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_2, O_2, 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 provides the energy required.
v) Cells have plasmadesmata 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.

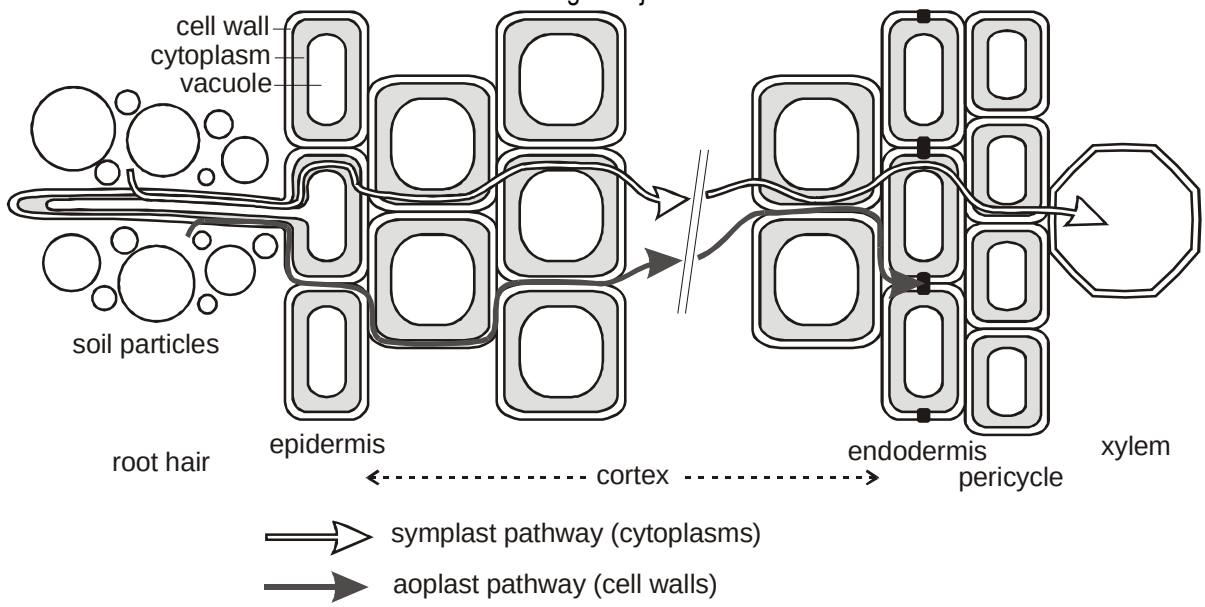
Absorption of water from the soil by plant roots.

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:

This is where water flows along the 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 plasmadesmata. 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.

Uptake of water in the xylem tissue

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.
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.

Uptake of ions

Ions are absorbed into the root hairs, transported across the root, and then into the xylem. They then travel in solution in water to all parts of the plant.

The mechanism by which ions are taken up by root hairs depends on their concentration in the soil solution. If a particular type of ion is in a higher concentration in the soil than inside the root hair cell, then it will be absorbed by ***facilitated diffusion***. This does not require any energy input by the plant. If, however, the concentration of the ion in the soil is lower than that inside the root hair cell, then it must be absorbed by ***active transport***. Specific transporter proteins use energy derived from the hydrolysis of ATP to move ions through the cell membrane into the cytoplasm.

TRANSPIRATION

This is the loss of water inform of water vapour from the aerial parts of the plant to the atmosphere. Transpiration is as a result of evaporation of water from the mesophyll cells into the air spaces then out of the leaf through the stoma. It normally occurs over the leaves that have numerous pores (stoma). It can also occur at the bark where there are lenticels and some water can be lost through the cuticle.

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.

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 outside. Transpiration therefore happens faster on a windy day than on a still day. ***Fig.1***.

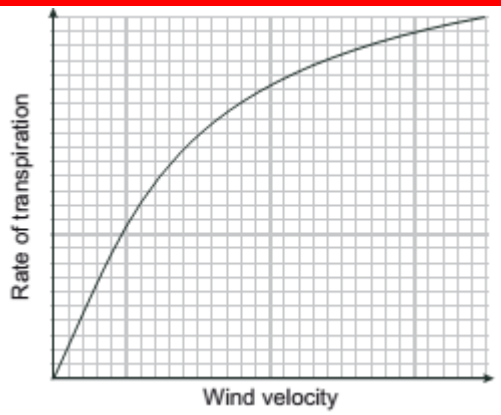


Fig.1: How wind affects the rate of transpiration

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.

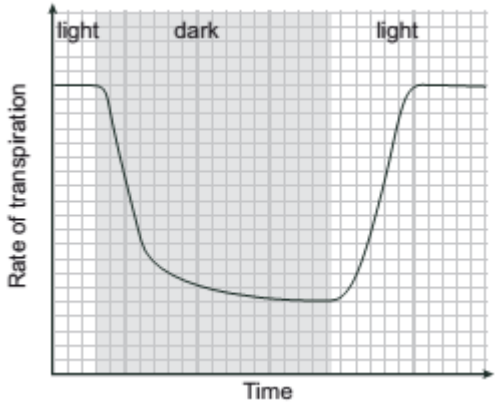


Fig.2: How stomatal closure affects transpiration

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.

