsible for the flow of water.

***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.

#### 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.

##### 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 **facilitated diffusion**.

*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. **Graphs FA 192.**

*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.

#### **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. Munch's hypothesis)
  - b. Electro-osmosis
  - c. Cytoplasmic streaming
- active transport and surface spreading.

#### **1. Mass flow**

Mass flow hypothesis explains translocation as a result of photosynthetic products moving through the phloem tissue from the leaves to the roots due to the turgor pressure gradient.

In the leaves, turgor pressure is high due to manufacture of food substances and materials produced e.g. sucrose increases the osmotic pressure of mesophyll cells which when absorbed would result into increase in turgor pressure. In the roots, turgor pressure is very low because food substances respired to release energy.

The difference in turgor pressure enables food substances to flow from the source to the sinks. An area of a plant from which sucrose is loaded into the phloem is called a **source**. An area that takes sucrose out of the phloem is called a **sink**.

#### **Mass flow or pressure flow hypothesis**

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

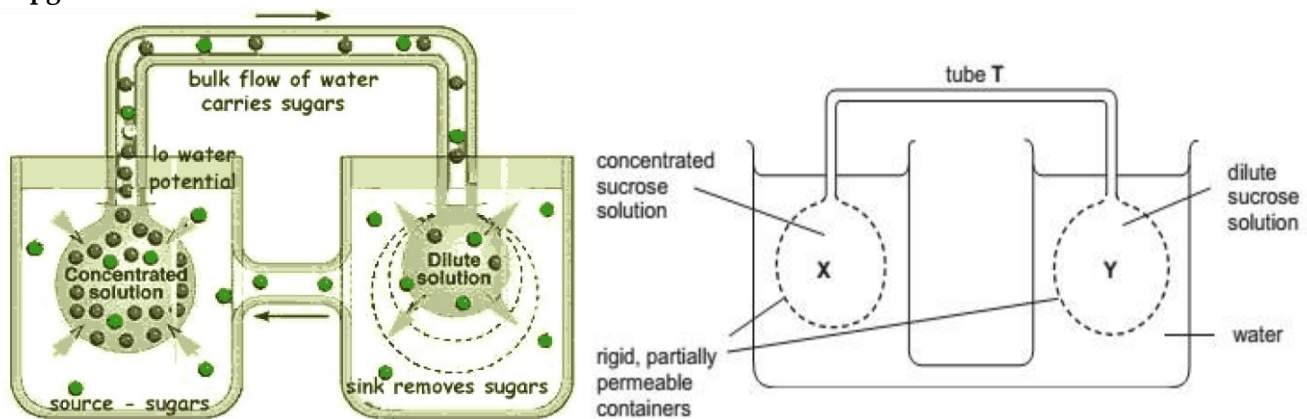
According to this theory, photosynthesis forms soluble carbohydrates like sucrose in the leaves. The photosynthesizing cells in the leaf therefore have their water potential lowered due to the accumulation of this sucrose. Sucrose is actively pumped into the phloem sieve cells of the leaf. As a result,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

Munch demonstrated mass flow as a physical process as illustrated below;

FA pg. 195



The model above illustrates mass flow i.e. bulk movement of food substances from higher turgor pressure to a lower turgor pressure.

Flask X contains a concentrated solution which in plants may stand for leaves. Flask Y contains a dilute solution which in plants may be roots. Fluid flows from flask X to flask Y through the delivery tube T. The delivery tube may represent phloem tissue which connects the source to the sink.

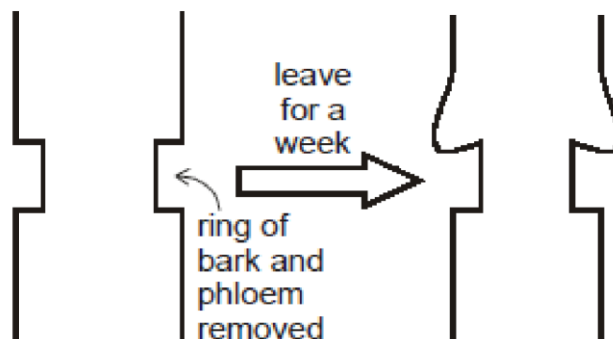
***There are several evidences to show that mass flow occurs in plants. These include;***

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.

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

- 1.1. 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.

**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.

**2. Electro-Osmosis**

This is the passage of water across a charged **membrane**.

This membrane is charged because positively charged **ions e.g.  $K^+$** , actively pumped by the companion cells across the sieve plate into the sieve tube element using energy from ATP of the companion cells. Potassium ions accumulate on the upper side of the **sieve** plate thereby making it positively charged. Negatively charged ions accumulate on the lower sides of the sieve plate thereby making it negatively **charged**. The positive potential above

the sieve plate is **further** increased by hydrogen ions, actively pumped **from** the wall to the upper sieve tube element into its cytoplasm.

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

The electrical potential difference is maintained across the plate by active pumping of positive ions, mainly potassium ions, in an upward direction. The energy used is produced by the companion cells. The movement of K<sup>+</sup> 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<sup>+</sup> 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 form 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

### **TRANSPIRATION**

This is the process of water loss in form 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 thiocyanate 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 thiocyanate 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

**Importance of transpiration in plants**

Transpiration has been described as a *necessary evil* because it is an inevitable but potentially harmful consequence of the existence of moist cell walls from which evaporation occurs. Water vapour escapes along the routes used for gaseous exchange between the plant and its environment which is essential for the process of photosynthesis and respiration. Loss of water can lead to wilting, cause desiccation and kill the plant if conditions of drought are experienced. Evidence shows that even mild water stress results in reduced growth rate. However, despite its inevitability, it is worth to note that there are some advantages associated with transpiration.

- i) It cools down the plant.
- ii) It helps in the movement of water and mineral salts through transpiration pull.
- iii) It leads to remove of excess water.
- iv) Keeping mesophyll cells moist ensures that gaseous exchange occurs especially in leaves.

**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.

**Measuring/Comparing 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**

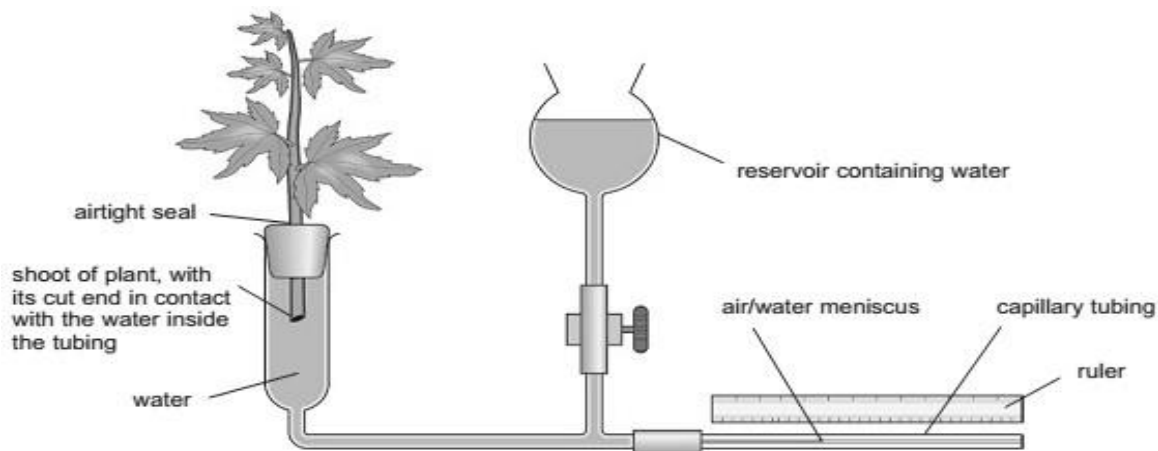
The rate of mass loss by the plant can be determined by using the potted plant placed on an automatic weighing balance whereby the change in mass is noted over a given period of time. Using this method, it is assumed that the mass loss is only due to water loss by transpiration. However, the whole pot 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**

It is not easy to measure the rate at which water vapour is leaving a plant's leaves. This makes it very difficult to investigate directly how different factors, such as light or air movement, affect the rate of transpiration. However, it is relatively easy to measure the rate at which a plant stem takes up water. A very high proportion of the water taken up by a stem is lost in transpiration. As the rate at which transpiration is happening directly affects the rate of



water uptake, this measurement can give a very good approximation of the rate of transpiration. The apparatus used for this is called a *potometer*.



It is essential that everything in the potometer is completely watertight and airtight, so that no leakage of water occurs and so that no air bubbles break the continuous water column.

To achieve this, it helps if you can insert the plant stem into the apparatus with everything submerged in water, so that air bubbles cannot enter the xylem when you cut the stem. It also helps to cut the end of the stem with a slanting cut, as air bubbles are less likely to get trapped against it.

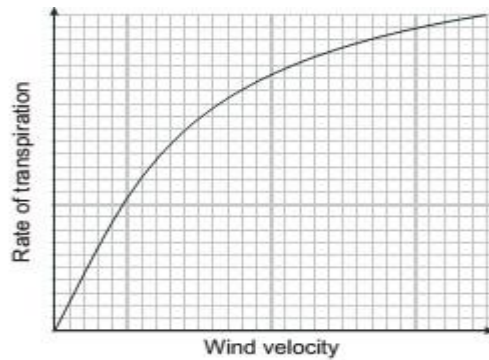
As water evaporates from the leaves, more water is drawn into the xylem vessels that are exposed at the cut end of the stem. Water is drawn along the capillary tubing. If you record the position of the meniscus at set time intervals, you can plot a graph of distance moved against time. If you expose the plant to different conditions, you can compare the rate of water uptake.

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

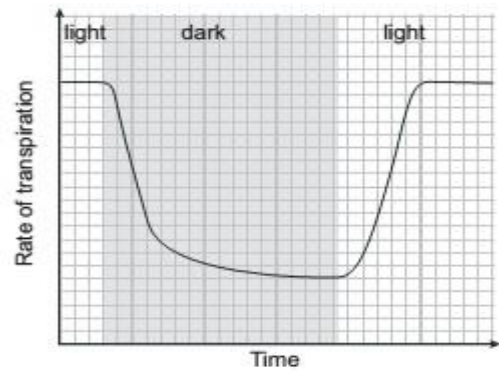
### Factors affecting transpiration

Anything that increases the water potential gradient between the air spaces in the leaf and air outside, or that speeds up the movement of the water molecules, will increase the rate of transpiration.

- i) **Humidity:** humidity is a measure of how much water vapour is held in the air. In conditions of low humidity – that is, when the air is dry – there is a steep water potential gradient between the leaf and the air. Transpiration rates are therefore greater in low humidity than in high humidity.
- ii) **Temperature:** an increase in temperature causes an increase in the kinetic energy of water molecules. This increases the rate of evaporation of water from the cell walls into the air spaces, and also the rate of diffusion of the water vapour out of the leaf. An increase in temperature therefore increases the rate of transpiration.
- iii) **Light intensity:** light does not normally have any direct effect on the rate of transpiration during the daytime. However, many plants close their stomata at night, when it is dark and they are unable to photosynthesis and so do not need to use carbon dioxide from the air.
- iv) **Air movements:** the more the air around the plant's leaves is moving, the faster the humid air surrounding them is carried away. This helps to prevent the leaf becoming surrounded by air that is saturated with water vapour, and maintains a water potential gradient from the air spaces inside the leaf to the air



*Fig.1: How wind affects the rate of transpiration*

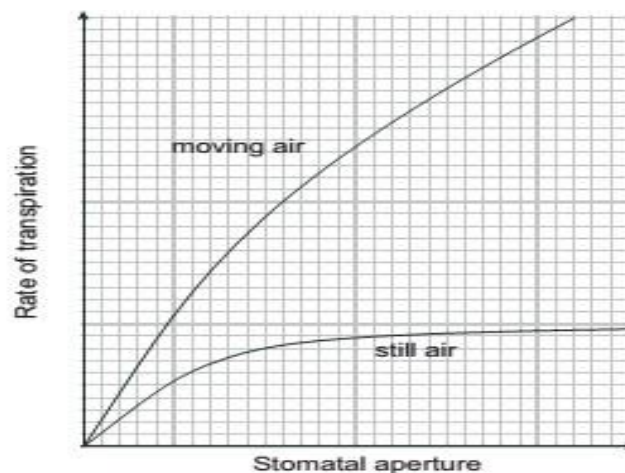


*Fig.2 How stomatal closure affects transpiration*

- v) **Stomatal aperture:** in many plants, stomata close at night. In the graph (*fig.2*) stomatal closure has occurred at night. In especially dry conditions, the plant may close its stomata even when light levels are ideal for photosynthesis, to avoid losing too much water from its leaves. There is often a compromise to be reached between allowing in enough carbon dioxide for photosynthesis, and not letting out too much water vapour. The rate of transpiration is higher at larger aperture.

However, if you look at the graph in *fig.3*, you will see that in still air, the increase in the rate of transpiration is very little at

larger apertures, whereas in windy conditions, the rate continues to increase even with larger apertures.



