GASEUOS EXCHANGE

Gaseous exchange the process by which respiratory gases are exchanged between the external environment and the cells of an organism. It involves extraction of oxygen from the external medium into the body cells and release of carbon dioxide into the external media following ventilation.

The need for gaseous exchange:

- Living cells/organisms need to respire and therefore obtain oxygen for oxidation of respiratory substances, to yield energy needed to run various process in the body.
- During respiration, carbon dioxide is produced, which if allowed to accumulate in the body is toxic to tissues and therefore must be removed the body into the external environment.

Common terms used.

Respiratory surface. This is a structural surface over which gaseous exchange occurs. Gaseous exchange occurs across the respiratory surface by a physical process called diffusion.

Ventilation. This is a special mechanism by which respiratory medium is supplied and drained from the respiratory surface.

Ventilation mechanism involves inhalation (inspiration) and exhalation (expiration). Ventilation mechanism supplies gills and lungs with fresh respiratory medium.

Inhalation/ inspiration is the taking in of fresh air or water with high concentration of oxygen while exhalation/ inspiration is the removal of the waste air or water with higher concentration of carbon dioxide into the external environment from the organism.

CHARACTERISTICS OF RESPIRATORY SURFACE FOR THEIR EFFICIENT FUNCTION

• ***Large surface area to volume ratio.***

Large surface area to volume ratio permits more rapid rate of diffusion, so. Sufficient amount of gases are able to be exchanged according to the organism's need. For example, body surface of small organisms and infoldings of the respiratory surfaces such as in the lungs and gills in large organisms.

• ***Permeable.***

A more permeable respiratory surface to respiratory gases permits easy passage of these gases.

• ***Very thin.***

Thinness of the respiratory surface reduces the distance over which diffusion of gases takes place.

• ***Moist***

Oxygen and carbon dioxide diffuse easily across a membrane in solution.

• ***Possession of network of blood capillaries***

Well supplied between blood capillaries for transportation of the diffusing respiratory gases.

Specialized respiratory surfaces.

These include the following; -

(i) External gills

Are the simplest found in the lugworm and young tadpoles. They are out growth on the body surface.

(ii) Internal gills

There are enclosed within body cavity found in the fines

(iii) Inner alveolar surface of lungs in mammals

Lungs have many tiny sac-like structures the alveoli which provide a surface area for gas exchange.

(iv)Tracheoles.

This is found in insects where an air- pore at the surface open into a system of branching tracheal tubes passing into the body, with association with the body tissue. NB. In plants leaves layout efficiently gaseous exchange and therefore a good respiratory surface.

(v) Cell surface membrane in unicellular organisms e.g. amoeba

Effect of size and surface area to volume ratio on gaseous exchange.

Large organisms such as mammals have small surface area to volume ratio and therefore have problems wit gaseous exchange compared to smaller organisms. They also possess a large diffusion distance over which gases must diffuse to deeper cell layers. Therefore, larger multicellular organisms have to develop means of bringing the external medium nearer to the cells. They therefore possess specialized respiratory surfaces and circulatory system with blood in most cases to solve the problem of large diffusion distance.

Respiratory medium

Comparison of water and air as respiratory media

Feature	Air	Water
Density	0.0013g/cm^3	1000g/cm^3
Viscosity	1	100
Oxygen	21%	0.8%
Diffusion rate	10,000	1

Problems associated with water as a respiratory medium

- Diffusion rate of oxygen in water is very low due to high viscosity and density of water.
- The high density and viscosity offer high resistance to diffusion of gases. This causes greater energy expenditure while water is being moved along the respiratory surface.
- There is much less oxygen in water and its solubility decreases with increase in temperature. Increase in temperature, dissolved salt content and organic matter tend to reduce levels of dissolved oxygen in water.

Note. The major advantage of water as a respiratory medium in that it easily eliminates carbon dioxide waste compared to air since the solubility of carbon dioxide is very much greater in water than in air.

How aquatic organism have solved the problem of gaseous exchange.

- High ventilation rates to keep a large volume of water over the gills. This solves the problem pf low oxygen content in water for example in fishes.
- Protozoans can solve the problem of low oxygen content by creating water currents using cilia and flagella to enhance diffusion of gases. This permits greater oxygenation.
- Water is moved over the gills in one direction to reduce the oxygen and energy expenditure that would be incurred if the back-and-forth type of ventilation is used.
- In some aquatic organisms like bony fish, they use counter current flow mechanism which allows greater oxygenation.

Advantage of gaseous exchange in air:

- The content of oxygen in air high and not rapidly fluctuating like in water.
- The diffusion rate of oxygen in air is greater than that in water.
- Air has a less viscosity which offers less resistance to diffusion of gases.

- Air has a low density hence can be moved faster during ventilation. This is why air breathing organisms can grow to very large sizes and are very active.
- The low density and low viscosity of air allow air to be moved in and out of the respiratory system in one direction through the same pathway with less energy expenditure i.e. back and forth system of ventilation system is used with less energy expenditure.

Disadvantages of air breathing.

- It is accompanied with loss of water/desiccation due to high temperatures in air.
- Nitrogen can form bubbles in blood that can block fine blood vessels and cause decompression sickness e.g. during diving to greater depths without air tanks, when a pilot ascends rapidly in non-pressured cabin.

Respiratory media, organs and surfaces common in living organisms:

Organism	**Respiratory media**	**Respiratory organ**	**Respiratory surfaces**
Amoeba	Water	None	Cell membrane
Flatworms e.g., tapeworms, flukes	Water	None	General body surface
Flowering plants	Air (mainly)	None	Moist cell surface
Insects	Air	Tracheae	Tracheoles
Fish	Water	Gills	Gill filaments
Amphibians	Water and air	Gills, buccal cavity, skin and lungs	Gill filaments, epithelium of buccal cavity, lining of the skin and alveolar membrane
Reptiles, birds and mammals	Water and air	Lungs	Inner surface of the alveolar membrane

GASEOUS EXCHANGE IN SELECTED ORGANISMS:

1. GASEOUS EXCHANGE IN FLOWERING PLANTS:

Flowering plants also lack specialized gas exchange organs. Gaseous exchange in flowering plants occurs mainly through the stomata in leaves and green stems, lenticels and cracks in the barks of woody stems and roots and roots. No special ventilation mechanism exists in plants.

Reasons why plants lack a specialized respiratory system and respiratory pigments.

- Plants do not locomote, making them to have low metabolic rates and therefore have relatively less respiratory demands compared to animals.
- Diffusion si adequate to meet the little respiratory demands in plants due to flowering plants having features that favour diffusion. these features include, broad, thin leaves, numerous stomata, large airspaces in leaves and lenticels, etc.

Note. Diffusion of gases across the whole body surface of a flowering plant is not possible because the outer surfaces are water proof to prevent desiccation which results from living on land, where temperatures are high.

Mechanisms of gaseous exchange:

- **In a lenticel:**

Lenticels are perforations in stems and barks of stems with loosely packed cells consisting of large intercellular spaces.

The oxygen from the outside diffuses through the lenticels, through air spaces and dissolves in the moisture surrounding the cells. It the diffuses into the cells where it is utilized during respiration. On the other hand, carbon dioxide diffuses out of cells into the air spaces and then through the lenticels to the external surrounding.

- **In a root hair:**

Oxygen dissolves in soil surface film of moisture, and then enters the rot hair by diffusion, down its concentration gradient. Carbon dioxide from the root hair diffuse in the reverse direction.

Note. Some plants have breathing roots/pneumatophores e.g. mangroves.

- **In a leaf:**

In the leaves, gases diffuse via the stomata into the air spaces in the mesophyll cell layer. Here they saturate and oxygen dissolves in the moisture of cell surfaces inside the cells. In the cells it is

used for respiration giving off carbon dioxide in the process. The carbon dioxide diffuses out of the cells into the airspaces, from where it diffuses out of the leaf via the stomata.

Cells which contain chloroplasts have a further source of oxygen, because it is released during photosynthesis and is immediately taken up by mitochondria. Similarly, the carbon dioxide released from the mitochondria can be used by the chloroplasts for photosynthesis hence the need to expel carbon dioxide is very limited. The rate of photosynthesis is affected by intensity of light and so the carbon dioxide used and oxygen released by this process vary considerably depending on the light intensity.

Adaptations of plants for efficient gaseous exchange:

- Leaves of plants are thin to reduce the distance over which diffusion of gases occurs.
- The leaves are broad to increase the surface area for gaseous exchange.
- Spongy mesophyll layer ha s airspaces for efficient gaseous exchange by diffusion.
- Leaves have numerous stomata to increase surface area for diffusion of gases.
- Woody plants have cracks in stems where gaseous exchange can occur.
- Woody plants have lenticels with large air spaces for diffusion of gases.
- Surfaces of mesophyll cells are moist to dissolve respiratory gases for faster diffusion.
- Carbon dioxide produced during respiration is utilized for photosynthesis and oxygen from photosynthesis is utilized for aerobic respiration in the leaf hence maintain a steeper diffusion gradient of gases. This allows continuous ventilation of the leaf.
- Root hairs are numerous and long to increase surface area for gaseous exchange.
- Root hairs lack cuticle hence air enters them with little resistance to diffusion.
- Prop roots of red mangrove have air-rich pneumatophores to supplement on the oxygen uptake from mud.