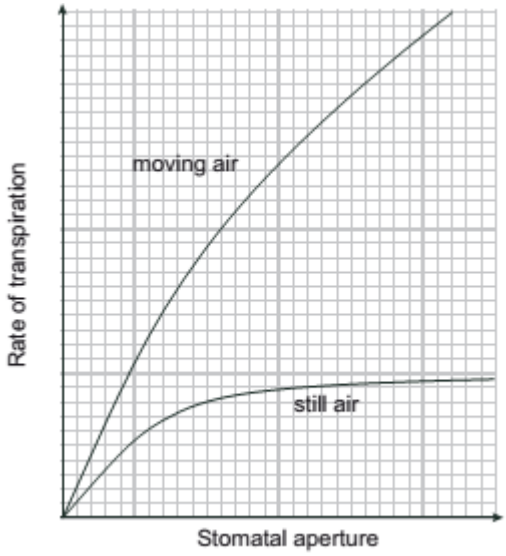
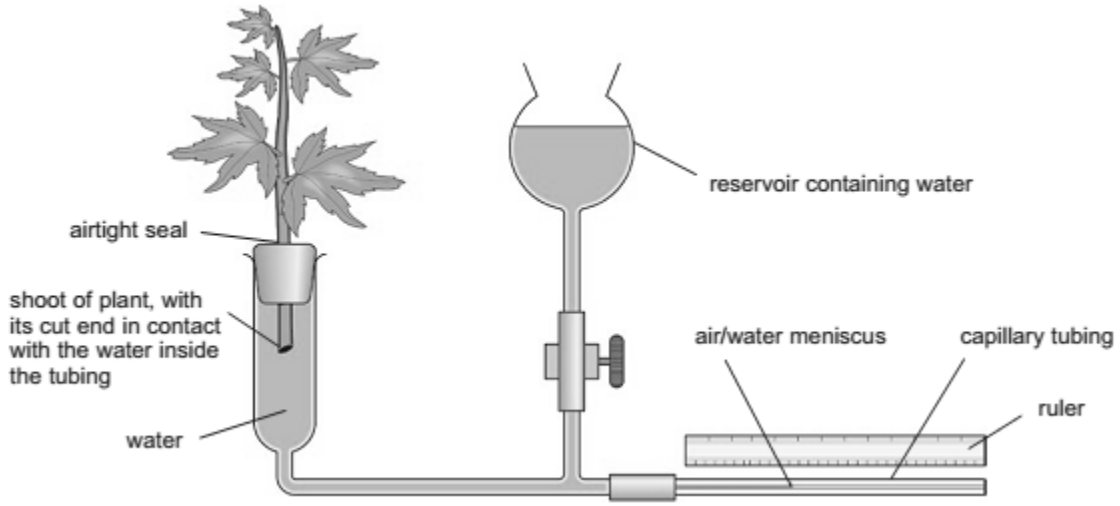


Fig.3: **The effects of wind velocity and stomatal aperture on the rate of transpiration**

Measuring/comparing the rate of transpiration

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.

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_2 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.

Transport in phloem

The transport of soluble organic substances within a plant is called **translocation**. These substances are sometimes called assimilates. The main substance transported in phloem is **sucrose**.
Assimilates are transported in sieve elements. Sieve elements and companion cells work closely together to achieve translocation.
There are several hypotheses put forward to explain movement of materials through the phloem. The most widely accepted is the mass flow hypothesis, however, the other mechanisms are cytoplasmic streaming, electro-osmosis, active transport and surface spreading.

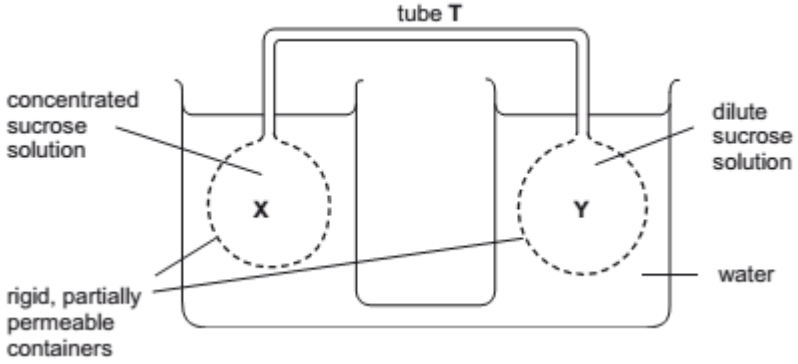
1. Mass flow

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

- There is flow of food substances/solution; there is flow of sap from a cut stem.
- There is flow of sap from aphid stylets.
- There is a difference in the concentration of sucrose between the leaves and roots. Concentration of sucrose is higher in leaves than the roots therefore turgor pressure gradient occurs.
- Some viruses and growth substances applied to the leaves move through the phloem to the roots.