*Fig.3: The effects of wind velocity and stomatal aperture on the rate of transpiration*

- vi) **Plant structure:** transpiration occurs from the surface of leaves and green stems. For plants that need to conserve water, reducing the area of these surfaces will limit the rate of transpiration. This can be done by dropping leaves in dry seasons, having small leaves or having no leaves (relying on green stems for photosynthesis).

- vii) **Leaf anatomy:** a number of structural features can reduce the rate of transpiration, even when stomata are open. All of these features act by trapping still air outside the stoma. This increases the distance water has to diffuse before it can be carried away in the mass flow of air in the wind. The further the distance water has to diffuse, the slower the rate of transpiration.

This is achieved by one of the following; having stomata set in pits, having stomata on a leaf surface that is on the inside

of a rolled leaf, having dense hairs on the leaf surface or having a thick layer of wax on the leaf

### Adaptations of plants to prevent water loss

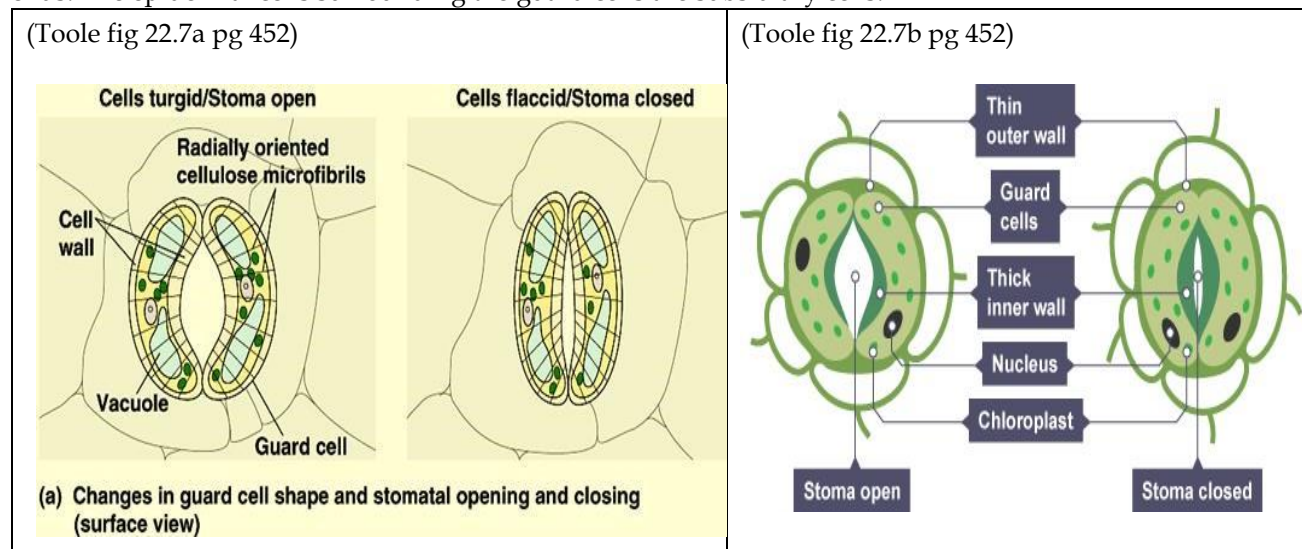
- ❖ Reduction of leaves to fine spines
- ❖ Small leaves
- ❖ Stem with hard thick epidermis covered with waxy cuticle.
- ❖ Ability to fix CO<sub>2</sub> at night so that the stomata can be closed during the day.
- ❖ Possession of thick succulent leaves that can store water.
- ❖ They have organ pipe-like stem that point vertically upwards to minimize the surface area exposed to the midday sun.
- ❖ They have sunken stomata reduced in number and confined to the surface of the leaf.
- ❖ Have a layer of stiff interlocking hairs in the inter-epidermis that reduces transparency by trapping air within the leaf.
- ❖ Have shallow but extensive root system so they allow efficient absorption of water.

### 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.

#### 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.



### 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<sup>+</sup>) 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<sup>+</sup> - pump on the cell membrane of the guard cells. This causes an active uptake of K<sup>+</sup> ions in the guard cells from the surrounding epidermal cells.

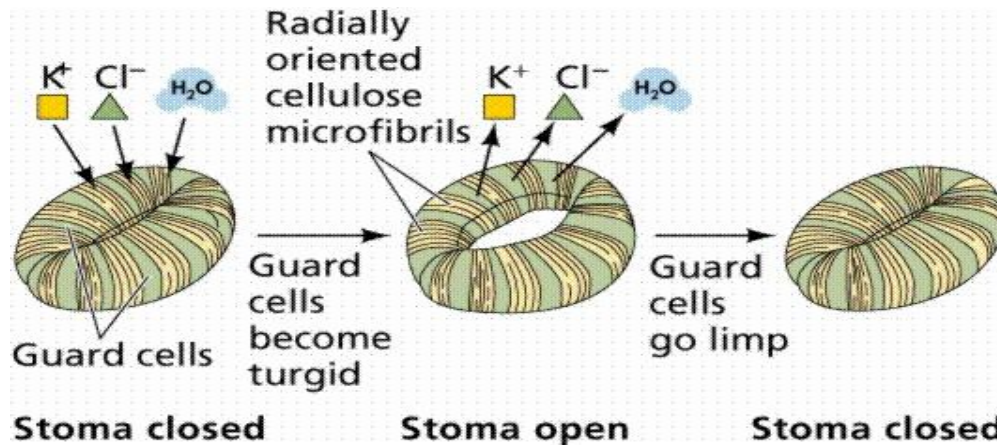
- Accumulation of K<sup>+</sup> in the guard cells increases the osmotic pressure of their cell sap. This causes water to move into the guard cells from neighboring epidermal cells by osmosis. The result is an expansion and increase in turgidity of the guard cells causing the stomata to open because when they become turgid, they expand 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<sup>+</sup> pump. K<sup>+</sup> 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  | Stomata closure   |
|--|---|
| Stomata opening is promoted by high light intensity and low mesophyll carbon dioxide levels. Guard cells generate ATP by photophosphorylation during photosynthesis. | Stomata closure can be triggered by water stress, high temperature, increasing carbon dioxide levels in the leaf mesophyll and low light intensity (night time) |

|   |   |
|---|---|
| Blue light is absorbed by blue-light photoreceptors which activate a proton-pump (H <sup>+</sup> -ATPase) in the cell membrane of the guard cell  | . The hormone abscisic acid (ABA) is secreted by plant cells when transpiration rate is high and soil water is low.   |
| ATPs generated by the light-dependent reaction of photosynthesis are hydrolysed to provide energy to drive the proton-pump. As protons (H <sup>+</sup> ) are pumped out of the guard cells, the cells become increasingly negatively charged. Potassium channels are activated and K <sup>+</sup> ions diffuse from subsidiary cells through the channels down this electrochemical gradient into guard cells. Chloride ions (Cl <sup>-</sup> ) then enter to balance the charge. | 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 <sup>+</sup> ) enter into the guard cell. The influx of calcium ions also triggers the release of Ca <sup>+</sup> from the cell vacuole into the cytosol. |
| . In some plants the starch is converted to malate  | Potassium ions (K <sup>+</sup> ) move out of the guard cells into the subsidiary cells  |
| The accumulation of K <sup>+</sup> (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.   | In some plants (Cl <sup>-</sup> ) and certain organic ions e.g. malate ions also move out of the guard cells  |
| . 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  | . 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.   |
| The increased turgor pressure therefore causes the guard cells to curve outward and the stoma opens   | . At night the chloroplasts in the guard cells do not photosynthesise, less ATP is produced and there's no active uptake of K <sup>+</sup> ions. Instead, the K <sup>+</sup> ions diffuse out of the guard cells. The cells become flaccid and the stoma closes.  |

## **TRANSPORT IN ANIMALS**

The unicellular organisms like amoeba, paramecium transport of materials in and out of the body is by simple diffusion since the bodies of such organisms are too small. They have a large surface area to volume ratio so that simple diffusion is efficient to transport substances in and out of their bodies. Such organisms therefore have no any specific vascular systems.

Vascular systems in multicellular organisms such as animals share the following basic features:

1. A circulatory fluid: most common one is blood though higher organisms contain lymph as an addition.
2. A pump organ: the heart
3. A system of tubes through which the circulatory fluid can move.

### **Types of circulatory systems in animals**

There are two types and these include; water circulatory system and blood circulatory system.

#### **Water circulatory system**

It exists in lower animals like sponges and hydra where water from the surrounding medium acts as a circulatory fluid.

##### **i) Canal system:**

It exists in poriferans like sponges. They have a system of tubes called canal system which could be simple or complex depending on the organization of the sponge. All canals ultimately communicate to the exterior through the numerous pores called Ostia. The body of the sponge is in form of a cylinder enclosing a cavity called spongocoel with a large opening called osculum.

The beating of flagella lining the canals causes the current of water to enter through Ostia which are like inhalant siphon. The current of water bring in food and oxygen for the sponge. As the water moves through the various canals,

food is taken in and wastes are given out and finally the water leaves the sponge through the osculum i.e. exhalant siphon.

Water in → ostia → canals → spongocoel → osculum → water out

## ii) Coelenterons water filled cavity:

All coelenterates possess a single large cavity called coelenteron lined by endodermal cells. This cavity has a single opening through which water enters and leaves the animal.

The water carrying food and oxygen passes in through the mouth and circulates through the coelenteron. After collecting the wastes and carbon dioxide the water leaves the coelenteron through the same mouth opening. The flagellated cells of the endoderm direct the movement of water.

## Blood vascular system

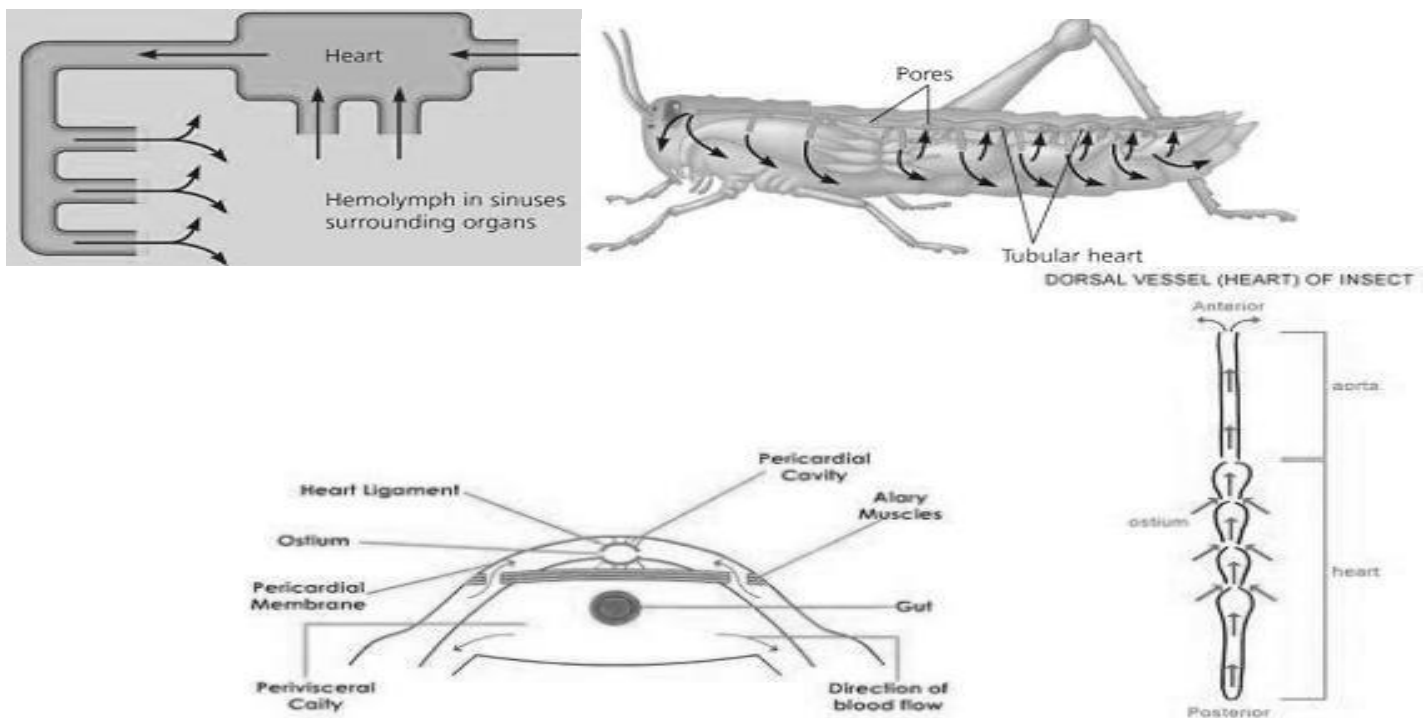
It exists in all higher animals where the heart and blood vessels together with the circulatory fluid (blood) constitutes a blood vascular system.