OPENING AND CLOSINGOF STOMAMATA

Stomata are microscopic pores in the epidermis of the leaves. Stomata are normally more abundant in the abaxial (lower) surface, and may be evenly distributed or absent on te adaxial (upper) surface.

The functions of the stomata are:

- Exchange of carbon dioxide and oxygen between the inside of the leaf and the surrounding atmosphere (gaseous exchange)
- Permit escape of water vapour from the leaf (transpiration)

Note.

i. Aquatic plants obtain carbo dioxide from the surrounding water in which it is dissolved as carbonic acid. Land plants obtain carbon dioxide from the atmosphere via the stomata by diffusion.

ii. Carbon dioxide diffuses much faster in air than In water, so it is an advantage for mesophyll cells to be in contact with air spaces within the leaves.

Structure of the stoma.

A stoma is a pore guarded by a pair of specialized epidermal cells, the guard cells. Each guard cell is sausage shaped (or bean/kidney/shaped) when turgid. It is unevenly thickened; the inner cellulose walls are thicker and less elastic than outer cellulose wall, guard cells also contain a large sap vacuole, dense cytoplasm, prominent nucleus and a few chloroplasts. Each pair of guard cells is surrounded by other cells (about four) and these lack chloroplasts.

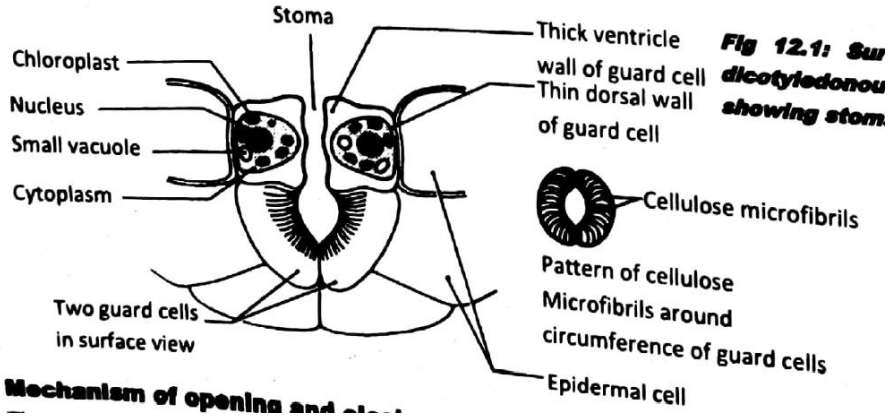


Fig 12.1: Su dicotyledonou showing stom

Mechanism of closing and opening of stomata:

Three theories explain stomatal opening and closure:

a) Starch-sugar interconversion theory

b) Photosynthetic theory

c) Ionic theory

Starch-sugar interconversion theory:

In the presence of light, carbon dioxide is utilized by plants for photosynthesis ad therefore the level of carbonic acid falls, raising the pH of guard cells. The increase in pH stimulates phosphorylase enzyme to catalyse the combination of starch with phosphoric acid, forming glucose-1-phosphate which is hydrolysed to glucose molecules (sugars).

Glucose molecules formed lower the water potential of guard cells below that of the surrounding epidermal cell. Water therefore moves into the guard cells by osmosis that become turgid. The thicker inner inelastic walls curve inwards as the outer thin elastic wall curve more, outwards forming stomatal pore between adjacent guard cells.

In absence of light, little or no photosynthesis occurs yet respiration is occurring. The carbon dioxide concentration increases, forming more carbonic acid, which lowers the pH inside the guard cells. The increase in pH stimulates the conversion of glucose to starch, and the water potential of guard cells increases beyond that of the surrounding epidermal cells. Water therefore leaves the guard cells and the guard cells become flaccid. The inner less elastic wall straightens to close the stomatal pore.

Photosynthetic theory.

In the presence of light, photosynthesis increases hence accumulating organic food substances, particularly sucrose within the guard cells. The sugars cause the water potential within the guard cells to fall below that of the surrounding epidermal cells, causing water to enter into the guard cells by osmosis and they become turgid. The thicker less elastic wall curve inwards and the outer thin elastic walls bend more outwards, forming a stomatal pore between adjacent guard cells.

In the absence of light, photosynthesis stops/reduces leading to formation of little/no organic food materials. This increases the water potentials within the guard cells beyond that of the surrounding epidermal cells, and water therefore moves out of guard cells by osmosis making them flaccid. The inner less elastic wall straightens to close the stomatal pore.

Short comings of starch-sugar interconversion and photosynthetic theory

- Starch is absent in guard cells of some plants for example onion.
- Some guard cells lack chloroplasts but still close and open stomata.
- Some plants open stomata at night/in the absence of light.

Ionic theory:

This suggests that the change in water potential within guard cells is due to movement of ions especially K^+.

During stomatal opening, K^+ ions are actively pumped into guard cells from the surrounding epidermal cells, using energy from mitochondria. The water potential of guard cell decreases below that of surrounding epidermal cells. This causes osmotic flow of water from the surrounding epidermal cells into guard cells, which become turgid and stomata open.

During closing of the stomata, K^+ diffuse out of guard cells down a concentration gradient. This increases the water potential within guard cells beyond that of surrounding epidermal cells, and water therefore moves out of guard cells by osmosis, making them flaccid and stomata closes.

Note.

i. A number of factors trigger active transport of potassium ions within the guard cells. Light, especially blue and redlight, may start active transport of ions by activating ATPase in guard cells. The ATPase increase ATP produced by photosynthesizing chloroplasts in guard cells, and ATP provides the energy for active transport.

ii. Other factors for example, too much wind, presence of metabolic poison such as cyanide, water stress due to abscisic acid (ABA), may cause stomatal closure.

In conditions of water stress, ABA triggers a metabolic pump which actively secretes potassium ions out of guard cells, causing them to lose water and become flaccid, closing the stomata.

GASEOUS EXCHANGE IN SMALLER ORGANISMS.

Small organisms have a large surface area to volume ratio and their external surface (membrane) are fully permeable to gases and therefore the respiratory gases like oxygen and carbon dioxide diffuse rapidly over their whole body surface. Being small in size, the body cells are not far from the surface of the body. The distance between the cells and the body surface is small to permit rapid diffusion.

Small organisms found to have low metabolic activity and their demand for oxygen is very low.

In this case small organisms such as amoeba (Protoctista) hydra (cnidarian) and planarian (Platyhelminthes) do not require specialized structures for gaseous exchange.

Amoeba measures less than 1mm in diameter and possess a larger surface area to volume ratio. Diffusion of gases occurs over the whole surface of the animal via permeable cell membrane.

In hydra and obelia (cnidarians) all cells are in contact with the surrounding aquatic medium and each cell is able to exchange gases sufficient for its need through the cell membrane adjacent to the surrounding water.

In a free-living Platyhelminthes such as planarian, its body is extremely flattened and this increase the body's surface area hence allowing rapid rate of diffusion. Sufficient amount of oxygen is supplied to the organism because they live in well aerated streams as ponds.

WHY A NEED FOR SPECIALISED RESPIRATORY SURFACE IN SOME ORGANISMS.

As animals increase in the size, may become bigger and the distance of their cells from the body surface become larger the rate of diffusion of respiratory gases such as oxygen into the respiring cells and carbon dioxide out of the cells is greatly lowered so the organism cannot receive adequate supply of oxygen and cannot achieve faster removal of carbon dioxide

Large sizes decrease the surface areas and transportation of oxygen and carbon dioxide into and out of the organisms by simple diffusion. becomes difficult.

Many large organisms/ animals have increased metabolic rate which increases their oxygen demand and carbon dioxide production. In some large sized organisms, the surface of the body becomes tough or hardened and impermeable to the respiratory gases. In some others the body is enclosed within in a protective shell. Therefore, larger animals need to develop special gaseous exchange mechanism.

GASEOUS EXCHANGE IN ANNELID.

Annelids do not posses specialized respiratory structure for gaseous exchange. Gaseous exchange occurs by diffusion over the whole body surface. The body is cylindrical in shape. Increasing surface area for rapid diffusion of gases. The organism is generally in-active and its metabolic activity is low and the demand for oxygen is reduced.

Annelids do possess a blood vascular system which contains respiratory pigment haemoglobin in solution. The contractile pumping activity by the blood vessels allows the passage of blood and dissolved gases round the body and maintains steep diffusion gradient.

In Earthworms (Lumbricus terrestris), Gaseous exchange occurs through the skin. The epidermis of the skin is made up of very thin cuticle covered with mucus. Within the skin, blood capillaries bring the blood, which contains the respiratory pigment haemoglobin close to the environment. The epidermis is the main respiratory surface. The cuticles are secreted by the epidermal cells. The cuticle is thin and permeable to the respiratory gases and allows rapid diffusion of oxygen into the

blood capillaries beneath the skin and carbon dioxide out. The skin is made moist by the mucus. This is for the dissolution of the respiratory gases, creating a concentration gradient.

Note: During hot, dry periods, earthworms burrow deep into the soil and become totally inactive to avoid excessive water loss. Most earthworms emerge out the burrows in darkens (at night) to feed and reproduce so as to escape desiccation during day.