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



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.

Shortcomings of the mass flow hypothesis

Although the mass flow hypothesis is widely accepted, there are some observation that regard translocation that it can't explain.

i) Different solutes have been observed to move at different speeds since the sieve tubes are not equally permeable to all solutes. The ratios of concentrations of various solutes changes as the solutes move along the sieve tube resulting in a change in their rate of flow.
ii) Materials have been observed to move up and down at the same time in the phloem tissue, mass flow can't account for bi-directional flow.
iii) In some plants, gradients of turgor pressure are insufficient to overcome the resistance caused by the sieve pores and plates to move the food substances.

2. Cytoplasmic streaming

Within the phloem tissue, there are cytoplasmic strands or filaments which are proteins in nature and they are continuous from one sieve element to another via the pores. Food substances are able to move along these strands due to wave-like contractions generated by the filaments. The sieve elements use energy provided by the companion cells to carry out such contractions.
Cytoplasmic streaming enables some food substances to move upwards while others downwards. It therefore accounts for the bi-directional flow of substances observed in the phloem tissue.

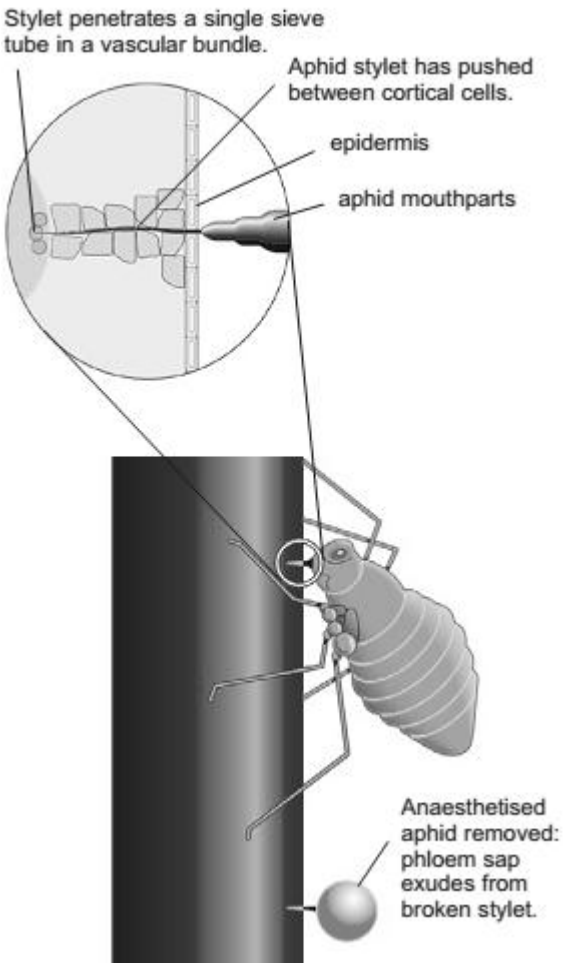
Shortcomings/criticisms:

Plants would require a lot of energy to transport the observed food units of food substances.

Evidence to support the fact that translocation of materials occurs via the phloem

1. Ringing experiment:

In natural tree trunks, the phloem is confined to the bark. If a ring is cut round the bark and stripped off a tree trunk, the sucrose concentration increases above the ring and decreases below, indicating that downwards the movement of sucrose is blocked at that point.



The feeding aphid

2. Radioactive tracers:

If a plant is exposed to CO_2 labelled with radioactive ^{14}C, the ^{14}C becomes incorporated into the end products of photosynthesis which are subsequently detected in the stem. That these substances are confined to the phloem and can be shown by cutting sections of the stem, placing the sections in contact with photographic film and auto radiographing, it is found that the sites of radioactivity correspond precisely to the position of the phloem.

3. Feeding aphid:

Aphids are a good way of collecting sap. Aphids, such as greenfly, feed by inserting their tubular mouthparts, called stylets, into the phloem of plant stems and leaves. Phloem sap flows through the stylet into the aphid. If the stylet is cut near the aphid's head, the sap continues to flow.

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. exhalent 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.

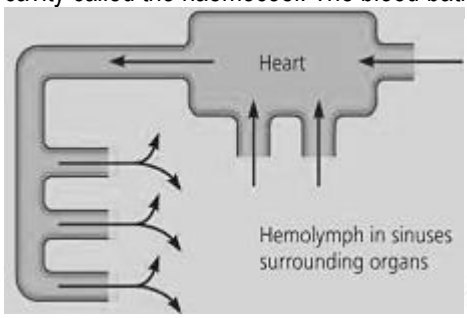
The heart Pumps and conducts the circulatory fluid to various tissues. Arteries take blood away from the heart and veins bring blood back to the heart.