The heart pumps and conducts the circulatory fluid to various tissues. Arteries take blood away from the heart and veins bring blood back to the heart.

The higher invertebrates and vertebrates have two types of circulatory systems i) Open circulatory system and ii) Closed circulatory system

### The open circulatory system

This is a system where blood is not confined to blood vessels through the course of its circulation in the body. It fills in open spaces known as the haemocoel. The blood is pumped at relatively low pressure from the heart into the main body cavity called the haemocoel. The blood bathes the cells directly and only slowly percolates through the tissues



(functional approach pg. 176)

As shown above the only blood vessel is the heart which is tubular and is perforated by tiny holes called Ostia. It is suspended by slender ligaments attached to the pericardial membranes on the lower side and body wall on the upper. It extends from the abdomen to the thorax and it is expanded to form a small chamber in each segment.

At positions corresponding to these chambers of the heart in the pericardial membrane are muscles known as alary muscles. These muscles are responsible for aiding expansion of the heart after its contraction.

During systole (contraction), the ostia and the valves close, waves of contraction take place in the heart from the posterior towards the anterior chambers. This occurs when the alary muscles are relaxed. This propels blood forward in the heart and when it reaches the anterior, blood flows out of the heart through the aorta to the haemocoel.



During diastole (relaxation), the alary muscles contract. This causes the ligaments to stretch the heart, the pericardial membrane is depressed, pressure in the perivisceral cavity increases due to reduction in volume. Fluid then flows from the perivisceral cavity to the pericardial cavity and it enters the heart through the ostia.

When the heart is full of blood, it contracts and the cycle continues.

### Functions of the circulatory system of insects

i) Transport of nutrients ii) To transport nitrogenous wastes to organs of elimination i.e. the malpighian tubules iii) To defend the body against disease causing organisms using phagocytes they contain.

**Note:** blood in insects does not transport respiratory gases.  $O_2$  is supplied directly to the tissues by the tracheal system.

### Closed circulatory system

A closed circulatory system is one where blood is confined to blood vessels throughout its course of circulation in the body. This is present in vertebrates and higher invertebrates like annelids.

There are two types of closed circulatory systems;

i) The single circulatory system: in this case the blood flows through the heart once in each complete circulation. ii) The double circulatory system. In this case the blood flows through the heart twice in each complete circulation.

### Single circulation in fish

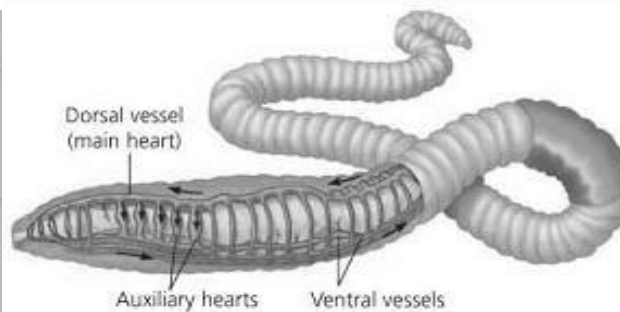
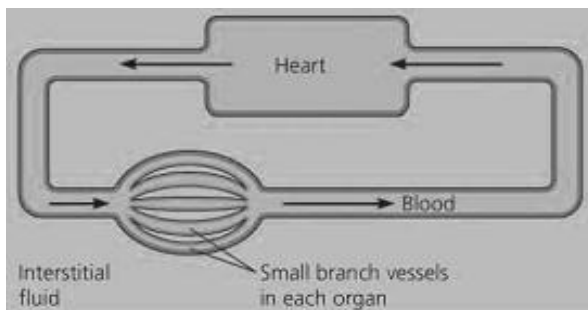
Deoxygenated blood flows from the heart to a capillary network in the gills then to the tissues of the body and finally back to the heart. The heart in fish has a single atrium and ventricle.

The functions of the circulatory system in fish are similar to those of earthworms.

### The single circulation of the earthworm

In the earthworm the circulatory fluid blood consists mainly of water in which are dissolved gases, sugars, amino acids, salts and many other molecules and ions taking part in metabolism. The blood also has haemoglobin and this makes it able to carry oxygen. However this haemoglobin is not confined in blood cells but is dispersed in the blood. The circulatory system here consists of a system of large longitudinal blood vessels on both the dorsal and ventral parts of the body which end in capillaries where exchange of materials between the blood and organs like the skin, intestines, nephridia and other tissues takes place. In addition to these blood vessels there is a "heart" which in essence consists of five pairs of aortic loops whose walls are capable of muscular contraction.

Blood is propelled from the aortic loops when muscles contract. Blood flows through vessels to organs and tissues where they terminate into capillaries. Once through the capillaries the blood is collected by a branching network of blood vessels leading into the dorsal blood vessel. This vessel contracts rhythmically forcing blood to flow forward to the anterior of the animal until it reaches the aortic loops and the cycle is repeated.



### The functions of blood circulatory system of earthworm are;

i) Transport of; nutritive molecules, respiratory gases and nitrogenous wastes ii) Defense against diseases. The blood has amoebocytes which engulf any disease causing organisms in the blood.

### Double circulatory system

This is one where blood passes through the heart twice in one complete circulation. This is a characteristic of all members of the vertebrata with the exception of the fish.



Blood entering the heart first flows to the lungs and back to the heart which is known as **pulmonary circulation** after which it is then pumped to the rest of the body. This is known as **systemic circulation**. For this reason, higher blood pressure can be attained than in single circulation.

### Double circulation in amphibians

The heart is three chambered with two atria and a single ventricle. The mixing of blood which would otherwise have occurred in the ventricle is prevented by the presence of **spiral valve in the conus arteriosus**.

The extensive blood supply to the lungs and the skin via pulmocutaneous blood vessels greatly increases the efficiency in transporting gases in addition to the presence of haemoglobin in the RBC. Again this is greatly enhanced by the structural arrangement of the circulatory system which ensures that blood is pumped to the skin and lungs where gas exchange occurs from the ventricles at the same pressure with that to the rest of the body.

### Double circulation in octopus

High blood pressure is maintained by branchial hearts. The blood is pumped at a high pressure by the main heart to the body, then taken up by the branchial heart, to the gills then back to the main heart.

*Note: check BS page 470.*

### Double circulation in mammals

Mammals have a complete double circulation. The heart is divided into a left and right section there by ensuring complete separation of deoxygenated and oxygenated blood. The heart is therefore two pumps in one and this is why it is able to send out different volumes of blood to different organs at different pressure. Both these pumps work simultaneously.

### Advantages of a double closed circulatory system over open one

- i) Relatively high pressure required for fast flow of blood is acquired than in open circulation.
- ii) Since the blood is returned rapidly to the heart for pumping, more rapid circulation can be attained.
- iii) The separation of oxygenated and deoxygenated blood in it improves efficiency of oxygen distribution and therefore sustain the high metabolic rate required by such animals.
- iv) The blood is piped directly to where it is needed.
- v) The amount flowing to certain organs can be regulated by changing the diameter of the blood vessels.
- vi) Blood cells and large molecules remain within vessels
- vii) Can support higher levels of metabolic activity

### Differences between open and closed circulatory system

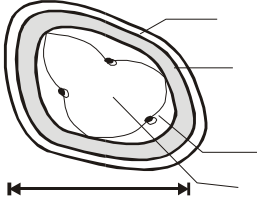
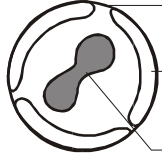
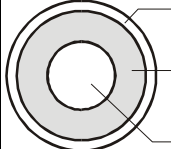
| Open circulatory system   | Closed circulatory system   |
|---|---|
| blood flows through large open spaces and channels called lacunae and sinuses among the tissues   | blood flows through a system of closed chambers and tubes called the heart and blood vessels  |
| tissues are in direct contact with the blood  | there is no direct communication with any tissue, open body cavity or space   |
| blood flows under very low pressure and moves slowly through the tissues  | By strong pumping action of the heart blood flows with great pressure in the arteries   |
| heart pumps oxygenated blood into an aorta which branches into number of arteries, which open into series of blood spaces and lacunae collectively known as haemocoel | Heart pumps oxygenated blood to aorta which branches into a number of arteries, then to arterioles and finally to a network of capillaries all over the body. |
| Blood takes comparatively longer time to circulate through the whole body   | Blood takes a much shorter time to circulate through the body.  |
| Exchange of gases takes place directly between blood and tissues  | Nutrients and gases pass through the capillary wall to the tissues  |
| Volume of blood flowing through a tissue cannot be controlled as blood flows out in open spaces   | Volume of blood flowing through a tissue or organ can be regulated by contraction and relaxation of the smooth muscles of the arteries.                       |

It is present in higher invertebrates like most arthropods, prawns, insects etc.

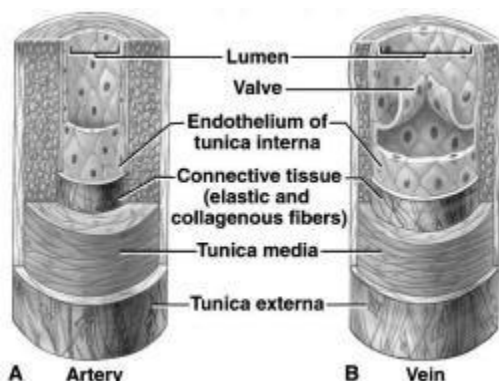
It is present in echinoderms, some mollusks, annelids and all vertebrates

### BLOOD VESSELS

Blood circulates in a series of different kinds of blood vessels as it circulates round the body. Each kind of vessel is adapted to its function.

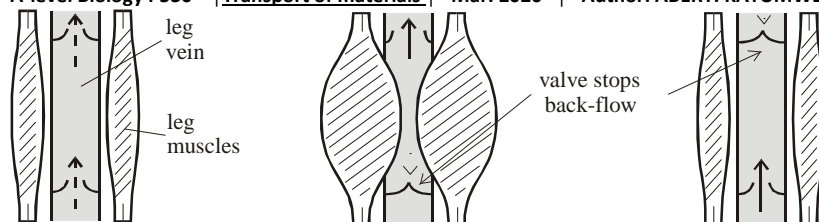
| Veins and Venules   | Capillaries   | Arteries and Arterioles   |
|---|---|---|
|  <p>collagen &amp; connective tissue;<br/>smooth muscle &amp; elastic tissue;<br/>semilunar valve;<br/>lumen (blood);<br/>0.1-20mm</p> |  <p>basement membrane (collagen)<br/>endothelium cell<br/>red blood cell<br/>8 <math>\mu</math>m</p> |  <p>collagen &amp; connective tissue<br/>smooth muscle &amp; elastic tissue<br/>lumen (blood)<br/>0.1-10mm</p> |
| Function is to carry blood from tissues to the heart  | Function is to allow exchange of materials between the blood and the tissues  | Function is to carry blood from the heart to the tissues  |
| Thin walls, mainly collagen, since blood at low pressure  | Very thin, permeable walls, only one cell thick to allow exchange of materials  | Thick walls with smooth elastic layers to resist high pressure and muscle layer to aid pumping  |
| Large lumen to reduce resistance to flow.   | Very small lumen. Blood cells must distort to pass through.   | Small lumen   |
| Many valves to prevent back-flow  | No valves   | No valves (except in heart)   |
| Blood at low pressure   | Blood pressure falls in capillaries.  | Blood at high pressure  |
| Blood usually deoxygenated (except in pulmonary vein)   | Blood changes from oxygenated to deoxygenated (except in lungs)   | Blood usually oxygenated (except in pulmonary artery)   |

**Arteries** carry blood from the heart to every tissue in the body. They have thick, elastic walls to withstand the high pressure of blood from the heart. The arteries close to the heart are particularly elastic and expand during systole and recoil again during diastole, helping to even out the pulsating blood flow. The smaller arteries and arterioles are more muscular and can contract (vasoconstriction) to close off the capillary beds to which they lead; or relax (vasodilation) to open up the capillary bed. These changes are happening constantly under the involuntary control of the medulla in the brain, and are most obvious in the capillary beds of the skin, causing the skin to change colour from pink (skin arterioles dilated) to blue (skin arterioles constricted).