Adaptations of an earthworm for gaseous exchange:

- An earth worm has a long and cylindrical body to offer a large surface area to volume ratio, so gaseous exchange takes place over the entire body surface.
- Has looped blood capillaries in the epidermis to transport gases and maintain a steep diffusion gradient.
- The moist glandular secretions on the cuticle of the epidermis dissolve respiratory gases for faster diffusion.
- Small distance between the body surface and blood capillaries in the epidermis of skin to shorten diffusion distance for gases.
- Pumping action of the heart causes blood to be circulated and therefore dissolved gases also circulated, hence maintaining steeper diffusion gradients.
- Epidermis of the skin is permeable to allow passage of gases by diffusion.
- They are generally less active hence low metabolic rates, to reduce rate of oxygen consumption.

GASEOUS EXCHANGE IN LARGER ORGANISMS

Larger organisms are multi cellular and have smaller surface area to volume ratio than the unicellular ones. Transport of oxygen and carbon dioxide by simple diffusion become difficult. The larger animals have a high metabolic rate and so require more oxygen and produce more carbon dioxide per unit volume than the unicellular one. The surface of the bodies of many these large organisms have become toughened and impermeable to the respiratory gases. In some organisms the body may be enclosed in a shell. Most of such larger organisms have developed special gaseous exchange which involve the following,

(i) Gills and lungs.

These are compact organs in which the surface area for gaseous exchange is increased by infoldings, leaf like plates or chambers with folded linings.

(ii) The ventilation mechanism.

This moves a fresh supply of air or water over the respiratory surface maintaining a high level of oxygen and low level of carbon dioxide at the site of gaseous exchange.

(iii) An internal transport system.

This is the blood circulatory system which maintains the concentration gradient across the respiratory surface.

(iv) The presence of the respiratory pigment in the blood.

This increases its oxygen carrying capacity. The respiratory pigment haemoglobin may be in blood plasma or enclosed in specific cells. Confining the pigment in cells has some advantages,

- Within the cell, the pigment is separated from the more variable chemical environment of the plasma.
- Enclosing the haemoglobin within the red blood cells will decrease the viscosity of the blood and maintains a normal heart beat that pumps blood throughout the body.

Larger organisms or multicellular organisms can achieve efficient gaseous exchange by any of the following means,

- Possession of a well-developed gaseous exchange mechanism, respiratory organs and transport system.
- Possession of flattened shape. For example, flatworms, no part of the body is far from the surface which supplies its nutrients.
- Hollow central regions. This allows external medium to enter the space, this allows exchange to occur across both inner and outer surfaces. For example, Cnidarians.

GASEOUS EXCHANGE IN ARTHROPODS (e.g. insects)

Insects have a hard exoskeleton unsuitable for gaseous exchange and yet oxygen is not availed to tissues by a transport system. Instead, they have a system of open tubes called the tracheole system for gaseous exchange. Tracheole system allows oxygen to diffuse from outside air directly to tissues without the need for transportation by blood. This mechanism is much faster than diffusion of dissolved oxygen through the tissues and therefore allows sustenance of higher metabolic rates.

Structure of the tracheole system:

Most adult insects have two pairs of spiracles in the thorax and eight pairs in the abdomen. The spiracles are guarded by valves and hairs that prevent excessive evaporation. Hairs also trap foreign particles. The spiracles open into tracheae lined with chitin. Spiracles branch into tracheoles, which spread and penetrate all cells in the body.

The tracheoles lack the chitinous lining and they are surfaces for gaseous exchange in insects. The tracheole end has got a watery fluid which regulates the surface area for gaseous exchange.

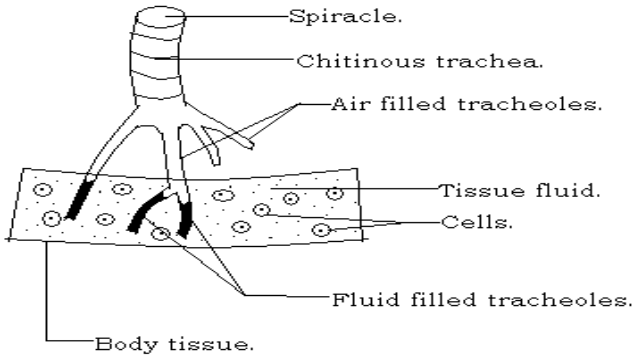
Mechanism of ventilation and gaseous exchange in insects:

- In small insects and those that are relatively inactive, air moves along the tracheal system by diffusion alone. The oxygen from the air dissolves in the moisture in the tracheoles and then diffuses into the tissues. Carbon dioxide diffuses from the tissues into the tracheoles, then diffuses out of the insect via spiracles down its concentration gradient.
- In some large and active insects, such as locusts, diffusion alone is not enough to enhance gaseous exchange. In large insects, the air has to be actively pumped by movements of the thorax and abdomen. These insects have a collapsible trachea called air sacs which are inflated and deflected by ventilation movements hence moving more air into the tracheal system.

During inspiration, abdominal muscles relax, increasing volume in the tracheal system and lowering its pressure below that of the atmosphere. This causes the thoracic spiracles to open while the abdominal spiracles remain closed. Air then enters through the thoracic spiracles into the trachea and then to the tracheoles. The oxygen from the air dissolves in the moisture in the tracheoles and then diffuses into the tissues into while carbon dioxide diffuses from the tissues into the tracheoles.

During expiration, abdominal muscles contract, reducing volume in the abdominal region and increase in its pressure above that of the atmosphere. The thoracic spiracles close while the abdominal spiracles open. Air is then expelled out of the tracheoles through the trachea and abdominal spiracles to the outside environment.

THE INSECT TRACHEAL SYSTEM.



Adaptations of insects for gaseous exchange

- Insects have numerous tracheoles to increase surface area for gaseous exchange.
- Tracheoles have thin walls to shorten the diffusion distance for gases.
- Tips of the tracheoles are in contact with tissue fluid to shorten te diffusion distance for gases.
- Walls of tracheoles are permeable to allow passage of gases.
- Insects have spiracles on the thorax and abdomen to allow passage of gases.
- Trachea are prevented from collapsing by chitin.
- Spiracles are guarded by hairs to reduce water loss.
- Valves regulate the opening of spiracles.

Control of ventilation and gaseous exchange in insects.

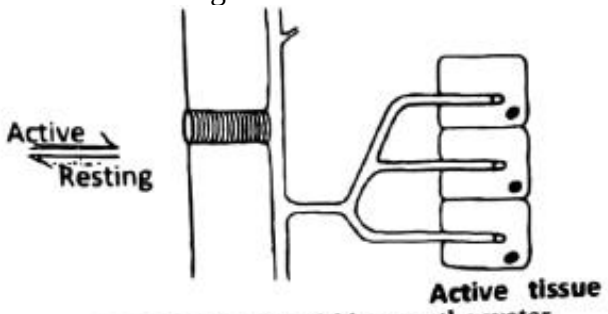
During activity (e.g., flight), lactic acid is produced due to the anaerobic muscular respiration. This increases the solute potential of the cells of the body tissues. They become hypertonic to the fluids in the tracheoles and water moves by osmosis into the body tissues resulting into further withdraw of air into the tracheoles, making more oxygen available for cellular respiration.

During inactivity, all the lactic acid is oxidized due to availability of high oxygen levels, the solute potential in the body tissues is lowered, so water moves by osmosis from the tissues to the tracheole fluids.

- Overall flow of air in and out of the insect is regulated by valve mechanism at the spiracles; and the size of spiracle aperture is adjusted according to level of carbon dioxide in the body;

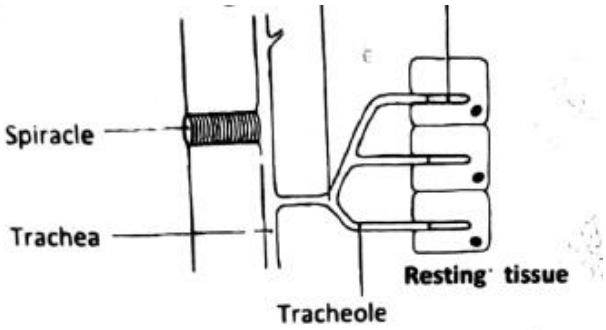
  Note:

- Since oxygen is supplied rapidly to tissues, by direct diffusion (not by blood), insects can achieve higher metabolic



Increased lactic acid lowers the water potential of the surrounding fluid; fluid withdrawn from tracheoles; air moves in to replace it

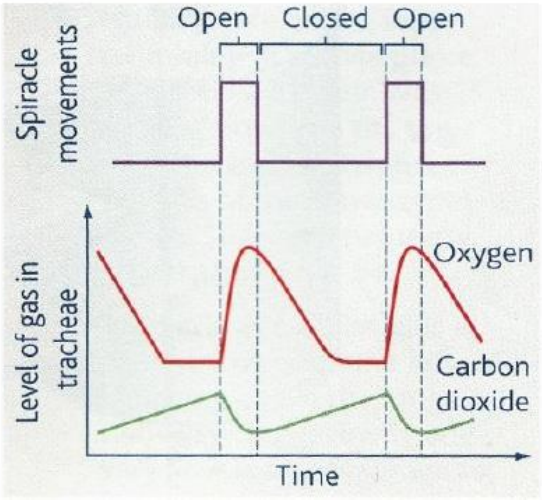
Since insects rely on diffusion to obtain oxygen, tracheal system cannot support metabolic rates of insects which are very large in size.



Fluids of a higher potential surround the Tracheole; fluids diffuse into tracheole.