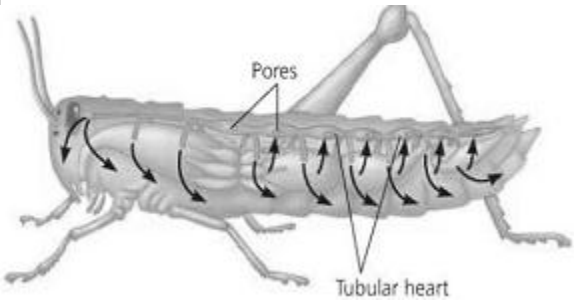
The higher invertebrates and vertebrates have two types of circulatory systems

i) Open circulatory system and
ii) Closed circulatory system

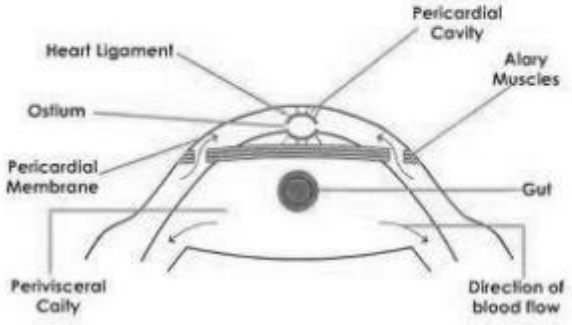
The open circulatory system

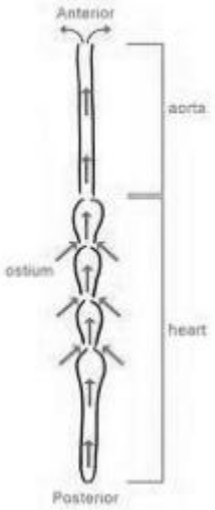
This is a system where blood is not confined to blood vessels through the course of its circulation in the body. It fills in open spaces known as the haemocoel. The blood is pumped at relatively low pressure from the heart into the main body cavity called the haemocoel. The blood bathes the cells directly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





DORSAL VESSEL (HEART) OF INSECT





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 ostea 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 pervisceral cavity increases due to reduction in volume. Fluid then flows from the pervisceral cavity to the pericardial cavity and it enters the heart through the ostea.

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 malphigian 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;

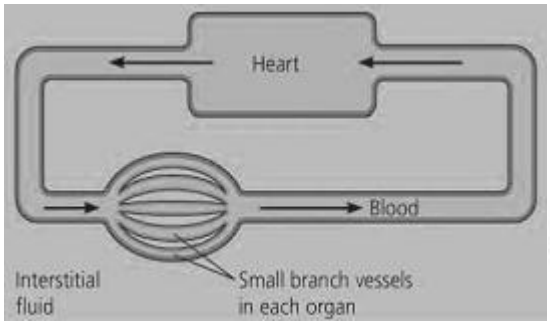
i) The single circulatory system: in this case the blood flows through the heart once in each complete circulation.
ii) The double circulatory system. In this case the blood flows through the heart twice in each complete circulation.

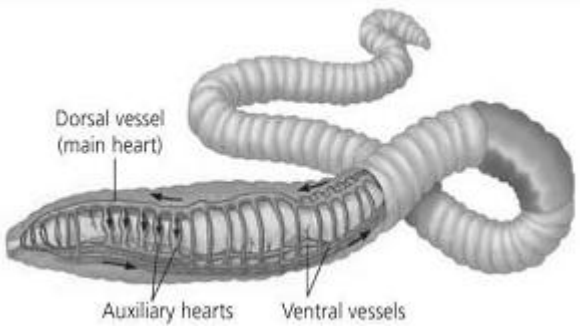
Single circulation in fish

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 pulmocutanous 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

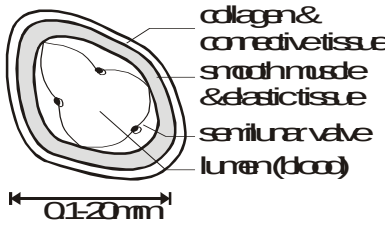
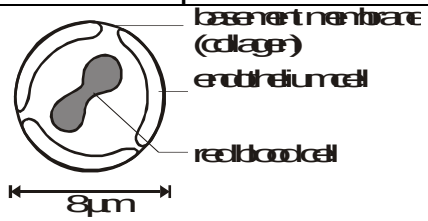
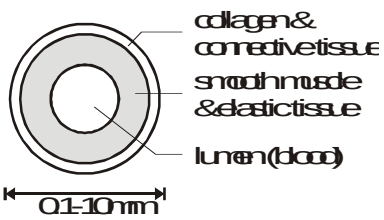
i) Relatively high pressure required for fast flow of blood is acquired than in open circulation.
ii) Since the blood is returned rapidly to the heart for pumping, more rapid circulation can be attained.
iii) The separation of oxygenated and deoxygenated blood in it improves efficiency of oxygen distribution 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

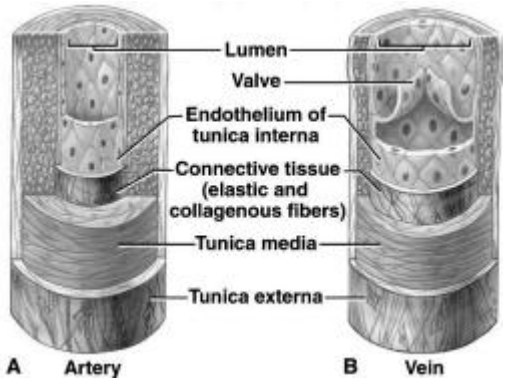
Open circulatory system	Closed circulatory system
blood flows through large open spaces and channels called lacunae and sinuses among the tissues	blood flows through a system of closed chambers and tubes called the heart and blood vessels
tissues are in direct contact with the blood	there is no direct 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.