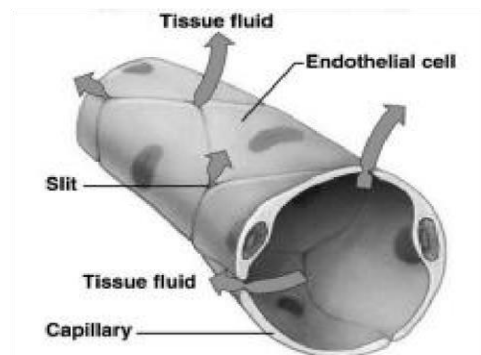


**Veins** carry blood from every tissue in the body to the heart. The blood has lost almost all its pressure in the capillaries, so it is at low pressure inside veins and moving slowly. Veins therefore don't need thick walls and they have a larger lumen than arteries, to reduce the resistance to flow. They also have semi-lunar valves to stop the blood flowing backwards. It is particularly difficult for blood to flow upwards through the legs to heart, and the flow is helped by contractions of the leg and abdominal muscles:

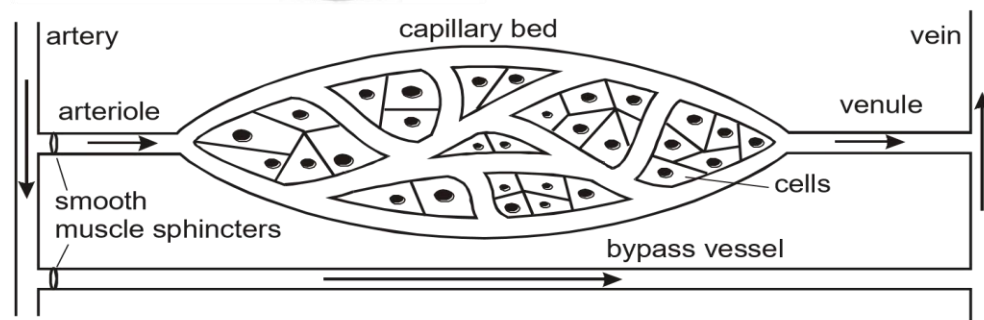
The body relies on constant contraction of these muscles to get the blood back to the heart, and this explains why soldiers standing still on parade for long periods can faint, and why sitting still on a long flight can cause swelling of the ankles and Deep Vein Thrombosis (DVT or "economy class syndrome"), where small blood clots collect in the legs.



relaxed leg muscles blood sucked upwards      contracted leg muscles blood forced upwards      relaxed leg muscles slow flow valve stops back-flow blood forced upwards



**Capillaries** are where the transported substances actually enter and leave the blood. No exchange of materials takes place in the arteries and veins, whose walls are too thick and impermeable. Capillaries are very narrow and thin-walled, but there are a vast number of them ( $10^8$  m in one adult!), so they have a huge surface area to volume ratio, helping rapid diffusion of substances between blood and cells. Capillaries are arranged in networks called capillary beds feeding a group of cells, and no cell in the body is more than 2 cells away from a capillary.



### Internal structure of the heart

The internal structure of the heart shows that the heart has two sides, the left side and right side. These are separated by a muscular wall known as septum.

The heart has the atria which collect blood from the body and pumps it to the lower chambers known as ventricles.

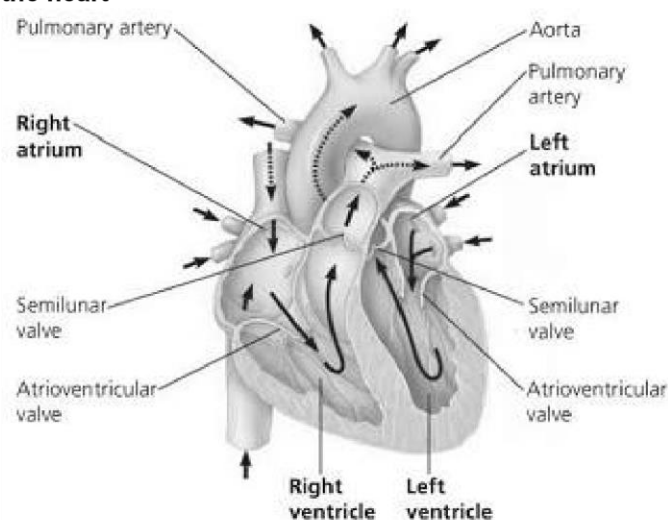
The ventricles pump blood to the arteries and this is the reason why they have thick walls.

The left ventricle which pumps blood to the rest of the body has a thicker and stronger wall than the right ventricle which pumps blood to the lungs which are a shorter distance away.

The atria and ventricles are separated by valves. The valve on left side consists of two flaps and is known as **bicuspid valve (mitral valve)** while that on the right is known as **tricuspid** but collectively both are known as **atrio ventricular valves**.

These valves are supported by strands of strong inelastic tissues known as **tenderone chords** or **chordate tendinae**. These prevent the valves from being turned inside out by the high pressure generated when ventricles contract.

The bases of the arteries in the heart also have valves shaped like crescents and are commonly known as the **semi lunar valves**. However to be more specific the valves at the base of the aorta are known as **aortic valves** while those at the base of the pulmonary artery are known as **pulmonary valves**. All valves serve to prevent blood flowing in the wrong direction. *Functional approach pg. 168 and 170*



### Cardiac cycle

Rhythmic contraction and relaxation of the cardiac chambers i.e. the auricles and the ventricles in a specific manner during one heart beat constitutes a **cardiac cycle**. The heart beats continuously without pause in life. Auricles and ventricles show rhythmic contractions and relaxations. On average heart beats 72 times per minute. Heart pumps about 5 litres of blood per minute. Both auricles contract simultaneously and the blood flows into the ventricles and both ventricles contract together forcing the blood into pulmonary artery and aorta.

**Systole:** Refers to the contraction of the cardiac chambers and as a result the heart contracts forcing the blood into the pulmonary artery and the aorta.

**Diastole:** This refers to the relaxation of the cardiac chambers hence enabling the heart to refill.

**Joint diastole:** This refers to the relaxed state of both atria and ventricles.

#### Sequence of changes in cardiac chambers during one cardiac cycle Atrial filling and joint diastole:

Filling of right atrium (RA) with deoxygenated blood from the great veins and left atrium (LA) with oxygenated blood from pulmonary vein.

As the pressure increases in the atria, the bicuspid and tricuspid valves open and blood flows into the respective relaxed ventricles.

The semilunar valves remain closed because of the low pressure and blood does not flow out of the ventricles.

#### Atrial systole and ventricular diastole:

At the end of joint diastole, next heart beat begins. The two atria contract, forcing most of the blood into the ventricles. Simultaneous closing of great vein roots (superior and inferior vena cava) by compression occurs. Bicuspid and tricuspid valves are open.

#### Ventricular systole (VS) and atrial diastole (AD):

Ventricles contract while atria relax. This forces the atrio ventricular valves to close producing the first heart sound 'lub'. This prevents the back flow of blood into the auricles. As the chambers contract, then the ventricular pressure exceeds the pressure in the pulmonary artery and aorta forcing the opening of the semi lunar valves.

Blood flows from ventricles to great arteries. It lasts for about 0.25 seconds.

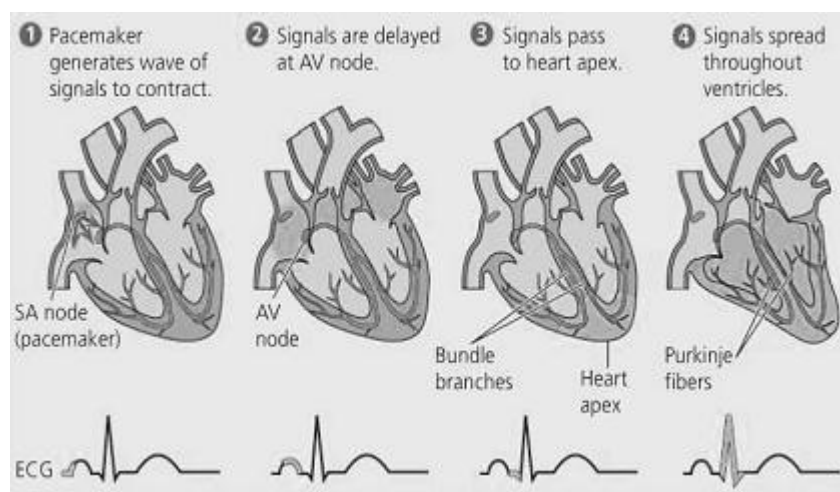
#### Ventricular diastole and atrial diastole (beginning of joint diastole):

Ventricles relax and the pressure falls below that in the great arteries. This causes the closing of the semilunar valves in the pulmonary artery and aorta to produce the second heart sound 'dub'.

This prevents backflow of blood into ventricles. As the low ventricular pressure is still greater than the atrial pressure, the AV valves remain closed.

Continued ventricular diastole decreases the pressure tremendously and now both atria and ventricles are in joint diastole. This lasts for about 0.4 seconds.

One complete systole and diastole (described above) forms a cardiac cycle which takes about 0.8 seconds. The new cardiac cycle begins with the atrial systole.



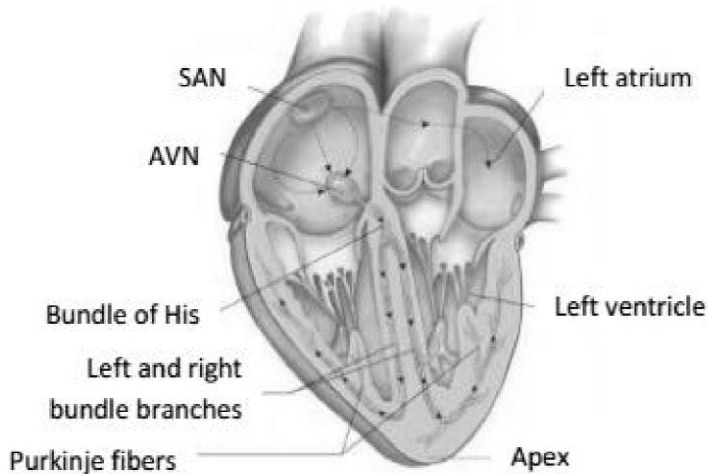
#### Control of the heart beat (FA. pg.172)

All vertebrate hearts are myogenic in nature, meaning their heart beat is initiated from within the heart muscles. In insects it is initiated by the nerves outside the heart and is known as neurogenic.

The initial stimulus for a heartbeat originates from a group of cardiac muscles known as the Sino Atrial node (SAN). This is located in the wall of the right atrium near where the vena cava enters the heart. The SAN determines the basic rate of heart beat and is therefore known as the **pacemaker**.

A wave of excitation spreads out from the SAN across the atria, causing them to contract more or less at the same time. The wave of excitation **reaches** a similar group of cells known as the Atrio-ventricular node (AVN) which lies

between the two atria. To allow blood to be forced upwards into the arteries, the ventricles need to contract from the apex upwards. To achieve this, the new wave of excitation from the AV node is conducted along purkinje fibres, which collectively make a bundle of His. These fibres lead along the intra-ventricular septum to the apex of the ventricles, from where they radiate upwards.



The spreading of excitations through the heart chambers can be monitored using an electrocardiogram. It shows characteristic waves as the excitation spreads through the heart.



**P-wave** which shows atrial depolarization over the atrial muscle and spread of excitation from SAN during atrial systole.

**QRS** wave shows spreading of excitation through the ventricles. (Ventricular systole).

**T-wave** shows recovery/ the beginning of ventricular diastole

Why is it important that the AV node delay the electrical impulse moving from the SA node and the atria to the ventricles?

## Heart Rate, Arterial Pulse and Blood Pressure

### i) Heart rate:

It refers to the number of times the heart beats per minute. Heart rate of humans is 68-72 times/min. at rest, Heart rate of elephant is 25 times/min and Heart rate of rat 300 times/min.

As is clear from the figures given above, heart rate varies in animals. The smaller animals have high metabolic rates and hence need greater action of heart to pump more oxygen and nutrients to tissues. This is the reason why smaller animals have much higher heart beat rate than the larger animals.

**Trachycardia:** It refers to the abnormal increase in heart beat rate. It could be due to many factors like emotional stress, anxiety, anger, excitement, etc. It can also be due to over activity of thyroid gland.

**Bradycardia:** It refers to the abnormal decrease in heart beat rate. Athletes who generally have a high heart rate may suffer low heart rates during rest. It can also be due to under activity of thyroid gland.

**ii) Arterial Pulse or Pulse wave:** It is a wave of distension followed by constriction experienced in the arteries as a result of ventricular systole and diastole. Pulse rate per minute = Heart beat rate/minute.

As the ventricles contract, blood is pumped out into arteries with force. It causes distension of the elastic wall of arteries and is felt as a pulse when a finger is placed on an artery near the wrist. This pulse becomes fainter and fainter as the blood moves further away and becomes so low in capillaries that it cannot be felt.

As the ventricles relax, there is a drop in the pressure in the arteries and the distended portion comes back to normal.

### iii) Blood Pressure:

It is the pressure or the force exerted by the blood against the walls of the arteries.

As the arteries already contain blood, the pressure in them increases due to sudden flow of blood during ventricular systole and falls slightly as the ventricles relax. The blood pressure is measured as two values, for example for a normal healthy man, it is equal to 120 by 80 mmHg. It means that the person has a systolic pressure of 120 mmHg and diastolic pressure of 80 mmHg.

**Systolic pressure:** It is the pressure experienced in the arteries as a result of contractions in the ventricles. It is equal to 120 mmHg for a normal healthy person.

**Diastolic pressure:** It is the pressure in the arteries when the ventricles relax.

It is equivalent to 90 mmHg for a normal healthy person.

The values of blood pressure change with age, sex or health of a person.

A **Sphygmomanometer** is an instrument used for the measurement of blood pressure in the brachial artery.