TYPICAL EXAMINATION QUESTION:

1. The figure below shows results of an experiment to measure the levels of oxygen and carbon dioxide in the tracheal system of an insect over a period of time. During the experiment, the opening and closing of the insect's spiracles was observed and recorded.



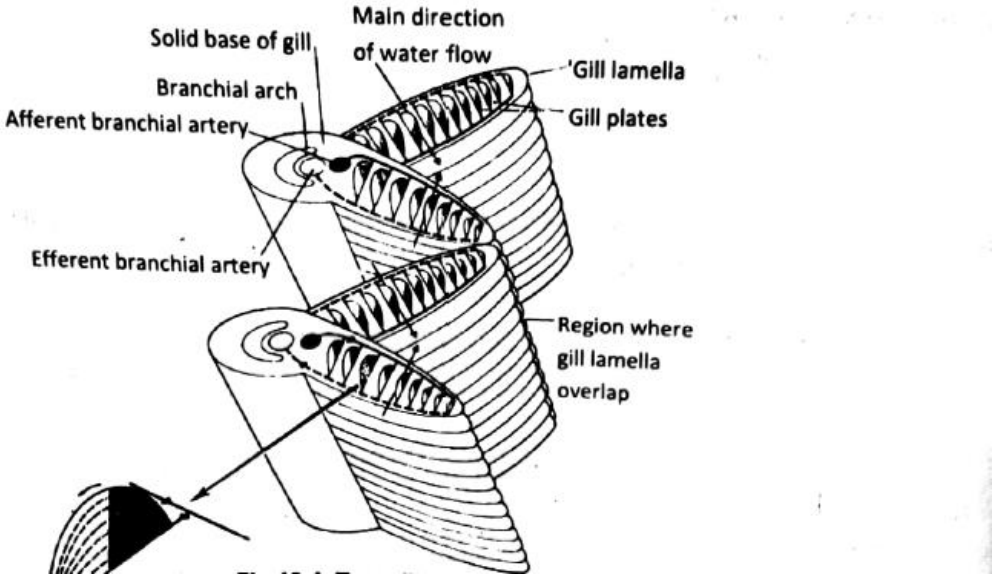
a) Describe the pattern of level of gases in tracheae in relation to spiracle movements.
b) Explain the pattern of level of gases in tracheae in relation to spiracle movements.
c) (i) From the information provided by the graph suggest what causes the spiracles to open
(ii) What is the advantage of the observed spiracle movements to a terrestrial insect?
d) Fossil insects have been discovered that are larger than insects that occur on earth today. What does this suggest about the composition of the atmosphere at the time when these fossil insects lived?

GASEOUS EXCHANGE IN FISH

Fish use water as a medium of gaseous exchange. Fish rely on specialized flaps of tissue called gills foe gaseous exchange. The efficient gaseous exchange system of fish allows them to live very active lives and colonise all types of water.

Note. Water is denser than air, so it offers support to the gills, maintaining the large surface area for gaseous exchange. When fish is pulled out of water the gills collapse and lie on top of each other, decreasing surface area for gaseous exchange, so fish suffocate and dies.
Fish possesses gill slits in the wall of the pharyngeal region of the gut (region between the buccal cavity and the gut). These connect with the eternal environment (water). The tissue between the slits forms the supports known as brachial arches or gill arches. In a bony fish there are four pairs of gill arches separating five pairs is gill slits.

GASEOUS EXCHANGE IN BONY FISH (*e.g trout, cod, herring*):

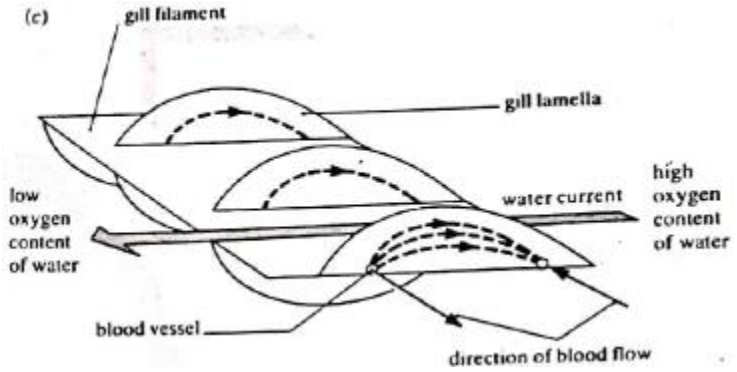


In a bony fish the delicate gills are located in a cavity called opercular cavity, which is covered by a muscular flap of tissue (operculum) which protects the gills and also lays a role in ventilation ***(provides fish with opercular suction pump and buccal pressure pump).*** This can maintain an almost continuous flow at water across gills.

Structure of a gill of bony fish. Bony fish has four pairs of gills, each supported by a bony gill arch. The gills consist of two row of gill filaments, arranged in a V-shape.

Each filament bears numerous **gill lamellae,** composed of thin-walled **gill plates.**
blood in the gill plates flows in a direction opposite to that in which water is flowing **(counter current exchange mechanism),** so that water always has a higher oxygen content that the blood it is flowing past. Diffusion of gases can therefore occur over the whole surface of the lamellae.

Note: Deoxygenated blood enters the gill capillaries via the afferent branchial artery. Oxygenated blood leaves in the efferent branchial artery to join dorsal aorta along which blood passes to the rest of the body.
The figure below shows one part of the gill filament of bony fish showing the lamellae which increase surface area.



Mechanism of ventilation in a bony fish:
Ventilation of fish is an active mechanism in which a fish draws in and out water over the gills.

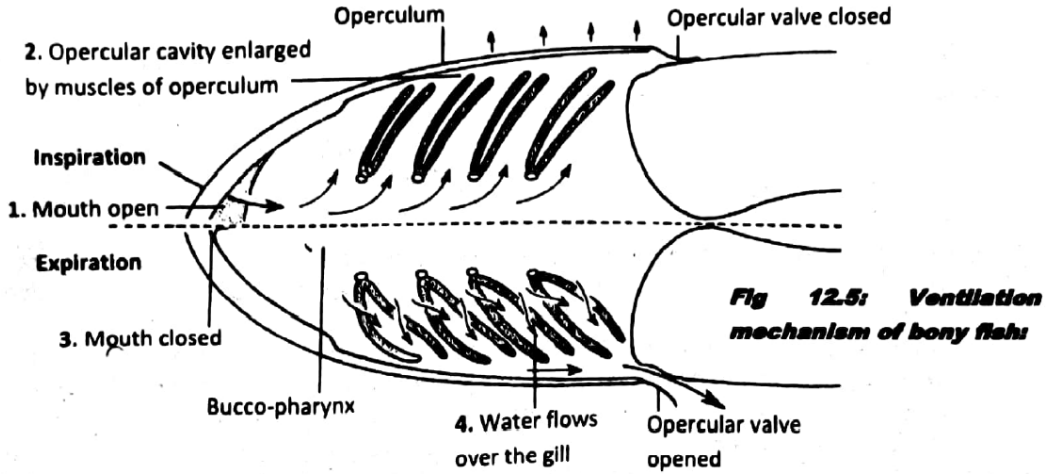
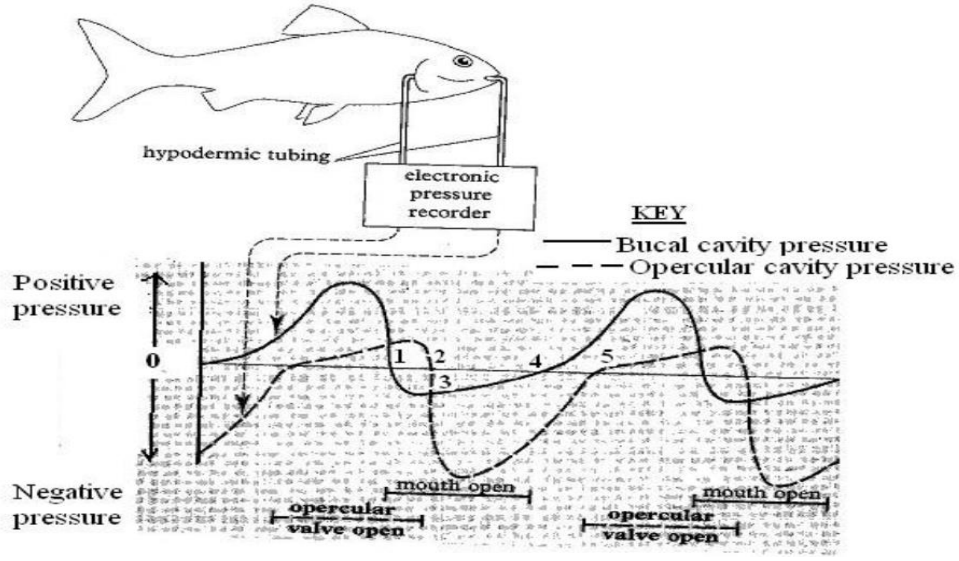


Fig 12.5: Ventilation mechanism of bony fish

- **During inspiration, the floor of the bucco-pharynx cavity is lowered, and the mouth opens.** This causes expansion of the bucco-pharynx cavity and its pressure falls below that of the surrounding water, so water flows into the buccal cavity via the opened mouth. At the same time, the outside water pressure presses the posterior end of the operculum shut, preventing entry of water from this region. Muscles of the opercular cavity then contract, causing the opercular cavity to be enlarged. Therefore, pressure in opercular cavity falls below that in buccal cavity, hence water is drawn from the buccal cavity, by opercular suction pump, over the gills in the opercular cavity. Therefore, gaseous exchange is allowed to continue even when the fish is taking in fresh supply of water.