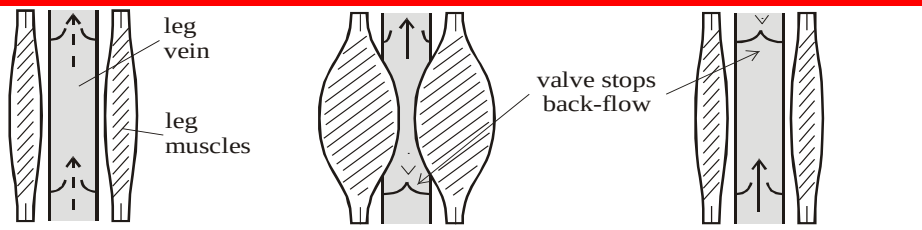
Veins and Venules	Capillaries	Arteries and Arterioles
		
Function is to carry blood from tissues to the heart	Function is to allow exchange of materials between the blood and the tissues	Function is to carry blood from the heart to the tissues
Thin walls, mainly collagen, since blood at low pressure	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)

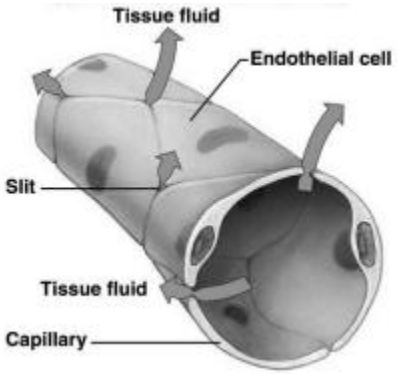
Arteries carry blood from the heart to every tissue in the body. They have thick, elastic walls to withstand the high pressure of blood from the heart. The arteries close to the heart are particularly elastic and expand during systole and recoil again during diastole, helping to even out the pulsating 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).



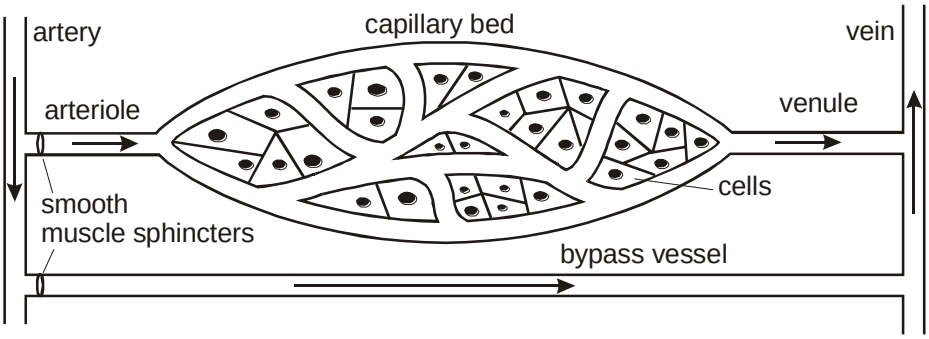
Veins carry blood from every tissue in the body to the heart. The blood has lost almost all its pressure in the capillaries, so it is at low pressure inside veins and moving slowly. Veins therefore don't need thick walls and they have a larger lumen that arteries, to reduce the resistance to flow. They 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.



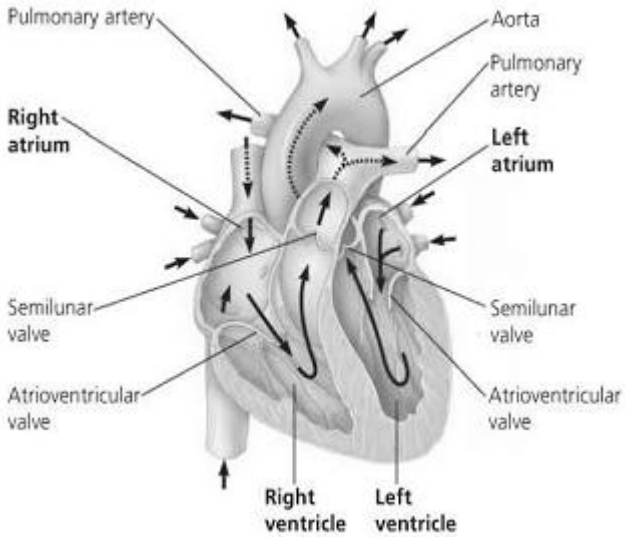


Capillaries are where the transported substances actually enter and leave the blood. No exchange of materials takes place in the arteries and veins, whose walls are too thick and impermeable.
Capillaries are very narrow and thin-walled, but there are a vast number of them (10^8 m in one adult!), so they 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 collects 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.