The blood pressure can also be affected by other conditions like arteriosclerosis where due to hardening of arteries, their lumens become narrower and so the blood pressure increases.



### Factors that affect the heart rate

- i) Size of the organism: small organisms have high rate than large organisms due to high metabolic rate. ii) Age: young mammals have higher rate of heart beat than old ones due to high metabolic rate since young ones are actively growing.
- iii) Health state: high heart rate in diseased organisms is due to response to increased levels of temperature and carbon dioxide. iv) Activity: increased muscular activities result in accumulation of carbon dioxide in the body and this results in a higher heart rate.
- v) Temperature: if the body temperature increases, the heart beat rate increases.
- vi) Presence of drugs such as epinephrine increases heart beat rate.

### Maintenance and control of blood pressure.

Blood pressure can be controlled and maintained via varying the activities of the SAN. This can be done from within the heart itself by increasing or reducing in the rate of excitation from the SAN which affects the heart beat rate. This determines the cardiac output which affects blood pressure. It can also be controlled via external factors which include;

#### 1. Temperature:

An increase of only 1°C raises the heart rate by about 10 beats per minutes. This is the reason your heart beats faster when you have fever.

#### 2. Hormonal activity:

Hormones like adrenaline, epinephrine, thyroxin, insulin and other sex hormones directly affect the SAN to increase its activity. When released in the body they increase blood pressure.

#### 3. Nervous system:

Via the cardiovascular regulatory center in the medulla oblongata, the nervous system can regulate blood pressure by varying the activities of SAN via the *vagus nerve which decelerates* the heart beat and via the *sympathetic nerve which accelerates* the activities of the SAN.

At the back of the aorta, there are sensory cells sensitive to *stretching* and *concentration of CO<sub>2</sub>*. These are carotid and aortic bodies. When they are stimulated, they send impulses to the cardiac regulatory center which in turn affects the SAN

e.g. when blood pressure is low or when CO<sub>2</sub> is high, the carotid bodies are stimulated, send impulses to cardiac accelerating center which responds by sending impulses via the sympathetic nerve to the SAN. This causes an increase in the cardiac output hence blood pressure.

Within the cells of the arteries, there are bare receptors, those are sensitive to pressure changes in the arteries. When the blood pressure in the arteries reduces, they are stimulated and they send impulses to the vasomotor center in the medulla. This responds by sending impulses through the sympathetic nerve to the smooth muscles of arteries which contract to increase the blood pressure.

## BLOOD

### Importances of a blood circulatory system (functions of blood)

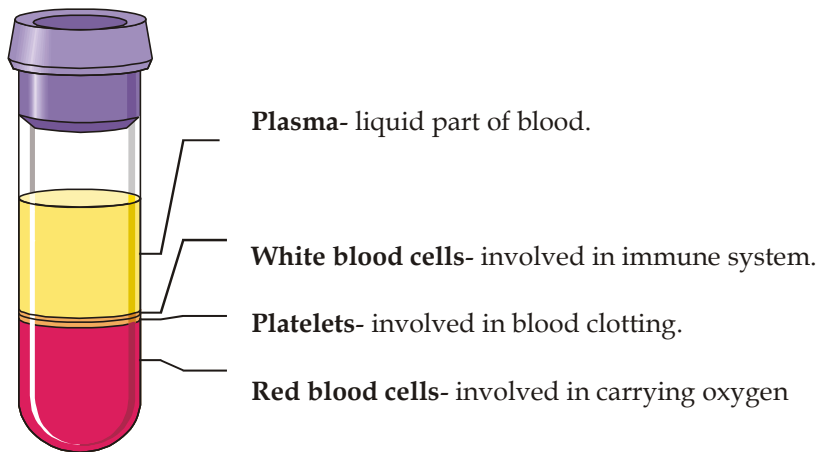
1. Tissue respiration. It enhances the formation of energy in the tissues by transporting oxygen and soluble food substances to the tissues to be used as raw materials for respiration. Carbon dioxide is also transported away from the tissues mainly in the form of bicarbonate ions (HCO<sub>3</sub><sup>-</sup>) as a by-product of respiration and then taken to the lungs for its removal from the body. Oxygen is transported in the form of oxyhaemoglobin from the respiratory surfaces to the tissues.
2. Hydration. Blood transports water from the gut to all tissues.
3. Nutrition. Blood transports the soluble well digested food materials from the gut to the body tissues.
4. Excretion. Blood transports metabolic waste products from the tissues to the excretory organs for their removal from the body e.g. blood transports urea from the liver to the kidney in order for it to be removed from the body.
5. Temperature regulation. Blood distributes heat from the organs where it is mainly generated e.g. the liver and the muscles, uniformly throughout the body.
6. Maintenance of constant pH. Blood maintains a constant pH through the maintenance of circulation of the plasma proteins manufactured by the liver which act as buffers to maintain the pH of the body fluids constant. This enables enzymes to function efficiently as charges will denature the enzyme.

7. Growth, development and co-ordination. Blood transport different metabolites such as glucose, amino acids and hormones needed for the growth and development of the body.
8. Defence. Blood defends the body against diseases through the following ways;
9. By using some white blood cells (leucocytes) which phagocytotically ingest and destroy pathogens that cause diseases.
10. By formation of a blood clot around the wound so as to prevent entry of microbes or pathogens into the body.
11. By use of the immune response mechanism towards infection e.g. by use of the different types of antibodies to destroy the microbes

### Components

There are three major components of blood i.e.

- i) Cells e.g. white blood cells and red solution of salts, glucose, amino acids, blood cells. vitamins, urea, proteins and fats.
- ii) Platelets (Fragments of cells).
- iii) Plasma (Fluid Matrix)



### Red Blood Cells (Erythrocytes)

#### Importance of Red Blood Cells

They transport oxygen from gaseous exchange surfaces to the tissues They transport carbon dioxide from tissues to the gaseous exchange surfaces.

#### Adaptation of Red Blood Cells to carry out their function

- They are biconcave in shape so as to avail a large surface area to volume ratio for absorption of oxygen.
- They have haemoglobin molecules that bind to oxygen and transport it from the lungs to the tissues.
- They have a thin membrane which reduces the diffusion distance for the respiratory gases in and out of the cells.
- They lack nuclei which provides enough space for packaging of haemoglobin
- They lack mitochondria and generate their ATP exclusively by anaerobic respiration to prevent them from using the oxygen they are carrying.
- They have an enzyme, carbonic anhydrase which plays a role in carbon dioxide transport □ They are numerous per mm<sup>3</sup> to increase surface area for transportation of oxygen.
- They have flexible membranes which make them able to squeeze through capillary networks as they exchange materials they transport with the surrounding tissues.

**NB:** The concentration of red blood cells increases as one climbs up a mountain because the concentration of oxygen in the air reduces with increase in height above sea level. So the body adopts by producing more red cells to increase the available total surface area to bind and carry oxygen to the tissues regardless the reducing oxygen partial pressure.

### White blood cells (leucocytes)

- ❖ They have nuclei
- ❖ They have an irregular shape and change their shape.



❖ They are manufactured in the bone marrow, spleen and lymph nodes. **Types of leucocytes**

### 1. Granulocytes:

These are WBC that possess granules in their cytoplasm and can easily be stained. Such leucocytes have an amoeboid shape and irregular. They also possess a lobed nucleus. They are mainly involved in engulfing germs. Granulocytes involve the following:

- i) **Neutrophil:** These constitute about 70% of all the WBC. They defend the body by engulfing foreign bodies or destroying old worn out cells.
- ii) **Eosinophil:** These constitute 15% of all WBC in the body, their major function is detoxification of toxins produced by foreign bodies.
- iii) **Basophil:** These constitute 0.5% of all WBC in the body. It produces heparin, an anticlotting protein and histamine, a chemical found in damaged tissues which is involved in inflammation.

**2. Agranulocytes:** (mononuclear leucocytes) These are leucocytes with no granules in their cytoplasm usually with a spherical or bean shaped nucleus and can't be stained. They originate in bone marrow and lymph nodes. They are divided into two types;

**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.

### Function of White Blood Cells

They defend the body against disease causing organisms (antigens) by producing antibodies. The antibodies defend the body by:

The antibodies defend the body by.

#### i) **Agglutination:**

Some antibodies have many binding sites and can join the antigens of many different pathogens. In this way, the pathogens can be joined together in clumps making them vulnerable to attack from other types of antibody.

#### ii) **Precipitation:**

Some antibodies bind together soluble antigens into large units which are thus precipitated out of solution. As such, they are more easily ingested by phagocytes.

#### iii) **Neutralization:**

Certain antibodies bind toxic molecules produced by pathogens and in doing neutralize their harmful effects.

#### iv) **Opsonisation:**

Antibodies bind cell surface antigens on bacteria cells and make them more susceptible to being digested by phagocytes.

#### v) **Lysis:**

Some breakdown pathogens' membranes and cell walls if they have them leading to water getting into it by pinocytosis. The pathogens swell and burst in the process called lysis.

They also defend the body by engulfing foreign materials (phagocytosis/endocytosis).

**NB:** The number of white blood cells increases during infection because the body manufactures more white blood cells to attack the disease causing organisms and prevent the infection from proceeding.

### Platelets (thrombocytes)

They are cell fragments. They lack nuclei

#### Functions

They play a role in blood clotting which protects the body against excessive loss of blood and entry of pathogens through the injured part.

#### The Process of Blood Clotting

Blood clotting is brought about by a soluble plasma protein called **fibrinogen** when it is converted to an insoluble form called **fibrin**.

The process begins when platelets exposed to air at the injured part break down releasing **Thromboplastin**.

**Thromboplastin** or **thrombokinese**, converts **prothrombin** to **thrombin** in presence of **calcium ions** and **vitamin K**.

**Thrombin is an enzyme** which catalyzes the conversion of **fibrinogen** to **fibrin** which fibrin forms a mesh that forms the blood clot. (Use the acronym **TPTFF** to remember the sequence with **P** to **T** occurring in presence of **calcium ions** and **vitamin K**)

**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

#### **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.

### **Blood plasma**

This is the fluid part of blood. It is made up of;

- i) A soluble protein called **fibrinogen** that plays a role in blood clotting.
- ii) Serum, a watery fluid containing a variety of substances transported from one part of the body to another e.g. hormones, lipids, enzymes, urea carbon dioxide, plasma, proteins, amino acids etc. Its function is transport of materials and substances around the body

### **BLOOD GROUPS AND BLOOD TRANSFUSION**

There are basically two blood group systems; ABO system and the Rhesus factor system. Both systems have to be considered during blood transfusion

#### **ABO system**

Under this system, there are four blood groups:

- i) Blood group A      iii) Blood Group AB
- ii) Blood Group B    iv) Blood Group O

A person's type of blood is determined by carbohydrate or protein structures located on the extracellular surface of the Red blood cell membrane. These structures are called **antigens**. So if a person is of;

- i) **Blood group A**, he or she has the **A type antigens**.
- ii) **Blood group B**, he or she has the **B type antigens**
- iii). **Blood group AB**, he or she has the **A and B types of antigens**
- iv) **Blood group O**, he or she **lacks antigens** on his or her red blood cells.

The antigens of an individual's red blood cells have corresponding antibodies in the plasma of blood which are different from the antigens in that;

- a) A person of **blood group A** has **antibodies of type b**.
- b) A person of **blood group B**, has **antibodies of type a**.
- c) A person of blood group AB, has no antibodies to any ABO blood group antigens.
- d) A person of **blood group O** has **antibodies of type b and a**.

During blood transfusion, the blood of the recipient should not have antibodies against antigens of blood donated by the donor otherwise agglutination will occur.

NB: Blood transfusion is the blood transfer process from the donor to the receiver.

Agglutination is the formation of a blood clot due to a reaction between the antigens in the donor's blood and antibodies in the recipient's blood.

a table showing blood compatibilities (fill in the table below relevant answers to the gaps)

#### **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  | ✓ |

Use key:

✓ - Represents safe transfusion. X - Represents agglutination will occur.

A person with blood group O is universal donor because he/ she lacks antigens A and B on the surface of his or her blood cells and his or her blood can be donated to any other person having any blood group without agglutination occurring.

A person of blood group AB is a universal recipient because he/ she lacks antibodies b and a in the plasma of his or her blood and can be transfused with blood of a donor having any blood group without agglutination occurring.

**Assignment:** a table summarizing the information above (fill the table below)

| Blood group | Antigens | Antibodies | Can donate to | Can receive from |
|-------------|----------|------------|---------------|------------------|
| A           | A        | b          |               |                  |
| B           | B        | a          |               |                  |
| AB          | A and B  | -          |               |                  |
| O           | -        | a and b    |               |                  |

### "RHESUS FACTOR" System

Rhesus factor is a protein (antigen) also found on the cell membranes of the red blood cells.

Many individuals have the Rhesus factor and are said to be rhesus positive (Rh<sup>+</sup>) while a few do not have the Rhesus factor and are said to be Rhesus negative (Rh<sup>-</sup>).