- **During expiration,** the mouth of the oesophagus closes, and the floor of the bucco-pharynx cavity is raised. The buccal pressure pump forces water over the gills, through the gill slits, and into the opercular cavity where the increased pressure forces open the posterior end of operculum. Water therefore leaves to the outside environment via the opened opercular valves.

Pressure changes in the buccal cavity and opercular cavities during the breathing in a bony fish:



Explanation of pressure changes in the buccal cavity and opercular cavity:

At 1, Buccal cavity expands, the pressure reduces and falls below atmospheric pressure (**acquires negative pressure);** mouth valve opens and water enters from outside.

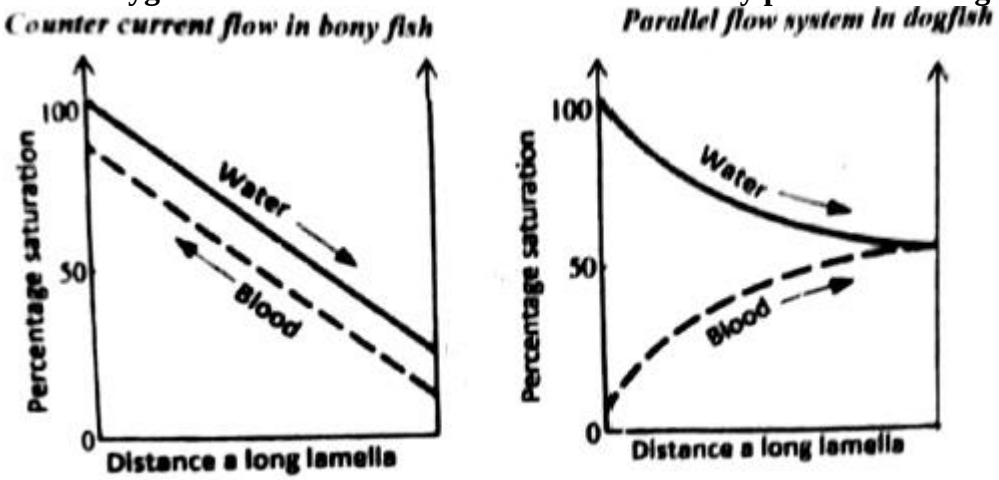
At 2, Opercular cavity expands, pressure reduces below atmospheric pressure (acquires negative pressure), opercular valve closes.

At 3, buccal cavity begins to contract, volume gradually decreases as pressure gradually increases while expansion of opercular cavity increases the volume further as pressure decreases further to fall below buccal cavity pressure, resulting in water being sucked into opercular cavity from buccal cavity.

At 4, Buccal cavity pressure increases above atmospheric pressure (acquires positive pressure); mouth valve closes and water flows along the pressure gradient from the buccal cavity to the opercular cavity.

At 5, Opercular cavity contracts, decreasing the volume as pressure increases above atmospheric pressure **(acquires positive pressure)** opercular valve opens and water is expelled.

Variation in oxygen concentration of blood and water as they pass across the gill lamellae:



Counter current system in gaseous exchange of a bony fish:

In counter current flow system, water flowing from the pharynx into the opercular chambers flows between the gill plates in a direction opposite to that of blood flow. This is due to the arrangement of gills within the lamellae being at right angles to each other. This is called counter-current system, and is more efficient than parallel current system in cartilaginous fish, in which water and blood flow in the same direction.

A counter current system ensures that blood constantly meets water with higher concentration of dissolved oxygen in it, and that a diffusion gradient will be maintained between blood and water throughout the entire length of the filament and across each lamellae. In this way, bony fish are able to extract 80 to 90% of oxygen from water.

The overlapping ends of gill filaments provide resistance to water flow, this slows down the passage of water over the gill lamellae, thus increasing the time available for gaseous exchange by diffusion to take place.

Note: the coordinated activity of the buccal cavity and opercular cavity ensures a continuous unidirectional flow of water over gills for most of the time. This maintains a high concentration of oxygen near the gills and a lower concentration of carbon dioxide.

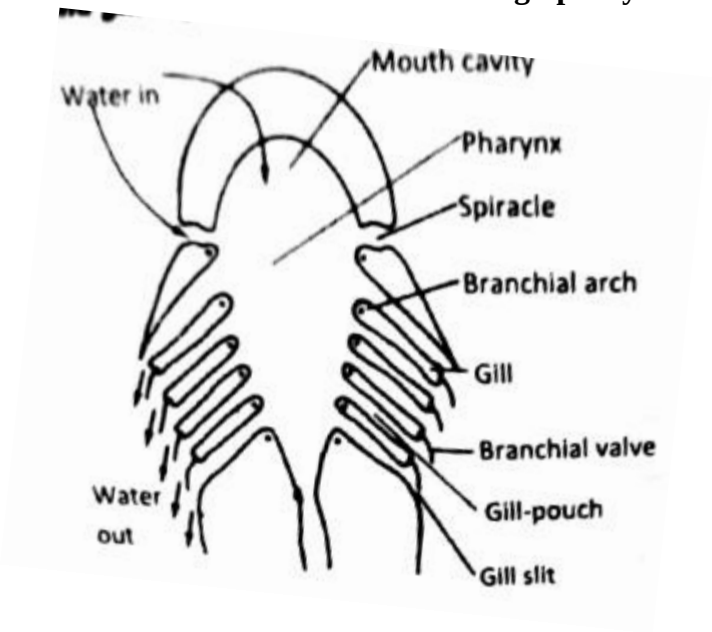
GASEOUS EXCHANGE IN CARTILAGINOUS FISH *(e.g dog fish, sharks, rays):*

In cartilaginous fish, five gill pouches connect the pharynx with the exterior on each side of the of the body. The gills are located between successive pouches

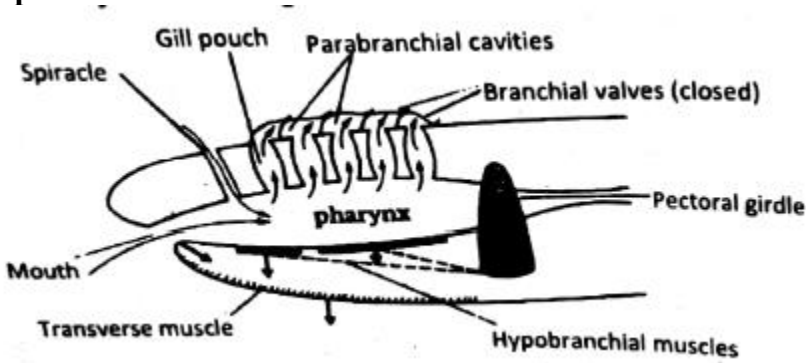
Each gill of dogfish is composed of about 70 **leaf-like lamellae** which project horizontally from a skeletal arch oriented vertically in the wall in the wall of the pharynx.

The lamellae are supported down the centre and are held in position by a vertical septum which project beyond the distal end of the gill as the **branchial valve.**

Vertical section through pharynx and gill region of dogfish:



Inspiration.



- During inspiration, the pharyngeal cavity expands due to lowering the floor of the mouth cavity and pharynx, brought about by contraction of the hypobranchial muscles accompanied by relaxation of transverse muscle. This causes water to be drawn into the pharynx via the mouth and spiracles. Water is then drawn into parabranchial cavities by outward movement of branchial valves.

Expiration

- During expiration, water is expelled out from the gill pouches by raising the floor of the mouth cavity and the pharynx, brought about by the relaxation of the hypobranchial muscles

accompanied by the contraction of the transverse muscles. As water is being passed out of the gill pouches it passes over the respiratory epithelium.

Note: Filling of the pharyngeal cavities with water is what starts expiration, and the spiracles are closed. The spiracles are lined with sensory epithelium which testes incoming water. If undesirable, the water is expelled, and the fish moves elsewhere.

Parallel flow and gaseous exchange in of cartilaginous fish:

In this system, blood and water move in the same direction and at the same speed. When blood water first meet, the concentration gradient of oxygen between them will be great. However, as blood and water flow along together, the concentration gradient decreases. On leaving the respiratory surface, blood will be in equilibrium with the water at a point well below its maximum saturation with oxygen. Parallel flow is therefore not efficient as counter current flow i.e it extracts about 50% of oxygen from the water.

Note:

(i) Some animals have improved parallel flow, by evolving very rapid flow of water compared with that of the blood. This ensures a higher saturation of the blood by the time it leaves the respiratory surface.

(ii) In a dogfish, it is probably true that to some extent water flows between the gill plates in a direction opposite to that blood, but a really efficient counter current flow is prevented by:

- The main flow of water being parallel to the lamellae
- The vertical septum which deflects the water so that it tends to pass over rather between the gill plates.

Adaptations of gill filaments for gaseous exchange

- The filaments are moist for dissolution of respiratory gases
- The filaments have a rich blood supply to transport the respiratory gases, maintaining a steeper concentration gradient.
- Possession of many gill lamellae to increase on surface area for gaseous exchange.
- Numerous gill plates on the lamellae further increase the surface area for the gills.
- Gill plates are thin to reduce to reduce the diffusion distance for respiratory gases.
- Possession of the gill arch that orients the gill filaments in such a suitable position for efficient gaseous exchange.
- Gill lamellae are permeable to allow passage of gases.by diffusion.