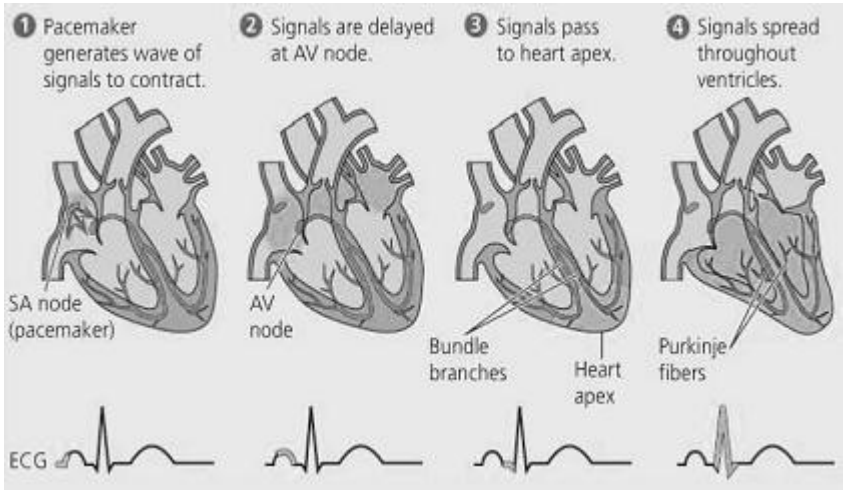
Cardiac cycle

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.

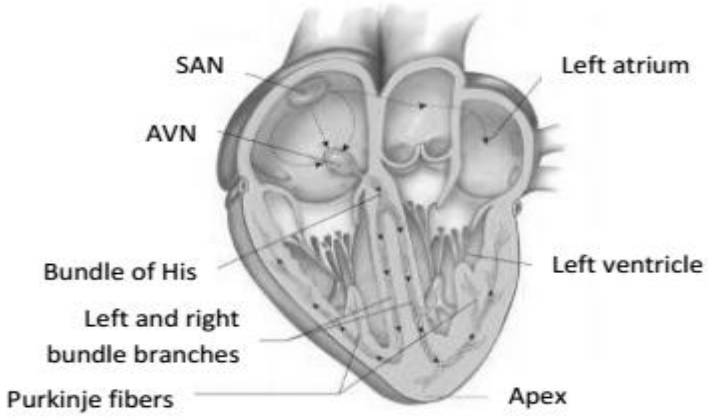
Control of the heart beat



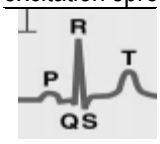
All vertebrate hearts are myogenic in nature, meaning their heart beat is initiated from within the heart muscles. In insects it is initiated by the nerves outside the heart and is known as neurogenic.

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 form 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^{o}C raises the heart rate by about 10 beats per minutes. This is the reason your heart beats faster when you have fever.

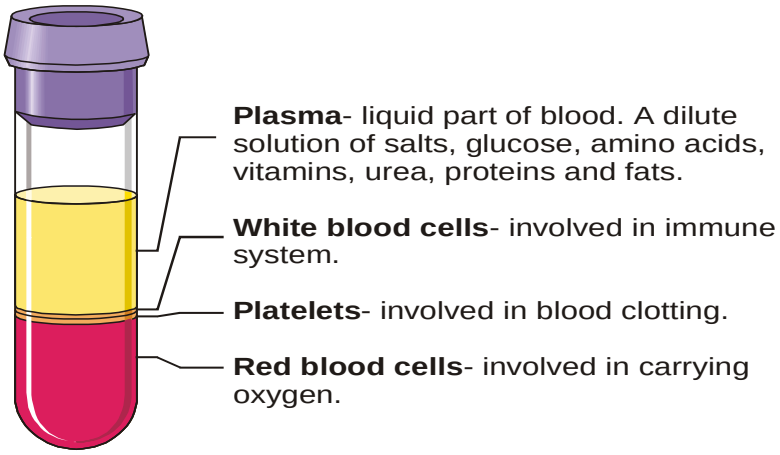
2. Hormonal activity:

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_2. 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_2 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

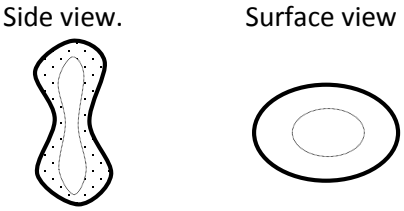


Blood Components:

There are three major components of blood i.e.

i) Cells e.g. white blood cells and red blood cells.
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^3 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:

These are WBC that don't contain any granules in their cytoplasm and can't be stained. They possess large rounded nucleus.

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 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**)*

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
ii) Blood Group B
iii) Blood Group AB
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.