The Rhesus factor was first discovered in a Rhesus Monkey hence its name.

A person who is Rhesus factor positive can receive a successful blood donation without agglutination from a person of Rhesus positive and a person of Rhesus negative.

However, a person who is Rhesus negative can only receive a successful blood donation without agglutination from his fellow Rhesus negative person though he can be transfused with blood which is Rhesus positive quite successfully only once and after this transfusion, his body produces antibodies against the Rhesus factor. Such antibodies attack the Rhesus factor with subsequent transfusion of Rhesus positive blood leading to agglutination.

The same concept can be applied to *pregnancy* in that a Rhesus positive woman can successfully carry on a pregnancy where the fetus is Rhesus positive or Rhesus negative.

A Rhesus negative woman can successfully carry a pregnancy where the fetus is only Rhesus negative; with such a woman, the first pregnancy with Rhesus positive fetus can be successful but during the pregnancy the woman's blood produces antibodies against the Rhesus factor. Such antibodies attack the Rhesus factor if the woman gets subsequent pregnancies where the Fetus is Rhesus positive.

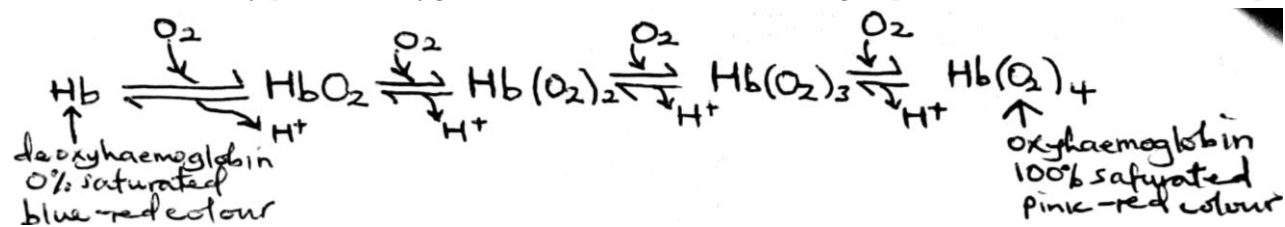
NB: During blood transfusion both the ABO system and the Rhesus factor system of blood groups are used together. So a person of blood group A Rh<sup>+</sup> can receive blood from a donor of A Rh<sup>+</sup>, A Rh<sup>-</sup>, O Rh<sup>+</sup> and O Rh<sup>-</sup>. Blood group AB<sup>+</sup> means AB Rh<sup>+</sup>, OB<sup>-</sup> means OB Rh<sup>-</sup>, etc.

### TRANSPORT OF OXYGEN

Oxygen is carried in red blood cells bound to the protein haemoglobin.

A **haemoglobin** molecule has a quaternary structure of four polypeptide chains (2 alpha and 2 beta). Each polypeptide chain is linked to a haem prosthetic group at the center of each chain. An iron atom in the ferrous form (Fe<sup>2+</sup>) is located within each haem group.

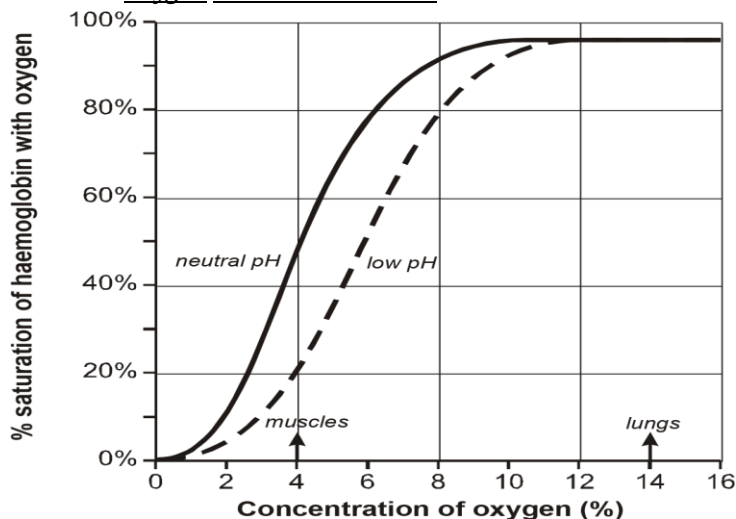
One haemoglobin molecule can bind up to four oxygen molecules. When this happens, a conformational change occurs that exposes the next haem group for binding with oxygen. Thus, oxygen easily binds to a haemoglobin molecule that already possesses oxygen. This means there are 4 binding steps as shown in this chemical equation:



#### Example questions:

1. Describe the structure of the haemoglobin molecule.
2. Explain why the affinity of haemoglobin for oxygen increases when it already possesses oxygen.

A sample of blood can therefore be in any state from completely deoxygenated (0% saturated) to fully oxygenated (100% saturated). Since deoxyhaemoglobin and oxyhaemoglobin are different colours, it is easy to measure the % saturation of a sample of blood in a colorimeter. As the chemical equation shows, oxygen drives the reaction to the right, so the more oxygen there is in the surroundings, the more saturated the haemoglobin will be. This relation is shown in the oxygen dissociation curve shown below.:



or partial pressure of oxygen (kPa) in the surroundings

The concentration of oxygen in the surroundings can be measured as a % (there's about 20% oxygen in air), but it's more correct to measure it as a partial pressure ( $\text{PO}_2$ , measured in kPa). Luckily, since the pressure of one atmosphere is about 100 kPa, the actual values for  $\text{PO}_2$  and %  $\text{O}_2$  are the same (e.g. 12%  $\text{O}_2$  has a  $\text{PO}_2$  of 12 kPa). The graph is read by starting with an oxygen concentration in the environment surrounding the blood capillaries on the horizontal axis, then reading off the state of the haemoglobin in the blood that results from the vertical axis.

This curve has an S (or sigmoid) shape, and shows several features that help in the transport of oxygen in the blood:

- In the alveoli of the lungs oxygen is constantly being brought in by ventilation, so its concentration is kept high, at around 14 kPa. As blood passes through the capillaries surrounding the alveoli the haemoglobin binds oxygen to become almost 100% saturated. Even if the alveolar oxygen concentration falls a little the haemoglobin stays saturated because the curve is flat here.
- In tissues, like muscle, liver or brain, oxygen is used by respiration, so is low, typically about 4 kPa. At this  $\text{PO}_2$  the haemoglobin is only 50% saturated, so it unloads about half its oxygen (i.e. from about 100% saturated to about 50% saturated) to the cells, which use it for respiration.
- In tissues that are respiring quickly, such as contracting muscle cells, the  $\text{PO}_2$  drops even lower, to about 2 kPa, so the haemoglobin saturation drops to about 10%, so almost 90% of the oxygen is unloaded, providing more oxygen for the muscle cells.

- Actively-respiring tissues also produce a lot of  $\text{CO}_2$ , which dissolves in tissue fluid to make carbonic acid and so lowers the pH. The chemical equation above shows that hydrogen ions drive the reaction to the left, so low pH reduces the % saturation of haemoglobin at any  $\text{PO}_2$ . This is shown on the graph by the dotted line, which is lower than the normal dissociation curve. This downward shift is called the Bohr Effect, after the Danish scientist who first discovered it. So at a  $\text{PO}_2$  of 2%, the actual saturation is nearer 5%, so almost all the oxygen loaded in the lungs is unloaded in respiring tissues.

### The Bohr Effect

This is the shifting of the oxygen dissociation curve to the right due to increased partial pressure of  $\text{CO}_2$  in tissues. The effect of increased  $\text{CO}_2$  is therefore to cause  $\text{O}_2$  to be released from the haemoglobin molecule.  $\text{CO}_2$  is a product of respiration, the faster respiration is occurring, the faster it is produced. These are the conditions when  $\text{O}_2$  is most needed, so it is an advantage that the  $\text{CO}_2$  makes the Hb release  $\text{O}_2$ .

$\text{CO}_2$  dissolves to form a weak acid which dissociates to release hydrogen ions. The hydrogen ions released combine with Hb and make it less able to carry  $\text{O}_2$ ; it reduces haemoglobin affinity for  $\text{O}_2$ .

The Hb of the human fetus has an  $\text{O}_2$  dissociation curve situated to the left of the mother's  $\text{O}_2$  dissociation curve because the fetal blood has got to pick up  $\text{O}_2$  from the mother's blood across the placenta and this can only take place if the fetal Hb has a higher affinity for  $\text{O}_2$  than the mother's Hb.

### 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 oxygen-carrying capacities and are located in different areas

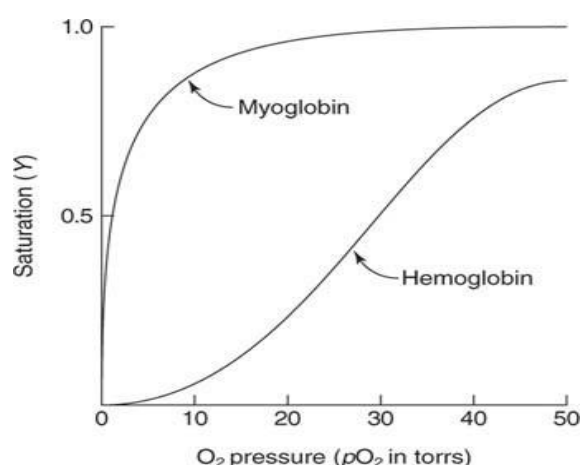
|  | Haemoglobin     | Chlorocruorin<br>(some annelids) | Haemocyanin (snails and<br>crustaceans) | Haemoerythrin<br>(some annelids) |
|--|-----------------|----------------------------------|---|----------------------------------|
| Colour of pigment                            | Red             | Green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

### Myoglobin

Myoglobin is a red pigment very similar in structure to one of the polypeptide chains of Hb. it 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. Comparison of Hb and myoglobin  $\text{O}_2$  dissociation curve shows that myoglobin is displaced to the left. This means that myoglobin retains its  $\text{O}_2$  in the resting cell but gives it up when vigorous muscle activity uses up the available  $\text{O}_2$  supplied by Hb.

*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)



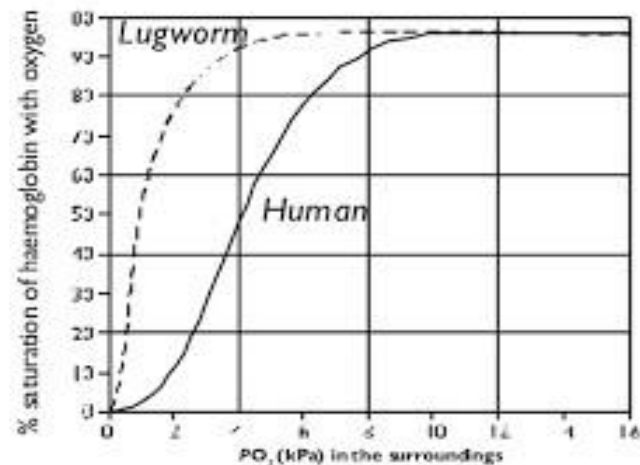
## Comparison between the oxygen dissociation curve for Lugworms' haemoglobin and that of Man

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.

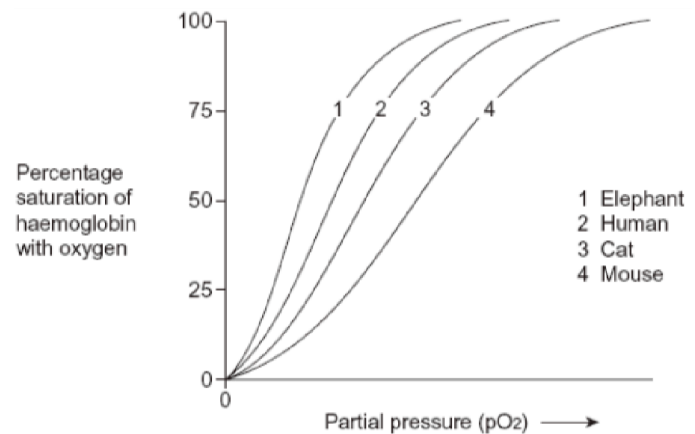
This implies that the lugworm's haemoglobin dissociates to release oxygen to its tissues compared to that of man which makes the lugworm less active than man, who releases much oxygen rapidly to the tissues.

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



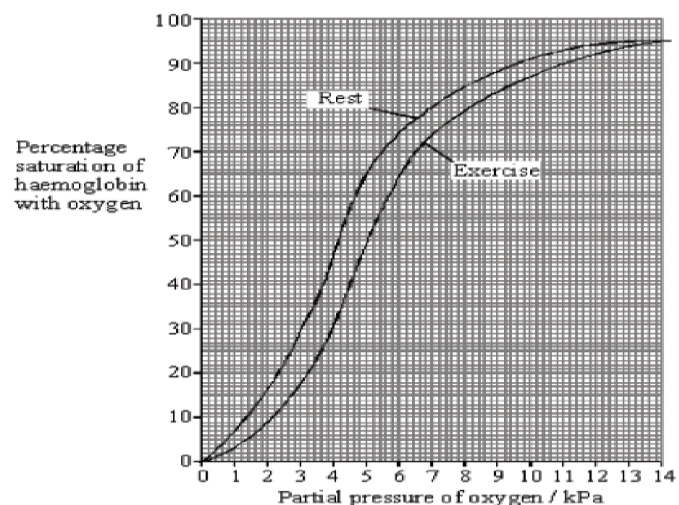
## Comparison between the oxygen dissociation curves at rest and during exercise

During exercise, the oxyhaemoglobin

releases oxygen more readily hence the

oxygen dissociation curve during exercise is

to the right of the curve when at rest.