Comparison between gaseous exchange mechanism in bony fish (teleosts) and cartilaginous fish (elasmobranch)

Similarities:

- In both, water is the respiratory medium;
- Gills are the gas exchange organs;
- Respiratory surfaces are gill filaments;
- Water enters via te mouth during inspiration;
- There is a ventilation mechanism that ensures continuous flow of medium over gills.

Differences:

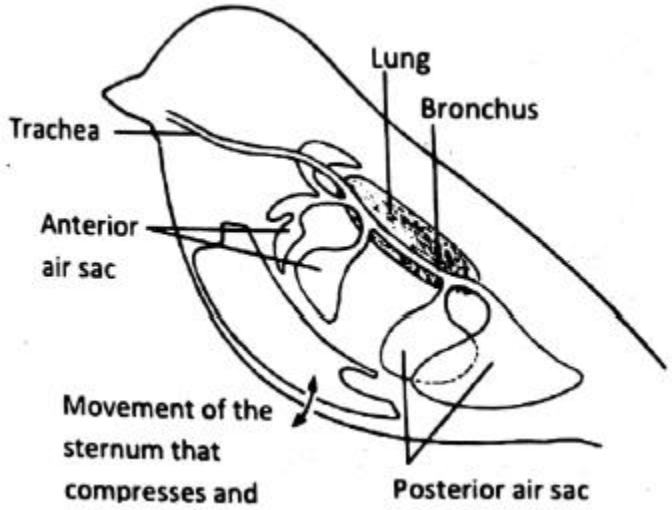
Cartilaginous fish	**Bony fish**
Ventilation is by adjustment of the buccal cavity and pharynx;	Ventilation is by adjustment in the buccal cavity, pharynx and opercular cavity;
During inspiration, water enters via the spiracles and mouth;	During inspiration, water enters via the mouth only;
During expiration, water exits via the gill slits;	Water exits via the opercular openings;
Opening of the gill slits is regulated by the branchial valves;	Opercular openings are regulated by opercular valves;
Employs parallel flow mechanism.	Employs the counter current mechanism.

GASEOUS EXCHANGE IN BIRDS:

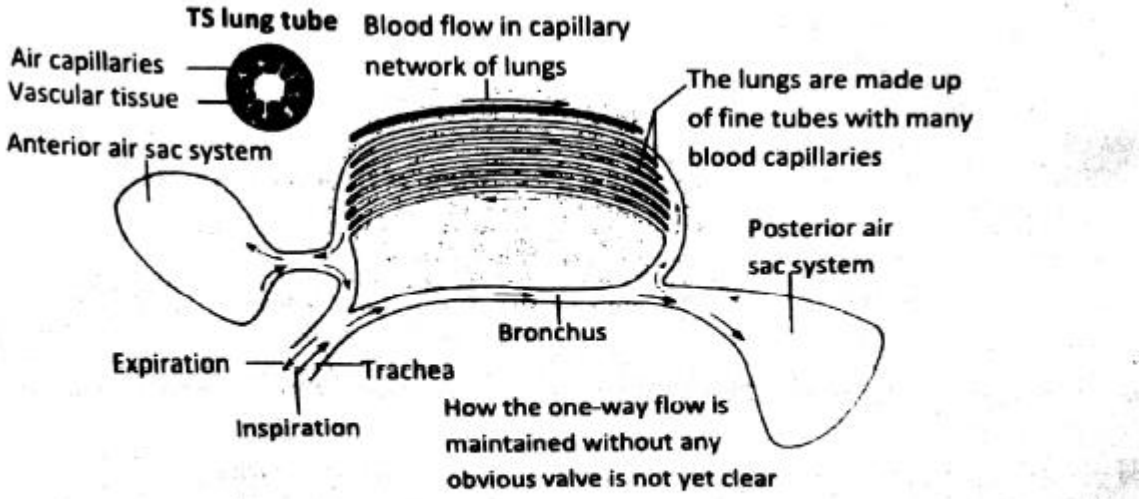
Birds need an efficient gaseous exchange system in order to cope up with their high metabolic rates needed to maintain a constant body temperature and to supply energy for their active life style. Including flapping the wings. The respiratory system of birds is a unique system of air sacs and lungs. The lungs consist of fine, highly branched tubes, open at both ends. Here air is continuously ventilated, in a one-way flow, from the extensive system of air sacs to the exterior; virtually no residual gas remains in te lung tubes.

Position of the lungs and air sacs in the body of a bird:

The position of the lungs ad air sacs:



How lungs and air sacs function.



- During inhalation, all the air is sacs fill with air, the posterior ones with fresh air and the anterior ones with air from the lungs.
- During exhalation, the air flows out of the air sacs; it flows from the posterior sacs to the lungs, and from the anterior sacs to the exterior via the bronchus,
- Ventilation of air sacs is driven by contraction and relaxation of intercostal and abdominal muscles. During vigorous flight contraction of the pectoral muscles enhance ventilation.

GASEOUS EXCHANGE IN AMPBIANS (e.g. frogs, toads etc.)

Tadpoles use external gills for gaseous exchange. External gills usually have a large surface area but they are less protected, hence prone to damage.

Mature amphibians employ the following respiratory surfaces;

- Epithelium lining of the skin (cutaneous respiration)
- Epithelial lining of the buccal cavity (buccal respiration)
- Inner alveolar membranes in the lungs (pulmonary respiration)

All the above three respiratory surfaces are highly vascularised, thin, permeable, present a large surface area and are moist to facilitate gaseous exchange.

Being thin and moist, amphibian's skin offer resistance to evaporation caused by high temperature on land. This explain why amphibians are generally restricted to damp habitat.

GASEOUS EXCHANGE IN MAMMALS (e.g man)

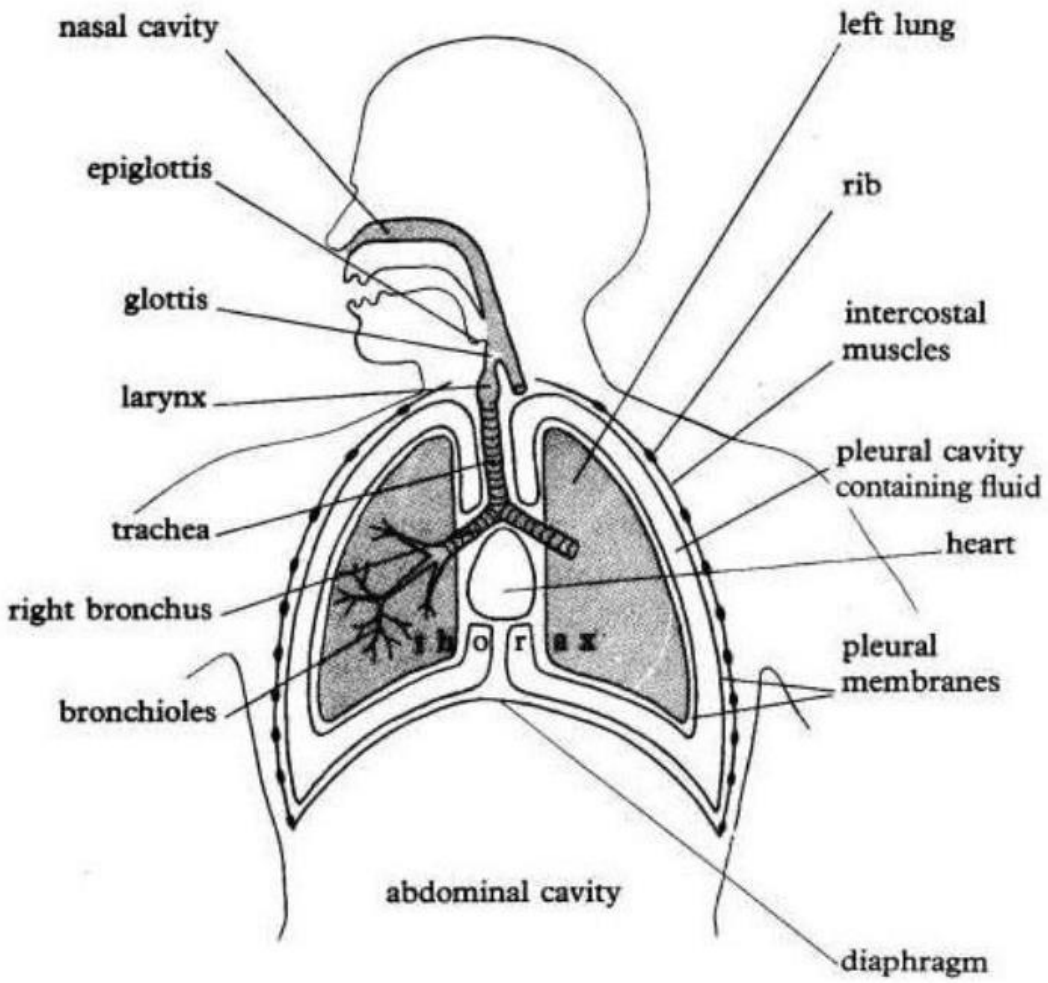
Mammals are mainly terrestrial organisms, so their respiratory medium is air and the respiratory organ is the lung, with alveoli as the respiratory surfaces. **Lungs** are delicate structures and, together with the **heart,** are enclosed in a ribcage for protection. There are twelve pairs of ribs in humans, all attached dorsally to the thoracic vertebrae. The anterior ten pairs are attached ventrally to the sternum. The remaining ribs are said to be floating. The ribs are moved by series of **intercoastal muscles**. The thorax is separated from the abdomen by a muscular sheet, called **diaphragm.**