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

Recipient's	**Antibodies in recipient's blood**	**Donor's Blood Group**			
		A	B	AB	O
A					
B					
AB					
O					

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^+) while a few do not have the Rhesus factor and are said to be Rhesus negative (Rh^-).

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+ can receive blood from a donor of A Rh^+, A Rh^-, O Rh^+ and O Rh^-.

Blood group AB^+ means AB Rh^+, OB^- means OB Rh^-, etc.

General functions of blood

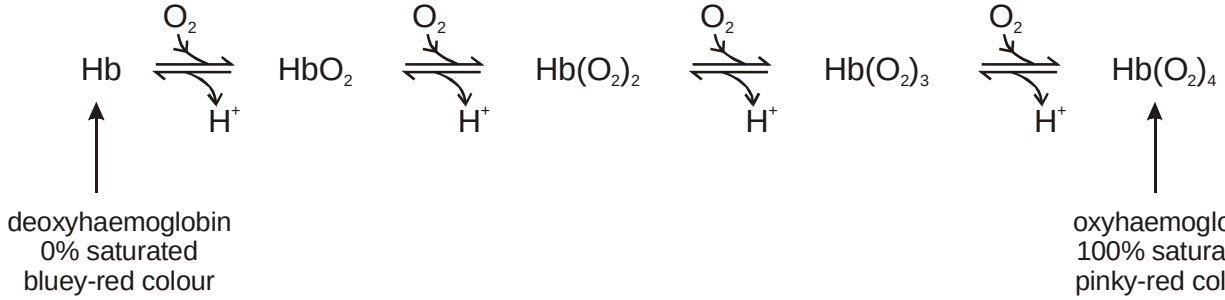
1. Transport where it transports;
   a) Food nutrients from sites of absorption to the liver for assimilation.
   b) Respiratory gases e.g. oxygen from the lungs to the tissues and carbon dioxide from the tissue to the lungs.
   c) Excretory products from tissues to excretory organs e.g. Kidney and the Skin.
   d) Hormones from organs that produce them to their target sites etc.
2. Defend the body where;
   a) It is involved in blood clotting to prevent excessive loss of blood and entry of pathogens during injury.
   b) It is involved in the immune responses which defend the body against pathogens.
3. Distribution of heat from the active metabolic organs hence regulating the body temperature.

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^{2+}) is located within each haem group.

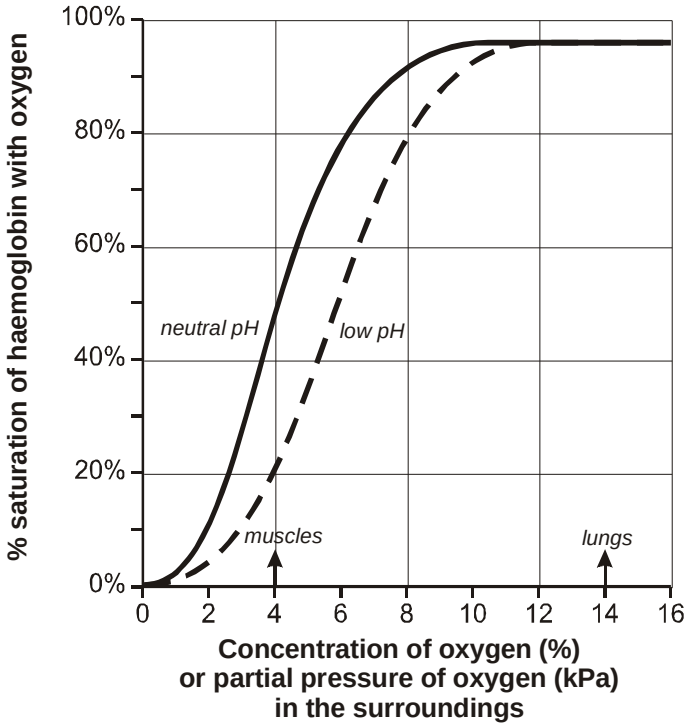
One haemoglobin molecule can bind up to four oxygen molecules. When this happens, a conformational change occurs that exposes the next haem group for binding with oxygen. Thus, oxygen easily binds to a haemoglobin molecule that already possesses oxygen. This means there are 4 binding steps as shown in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



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 (PO_2, measured in kPa). Luckily, since the pressure of one atmosphere is about 100 kPa, the actual values for PO_2 and % O_2 are the same (e.g. 12% O_2 has a 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 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 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 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 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 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 CO_2 in tissues.

The effect of increased CO_2 is therefore to cause O_2 to be released from the haemoglobin molecule. CO_2 is a product of respiration, the faster respiration is occurring, the faster it is produced. These are the conditions when O_2 is most needed, so it is an advantage that the CO_2 makes the Hb release O_2.

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 O_2; it reduces haemoglobin affinity for O_2.

The Hb of the human fetus has an O_2 dissociation curve situated to the left of the mother's O_2 dissociation curve because the fetal blood has got to pick up 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 O_2 than the mother's Hb.