(Clegg fig 17.36 pg 363 OR Toole fig 21.7 pg 416)

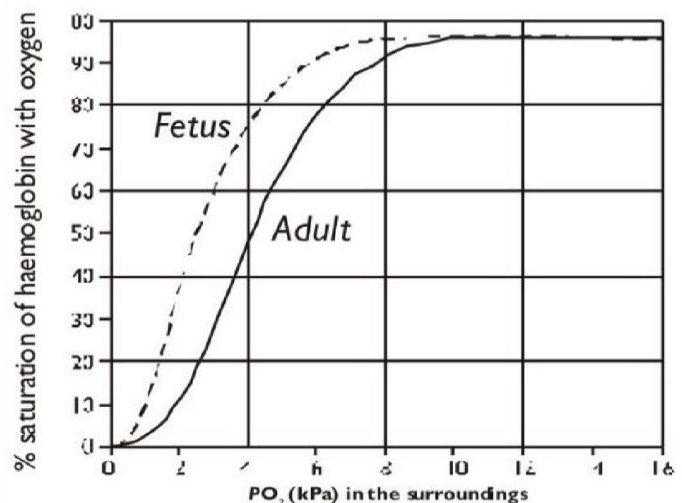
## Comparison between the oxygen dissociation curve of maternal haemoglobin and that of the foetal haemoglobin



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 haemoglobin 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.

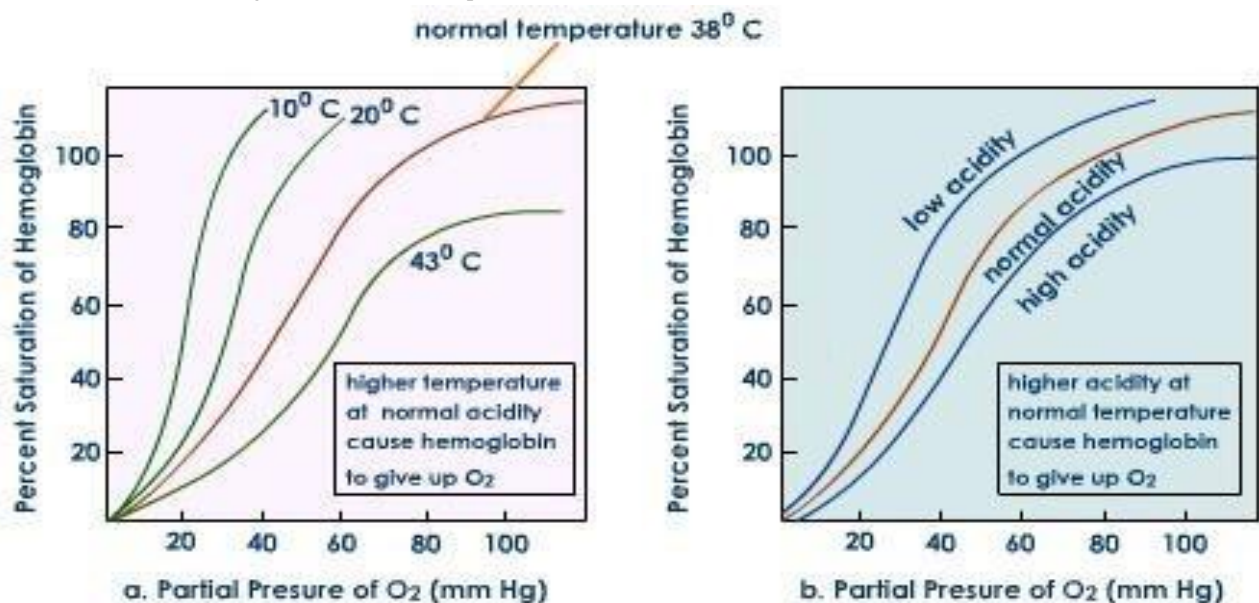


### Effect of temperature on haemoglobin oxygen dissociation curve

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.

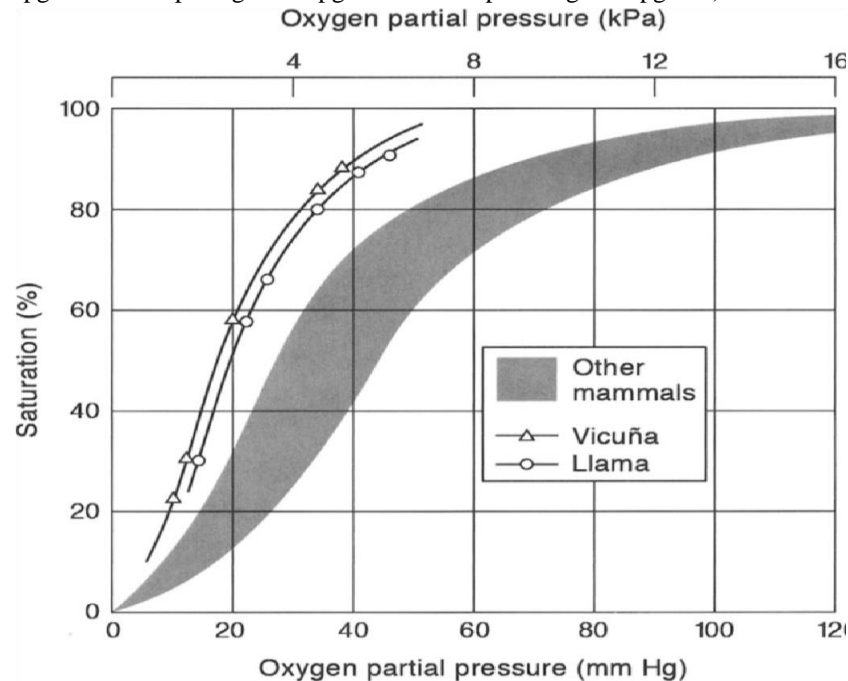
The amount of haemoglobin and the red blood cell count increases together with the rate of breathing and the heartbeat. More red blood cell formation occurs in the bone marrow under the control of the hormone called *erythropoietin* secreted by the kidney. Secretion of erythropoietin is stimulated by 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 explains why the oxygen dissociation curve of the haemoglobin of the llama lies to the left of that of other mammals at sea level. The vicuña 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 carried between respiring tissues and the lungs by 3 different methods:

#### 3. As dissolved gas in blood plasma (2%)

Very little travels this way as  $\text{CO}_2$  is not very soluble in water (about 0.02%)

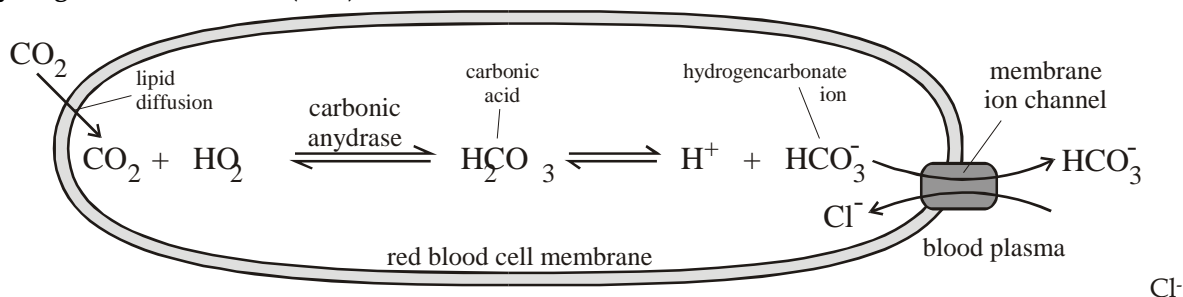
#### 4. As Carbamino Haemoglobin (13%)

Carbon dioxide can bind to amino groups in haemoglobin molecules, forming carbamate ions:



Since there are so many haemoglobin molecules in red blood cells, and each one has many amino groups, quite a lot of  $\text{CO}_2$  can be carried this way.

#### 5. As Hydrogen carbonate ions (85%)



Carbon dioxide diffuses through the cell membrane into red blood cell and reacts with water to form carbonic acid, which immediately dissociates to form a hydrogen carbonate (or bicarbonate) ion and a proton. This proton binds to haemoglobin, as in the cause of the Bohr Effect. Hydrogen carbonate is very soluble, so most  $\text{CO}_2$  is carried this way. The reaction in water is very slow, but red blood cells contain the enzyme carbonic anhydrase, which catalyzes the reaction with water.

In respiring tissues  $\text{CO}_2$  produced by respiration diffuses into the red blood cells and forms hydrogen carbonate, which diffuses out of the cell into the blood plasma through an ion channel in the red blood cell membrane. This channel carries one chloride ion into the cell for every hydrogen carbonate ion it carries out, and this helps to keep the charge in the cell constant (*chloride shift*).

**Chloride shift** is the movement of chloride ions into red blood cells as bicarbonate ions leave during the picking up of carbon dioxide from the tissues by the blood. It helps to restore electronegativity within the red blood cells in tissue capillaries when bicarbonate ions diffuse into plasma.

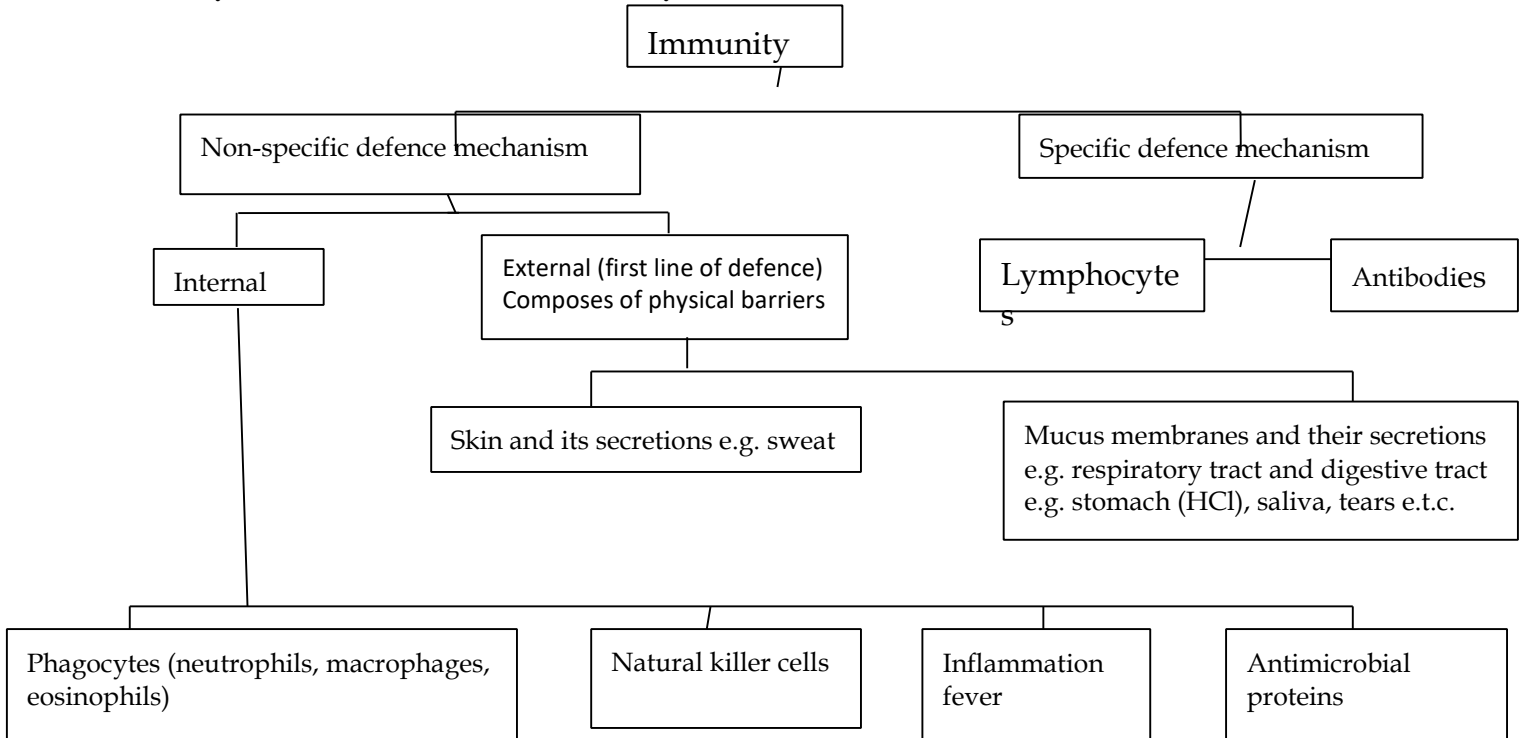
In the lungs the reverse happens: hydrogen carbonate diffuses back into the red blood cell through the channel (and chloride goes out) and  $\text{CO}_2$  is formed by carbonic anhydrase (remember enzymes will catalyze reactions in either direction), which diffuses into the plasma and into the alveoli.