Air flow in lungs of mammals is tidal, air entering and leaving along the same route.
Using lungs as respiratory organs has some challenges, which include the following,

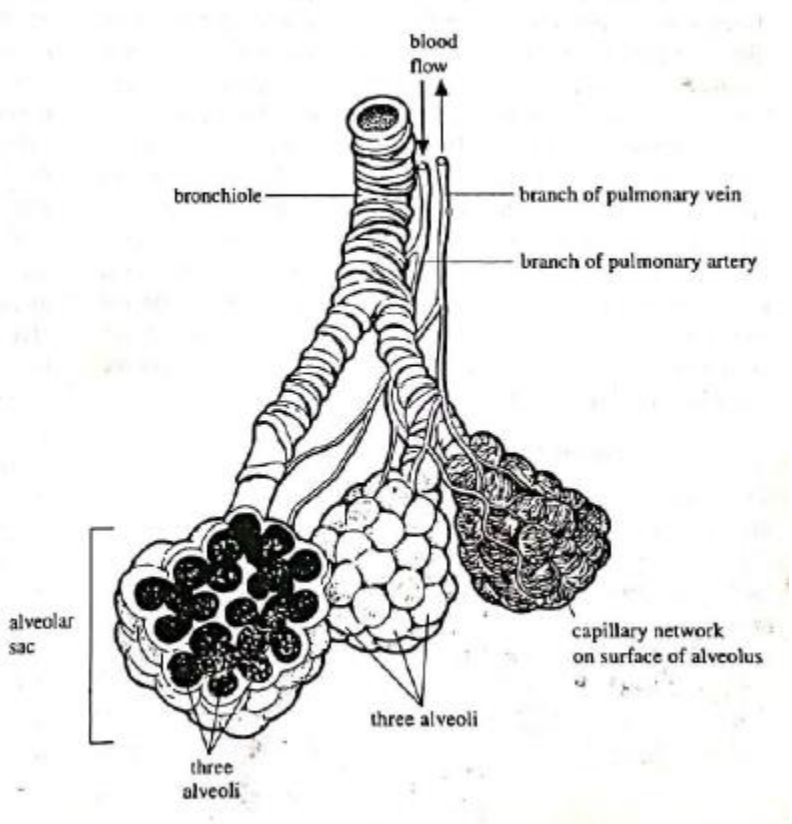
- Being deep inside the thorax of the body, lungs need an efficient ventilation.
- Water loss by evaporation from the moist alveoli surfaces in hot temperatures of land.

Note that because mammals can regulate their breathing rate, there is some control over water loss from their lungs.

Structure of man's respiratory system with its associated a structure:



Human bronchioles and alveoli of the lungs



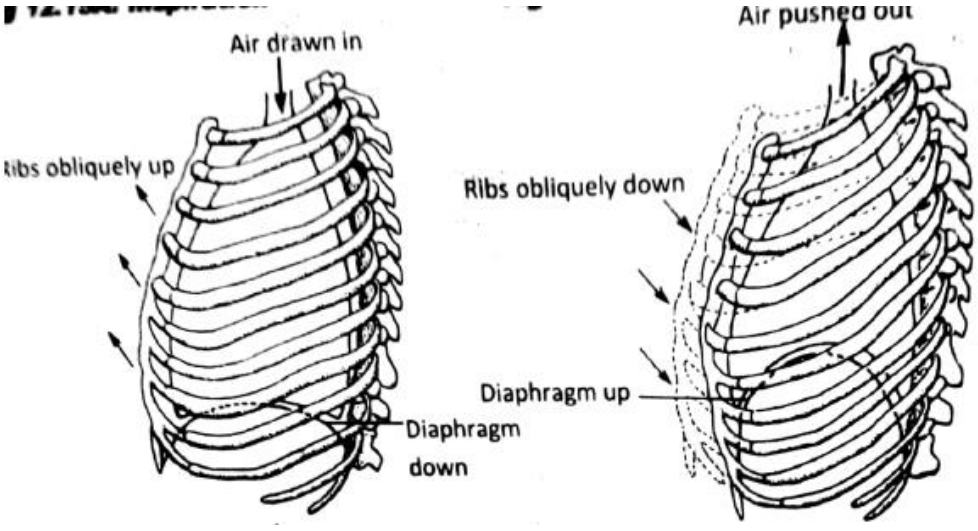
- The nasal and buccal cavities leads to the pharynx, a tube that conducts both food and air.
- The **larynx** is a box-shaped structure just above the trachea. The flow of air in and out of the respiratory system makes the vocal cords (folds of mucous membrane) to expand and vibrate, producing sounds. The sound is varied by changing the position of tension of the cords.
- Air passes through the larynx into the **trachea.** This single tube forms the major airway. The walls of the trachea are strengthened and held by horizontally arranged C-shaped bands of cartilage. Without cartilage bands, the trachea would collapse during breathing out. The trachea are lined with mucous membrane containing **ciliated epithelium.**
- At its lower end, the **trachea** splits into two **bronchi,** where each bronchus is subdivided into numerous much smaller tubes called **bronchioles**. Theses branch into finer and finer tubes, ending with the **alveolar ducts** which lead into sacs called **alveolar sacs.** Into each alveolar sac opens a group of **alveoli.**
- All parts of the respiratory pathway contain smooth muscles and connective tissue with elastic fibres and collagen.
- Trachea, bronchi and bronchioles contain smooth muscle which allows them to constrict. Small bronchioles can constrict completely because they lack cartilage. Smaller bronchioles have *flattened* **cuboidal epithelial cells.** Some gaseous exchange takes place through these.
- Trachea, bronchi and bronchioles have cartilage and goblet cells. Though cartilage is gradually lost bronchioles, especially smaller bronchioles, making them to collapse quite easily. From alveolar ducts to alveoli, there are no cartilage bands, cilia and goblet cells.

Adaptation of the human respiratory system:

- Lungs are elastic to stretch and accommodate more air.
- Lungs have numerous alveoli to increase surface area for gaseous exchange.
- External and internal intercostal muscles contract and relax antagonistically to adjust the volume of the thoracic cavity during ventilation of the lungs.
- Pleural membranes (pleura) protect the lungs, stop them from leaking air into the thoracic cavity and reduce friction between the lungs and the wall of the thorax.
- Pleural membranes secrete the fluid in the pleural cavity for lubricating the pleura, and reduce friction as membranes rub against each other during breathing movements.
- C-shaped cartilage bands prevent the trachea from collapsing when the pressure inside falls.
- The gaps in the cartilage rings allow trachea to be flexible so that food can pass through the oesophagus which runs behind the trachea.
- Smaller bronchioles contain smooth muscles and lack cartilage to allow them constrict completely.
- Nostrils have hairs that trap and filter out dust particles and bacteria from incoming air stream.
- Nasal channels secrete mucus from goblet cells in their ciliated epithelia; mucus traps dust particles.
- The beating of the cilia in the trachea, bronchi and bronchioles, carries the dust and bacteria trapped by mucus to the buccal cavity, where they are swallowed.
- The flap of tissue **(epiglottis)** closes over the **glottis** during swallowing of food. This is a reflex action that prevents food from going into the **trachea** (wind pipe).

VENTILATION (BREATHING) MECHANISM IN MAN:

Inspiration **Expiration**



Inspiration (breathing in). This an active process:

- The external intercostal muscle contract and the internal muscle relax;
- This raises the ribcage upwards and outwards;
- At the same time, the diaphragm muscle contract, and this flattens the diaphragm;
- The volume of the thoracic cavity increases, causing a decrease in pressure, and hence the pressure of the lungs is reduced to less than the atmospheric pressure;
- Air therefore enters the lungs, inflating the alveoli, until the air pressure in the lungs is equal to that of the atmosphere.

Expiration (breathing out). This is a passive process:

- The external intercostal muscles relax and the internal intercostal muscles contracts. The ribcage drops mainly due to its weight;
- At the sane time, the diaphragm muscles relax. The dropping ribcage forces the diaphragm a dome shape, pulling it up into the thoracic cavity;
- These events reduce the volume of the thorax and raise its pressure above that of the atmosphere
- Consequently, air is forced out of the lungs.

Note:

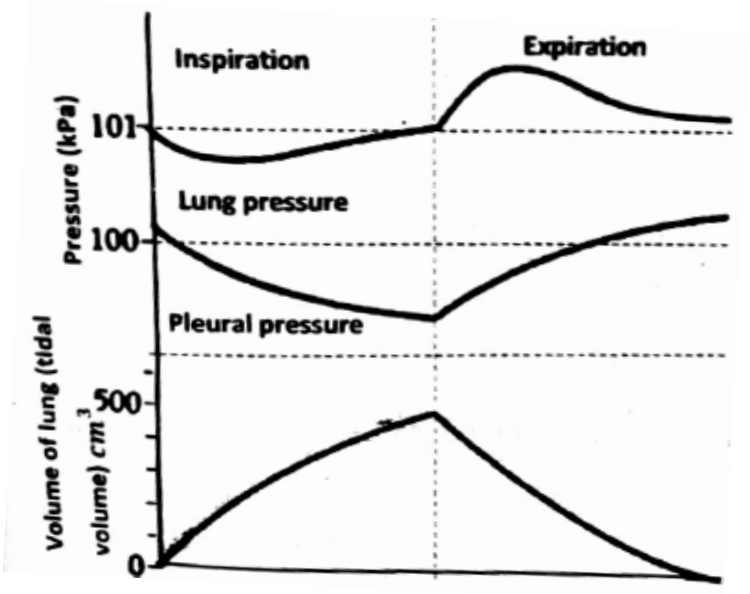
(i) Pleural cavity is air-tight and its pressure stays at 3 to 4 mmHg lower than that of the lungs. This negative pressure is maintained during inspiration and allows the alveoli to inflate and hence fill any extra available space provided by the expanding thorax.