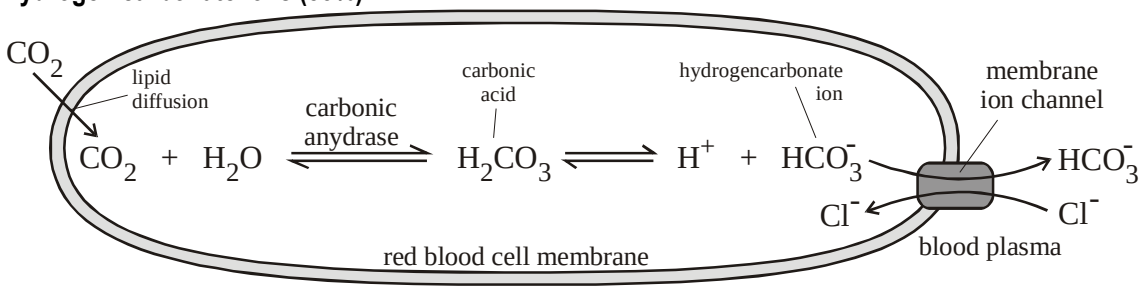
Myoglobin

Myoglobin is a red pigment very similar in structure to one of the polypeptide chains of Hb. Comparison of Hb and myoglobin O_2 dissociation curve shows that myoglobin is displaced to the left. This means that myoglobin retains its O_2 in the resting cell but gives it up when vigorous muscle activity uses up the available O_2 supplied by Hb.

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 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:
   $$Hb—NH_2 + CO_2 \rightleftharpoons Hb—NHCOO^- + H^+$$
   Since there are so many haemoglobin molecules in red blood cells, and each one has many amino groups, quite a lot of 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 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 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 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 CO_2 concentration. So in the tissues, where CO_2 is high, the reactions go to the right, while in the lungs, where 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.

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 (immunoglobin 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: 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.
      - Increased body temperature speeds up the immune system and makes it more difficult for microbes to function.

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.

   ii) Phagocytes
   iii) Interferon: chemicals released by the immune system to block against viral infections.

Specific immune response

Lymphocytes undergo maturating before birth, producing different types of lymphocytes

i) Humoral response - B lymphocytes
- Produce and release antibodies into blood plasma
- Produce antibodies from B plasma cells
- Recognize foreign antigen directly

ii) Cellular response - T lymphocytes
- Bind to antigen carrying cells and destroy them and/or activate the humoral response.
- Recognize foreign antigens displayed on the surface of normal body cells
- They promote inflammation
- They stimulate B cells to make antibodies.

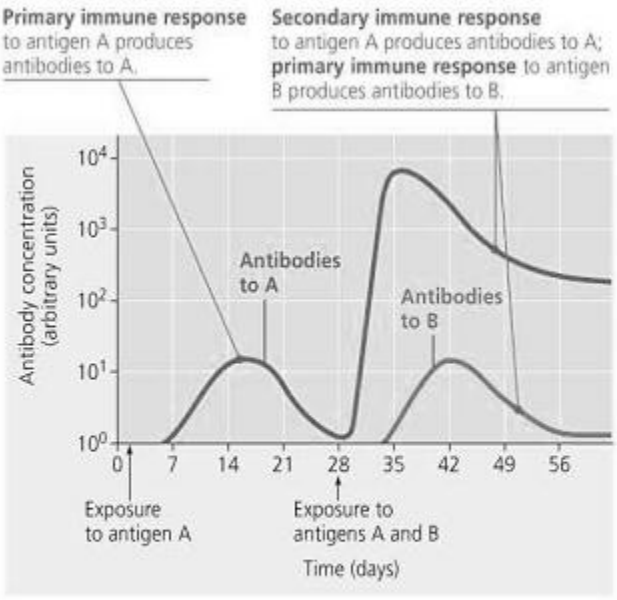
iii) **Primary response** produces memory cells which remain in the circulation.

iv) **Secondary response** new invasion by same antigen at a lower state. Immediate recognition and distraction by memory cells - faster and larger response usually prevents harm.

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).

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 Histocompability 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 the T and B cell responses when infection clears
  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

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

How vaccines produce responses by the immune system (Artificial active immunity)

Types of vaccine

1. Vaccine containing dead pathogens. Antigen is still recognized and an immune response made
    - Salk polio vaccine (Polio vaccine is injected)
    - Influenza
    - Whooping cough
2. Vaccine containing a toxin
    - Diphtheria
    - Tetanus
3. 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)
4. 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;

i) **Autograft**; the tissue is grafted from one area to another on the same individual. E.g. skin. Rejection is not a problem.
ii) **Isograft**; a graft between two genetically identical individuals' e.g. identical twins. Rejection is not a problem.
iii) **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.
iv) **Xenograft**; a graft between individuals of different species such as from sheep to human.

"Life's battles don't always go to the stronger or faster man, but soon or later, the man who wins is the man who thinks he can".