In all three cases the direction of the reactions is governed by the  $\text{CO}_2$  concentration. So in the tissues, where  $\text{CO}_2$  is high, the reactions go to the right, while in the lungs, where  $\text{CO}_2$  is low, the reactions go to the left.

## THE PRINCIPLE OF IMMUNOLOGY

Immunology is the study of the immune system. Immunity is defined as the capacity to recognize the entry of foreign materials in the body and to mobilize cells to help and remove the foreign particles immediately it enters the body or before they enter the body.

A summary of defence mechanisms in an animal's body



### Antigen:

Molecule that stimulates an immune response. Usually proteins (polysaccharides, nucleic acid, lipids can also act as antigens) and other inorganic molecules important for self-recognition.

**Self-antigen:** Only found on the host's own cells and does **not** trigger an immune response. There is only 1:4 change that siblings will possess an identical antigen.

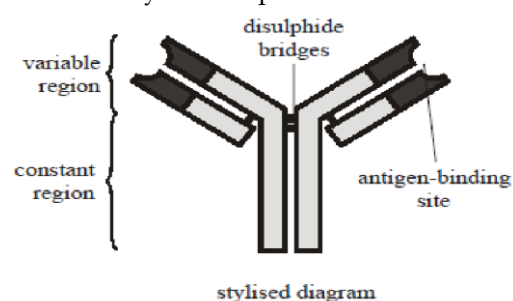
**Non-self-antigen:** Found on cells entering the body (e.g. bacteria, viruses, and another person's cell) and can cause an immune response.

### Antibody (immunoglobulin protein):

Secreted by B-lymphocytes and produced in response to a specific (foreign) non-self-antigen. B-lymphocyte's receptor site matches the non-self-antigen.

Each antibody is produced by one type of B-lymphocyte for only one type of antigen

An antibody is Y-shaped



- ❖ The two ends of the Y are called the Fab fragments
- ❖ The other end is called the Fc fragment
- ❖ Fab fragment is responsible for the antigen-binding properties
- ❖ Fc fragment is the effector component and triggers the immune response B cells divide and form memory cells and antibody-secreting plasma cells:
- ❖ **Agglutination** makes pathogens clump together.
- ❖ Antitoxins **neutralize** toxins produced by bacteria.
- ❖ **Lysis** digests bacterial membrane, killing the bacterium.
- ❖ **Opsonisation** coats pathogen in protein that identifies them as foreign cells.

**Types of Immune Response** The immune system defends the body in the following ways:

**Non-specific way** This works by attacking anything foreign. It involves:

1. **First line of defense:** this is a barrier that helps prevent pathogens from entering the body. The body has several different types of barriers:

- ☞ Tears = wash germs away, kill germs
- ☞ Skin = Germs can only enter skin when you have a cut, burn or Scrape.
- ☞ Mucous Membranes = in your nose, mouth, and throat secrete a fluid called mucus that traps germs.
- ☞ Saliva = washes germs from your teeth and helps keep your mouth clean.
- ☞ Gastric juice = destroys germs that enter through food or drink.

2. **Second line of defense:** microbes that get into the body encounter the second line of non-specific defense. It is meant to limit the spread of invaders in advance of specific immune responses. There are 3 types:

i) **Inflammatory response:**

**Inflammation:**

*This is a localized reaction which occurs at the site where a wound has been formed. It causes swelling and a lot of pain. The site appears red due to increased blood flow. Capillary network dilate and become more permeable to lymph and release lymphocytes. Chemical substances called histamines are released to bind the pathogens (agglutination) for easy recognition by lymphocytes. Fibrinogen also present to assist blood clotting if necessary.*

Inflammation works in two ways;

-Histamine triggers vasodilation which increase blood supply to that area, bringing more phagocytes to engulf germs. Histamine is also responsible for the symptoms of the common cold, sneezing, coughing, redness and itching and runny nose and eyes - all attempt to rid the body of invaders.

-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 release 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°C hence causing a fever. The fever has several beneficial effects;

It increases the activity of phagocytes which then attack the invading microbes more efficiently.

*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.*

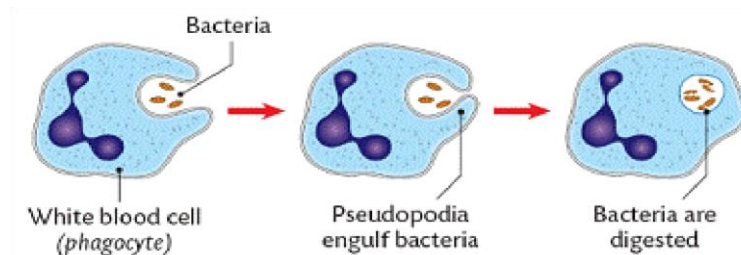
**ii).Phagocytes** Certain white blood cells particularly neutrophils and monocytes are attracted by chemicals released by body cells which have been damaged by invading pathogens. These white blood cells show amoeboid movements which engulf, ingest and destroy pathogens.

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 damage the invader .

**iii).Interferon:** fever 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

#### NATURAL KILLER (NK) CELLS

This is a class of white blood cells which attack virus injected body cells and abnormal cells that could form tumours. The virus infected cells have viral proteins displayed on their surfaces and these are recognized by the natural killer cells contains perforin – filled vesicle.

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

#### ANTIMICROBIAL PROTEINS

These are proteins that function in the mechanisms by attacking microbes directly or 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 steps, leading to lysis (bursting) of invading cells.

#### 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)

##### 1. HUMORAL 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.

##### B-Lymphocytes: The Humoral Response

Response for pathogens not entering our cells i.e. antibodies defend against infection in body fluids. (E.g. bacterium). Each B-lymphocyte recognizes only one specific antigen or need T-helper cell to be activated.

Mature B-cells develop to give many different variants of specific immune system responding to any type of pathogen entering the body.

##### 1. Primary response:

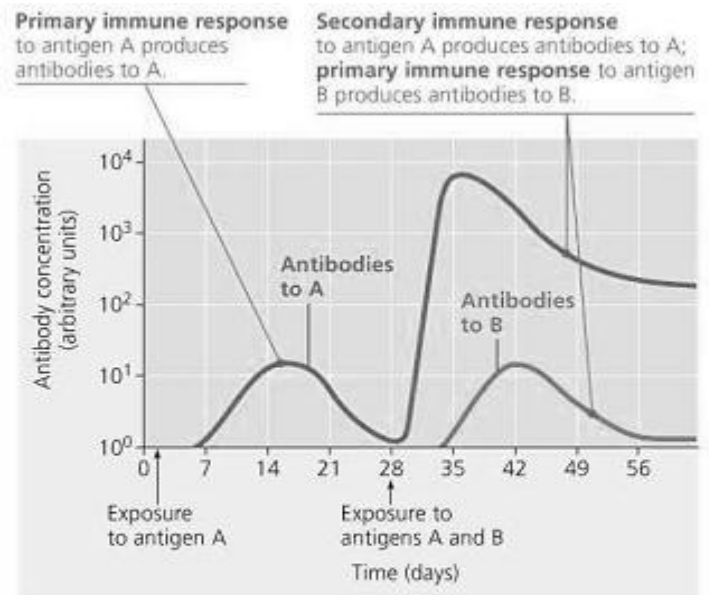
Pathogen is ingested by macrophages / macrophage displays the pathogens surface non-self-antigen on its surface (antigen presentation).

It then joins with specific T-helper cells and B lymphocytes that have membrane receptors and are complementary in shape to the non-self-antigen. T-helper cells will release cytokines to activate selected B-cell/lymphocyte:

- i) Secretes antibodies of the same type into the blood
- ii) Divided by mitosis to produce a clone
- iii) Cells grow to form plasma cells producing masses of free antibodies

Some of the cells remain in the blood as memory cells.

**2. Secondary response:** this occurs if an individual is exposed again to the same antigen. There is immediate recognition and distraction - faster, larger response usually prevents harm. Antibodies are produced more rapidly and in larger amounts.



**▲ Figure 43.15 The specificity of immunological memory.** Long-lived memory cells generated in the primary response to antigen A give rise to a heightened secondary response to the same antigen, but do not affect the primary response to a different antigen (B).

## 2.CELLULAR T-CELLS (T-LYMPHOCYTES)

The T-lymphocytes regulate the immune response (in case of  $T_H$ -cells) or kill certain types of cells ( $T_C$ -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.

### T-Lymphocytes: Cell-Mediated Response

Cytotoxic lymphocytes defend against infection in body cells. This occurs when a Virus enters a cell thus more difficult to remove.

No antibodies involved / work directly on the infected cell by destroying it.

Special proteins called Major Histocompatibility Complex (MHC) are present on all human cells. Non-self-antigen interacts with MHC as human cell becomes infected by a pathogen.

□ Specific T-lymphocyte recognizes specific non-self-antigen only with a chemical marker next to it (MHC) □ Activated T-lymphocytes multiply by mitosis and enter circulation □ Cells differentiate into different types of cell.

- i) **Cytotoxic T-Cells:** destroy pathogens and infected cells by enzyme action, and secrete chemicals which attract and stimulate phagocytes.
- ii) **Helper T-Cells:** stimulate the activity of the cytotoxic T-Cells and B-lymphocytes by releasing chemicals (cytokines and interleukins). It's the one destroyed by HIV.
- iii) **Suppressor T-Cells:** switch off/ Suppress the T and B cell responses when infection clears. thus prevent T and B 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.
- iv) **Memory T-Cells:** Some activated T-Cells remain in the circulation and can respond quickly when same pathogen enters body again.

**Different types of immunity**

|                                  |  |   |
|----------------------------------|--|---|
|                                  | <b>Active</b> (Antibodies made by the human immune system, long term acting due to memory cells) | <b>Passive</b> (Given-Antibodies, short term acting)                                    |
| <b>Natural</b>                   | - Response to disease<br>- Rejecting transplant  | - Acquired antibodies (via placenta, breast milk)                                       |
| <b>Artificial</b> (immunization) | - Vaccination (Injection of the antigen in a weakened form)                                      | - Injection of antibodies from an artificial source, e.g. anti-venom against snake bite |
| <b>Differences</b>               | - Antibody in response to antigen<br>- Production of memory cells<br>- Long lasting              | - Antibodies provided<br>- No memory cells<br>- Short lasting                           |

**How vaccines produce responses by the immune system (Artificial active immunity)****Types of vaccine**

- Vaccine containing dead pathogens. Antigen is still recognized and an immune response made.
  - o Salk polio vaccine (Polio vaccine is injected)
  - o Influenza
  - o Whooping cough
- Vaccine containing a toxin
  - o Diphtheria
  - o Tetanus
- Vaccine containing an attenuated (modified or weakened) organism which is alive but has been modified so that it is not harmful
  - . Sabin polio vaccine (Taken orally, often sugar pumps)
- Purified antigen - genetically engineered vaccine.
  - . Hepatitis B (A gene coding for a surface protein of the hepatitis B virus has been inserted into yeast cells which produce the protein when grown in fermenters)

**Transplantation**

This is the replacement of diseased tissue or organs by healthy ones through a surgery. It's less successful than blood transfusion because the organ contains more antigens than blood so they are likely to be rejected by the body's immune system. Tissue rejection has been perfectly overcome by:

- Careful tissue typing i.e. using tissue which meets the donor and recipient antigens as exactly as possible.
- Use of immune suppressive drugs which suppress the recipient's immunity in order to increase the chances of transplant success.

**Tissue typing can be effected through the following ways;**

- Autograft**; the tissue is grafted from one area to another on the same individual. E.g. skin. Rejection is not a problem.
- Isograft**; a graft between two genetically identical individuals' e.g. identical twins. Rejection is not a problem.
- Allograft**; a tissue from individual to individual but the two must be closely attached or related though of different genetic constitution. In case of rejection, immune suppressive drugs can be used.
- Xenograft**; a graft between individuals of different species such as from sheep to human.

- "The ultimate measure of a man is not where he stands in moments of comfort and convenience, but where he stands at times of challenge and controversy." **Martin Luther King, Jr.**
- "The greatest mistake you can make in life is to continually be afraid you will make one." **Elbert Green Hubbard**
- "Victory belongs to the most persevering." **Napoleon Bonaparte**
- "Nothing can stop the man with the right mental attitude from achieving his goal; nothing on earth can help the man with the wrong mental attitude." **Thomas Jefferson**
- "It's never too late to be what you might have been." **George Eliot**
- "Do not spoil what you have by desiring what you have not; but remember that what you have was once among the things only hoped for." **Epicurus**

**END**