(ii) Air enters human pathway either through the nose or the mouth. Air entering via the nasal cavity is filtered by hairs in the nasal passages, warmed by contact with the tissues in the nasal cavity. Mucous membrane line much of the air pathway, and contain goblet cells, which secrete mucus, a slimy material rich in glycoproteins. If any irritating substance is breathed in, they can stimulate a sneeze.
Air entering the respiratory system via the buccal cavity through the mouth is not warmed and moistened as air passing through the nose, and is not filled at all.

(iii) Inhalation requires considerable work. The active contraction of the external intercostal muscles and the diaphragm muscles has to provide enough force to overcome a series of resistances. These include:

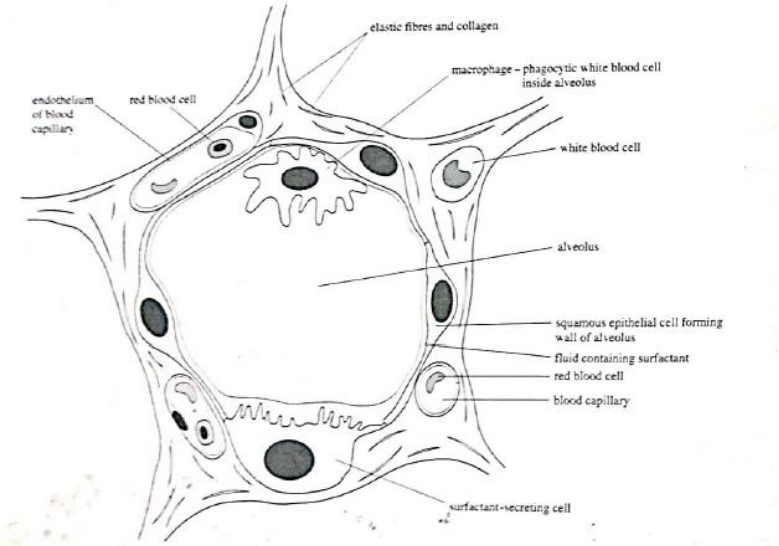
- The elastic recoil of the tissue of the lungs and thorax (their resistance to being stretch)
- The friction resistance of air as it passes through the hundreds of thousands of small bronchioles leading into alveoli;
- The resistance created by surface tension at the fluid-gas interface in the alveoli.

(iv) During forced breathing, for example during exercise, expiration becomes more active; the internal intercostal muscles contract more strongly and move the ribs vigorously downwards. The abdominal muscles also contract strongly, causing more active upward movement of the diaphragm. This also happens when sneezing or coughing.



At rest, the pressure in the lungs is atmospheric pressure i.e pressure gradient is zero. But because the lungs are elastic and tend to pull away from the wall of the thorax, the pressure in the pleural cavity is slightly less than atmospheric pressure.
During inspiration, when the walls and the floor of the thorax are moving outwards and downwards respectively, the pleural pressure falls. This has the immediate effect of lowering the lung pressure to below atmospheric, so that air rushes into the lungs. This increases their volume ands returns the lung pressure to atmospheric pressure.
On expiration, the pressure of the thoracic wall and diaphragm against the pleural cavity raises the pleural pressure. This is transmitted to the lungs whose pressure therefore increases and volume decreases as air is expelled.

Alveolar structure an gaseous exchange.



Adaptations of the alveolus

(i) Has a good blood supply, accompanied with presence of haemoglobin, to transport respiratory gases and maintain steep diffusion gradient.

(ii) The alveolus possesses squamous epithelial cells that are flattened to shorten distance for diffusion of gases, and to also increase surface area for diffusion.

(iii) Possession of the permeable epithelium to allow passage of gases.

(iv) Breathing movements constantly ventilate the alveolus, and the action of the heart constantly circulates blood around the alveolus; these together maintain steep diffusion gradients for gases.

(v) Possession of the moist epithelium to dissolve respiratory gases.

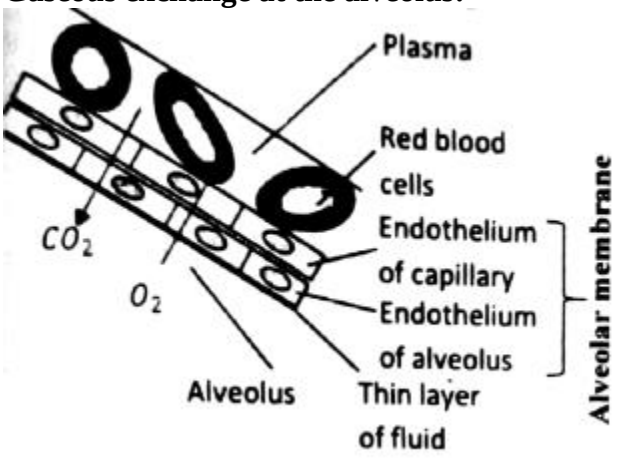
(vi) Elastic fibres allow the alveolus to expand and recoil easily during breathing.

(vii) Phagocytic macrophages destroy foreign materials drawn into the lungs during inspiration.

(viii) Surfactant cells (special epithelial cells) secrete a s**urfactant** on the inside lining of the alveolus, which serves the following roles:

- Reduces surface tension of the fluid layer thereby reducing the effort needed to breath in and inflate the lungs.
- It speeds up transport of oxygen and carbon dioxide between the air and moisture lining of the alveolus.
- Kills bacteria that reaches the alveolus.

Gaseous exchange at the alveolus:



The oxygen in inspired air dissolves in the moisture of alveolar epithelium and diffuses across this and the endothelium of the capillary into the erythrocytes. Inside the red blood cells, the oxygen combines with haemoglobin to form **oxyhaemoglobin.** Carbon dioxide diffuses from blood capillaries, down its concentration gradient into the alveolus to leave the lungs in expired air.

Note:

(i) The alveolar epithelium is covered with a very thin layer of fluid in which oxygen dissolves before it diffuses through the cells. If this fluid had a normal surface tension it would pull the alveolar walls inwards, making it difficult to expand the lungs and possibly causing the alveoli to collapse. However, the fluid contains a

surfactant, a detergent-like, which reduces the surface tension and prevents this from happening.

(ii) In passing from the alveolus to haemoglobin, a molecule of oxygen diffuses five times across cell membranes i.e., into the epithelial cell lining of the alveolus, out of this cell, and into red blood cell.

(iii) The diameter of red blood cell is larger than that of its capillary. This relationship has the following significance:

- The red blood cell has to just squeeze through the capillary which distorts its shape, hence exposing a large surface area for diffusion of oxygen and carbon dioxide.
- Increases contact with the endothelium, shortening diffusion distance for gases
- The movement of red blood cells, and blood itself also slows down hence allowing ample time for maximum diffusion of oxygen.

Composition of inspired (atmospheric), alveolar and expired air of a resting person:

GAS	**PERCENTAGE BY VOLUME**		
	Inspired air	**Alveolar air**	**Expired air**
Oxygen	20.90	13.90	15.30
Nitrogen	78.60	No available data	74.90
Carbondioxide	0.03	4.90	3.60
Water vapour	0.47 (usually varies)	No available data	6.20 (saturated)

From the above table:

Observations	**Explanations**
Inspired air contains a higher percentage volume of oxygen than exhaled air	*Inspired air is rich in oxygen released by plants during* *photosynthesis. On entering the alveoli, some of the oxygen* *diffuses into blood capillaries along a diffusion gradient for* *use in respiration*
Exhaled air contains a higher percentage volume of carbon dioxide (120 times) than inhaled air	*Tissue respiration forms carbon dioxide some of which* *diffuses into alveolar air and expelled during exhalation*
Exhaled air contains a lower percentage volume of water vapour than inhaled air	*Tissue respiration forms water some of which diffuses into* *alveolar air and is expelled during exhalation*
The percentage volume of nitrogen in expired air is higher than in inspired air	*Although nitrogen is not used in respiration, its percentage* *in air during gas exchange changes because of the increased partial pressure of carbon dioxide and water* *vapour*

The percentage volume of oxygen in expired air is intermediate between the inspired and alveolar values	*Some oxygen in inspired air is absorbed into the blood stream in the alveolar thus alveolar air contains less oxygen than inspired air.* *During transit, some air does not reach the respiratory surface in the alveoli. It is trapped in the respiratory air ways (inspired) air.* *The air expelled from the alveoli mixes with the air in the dead spaces, this increases the oxygen content in expired air to a value above alveolar air though less than atmospheric (inspired) air.*

Note:

(i) Blood leaving the lungs has a similar composition of oxygen and carbon dioxide as alveolar air.

(ii) The process of gaseous exchange in the lungs is not as efficient as it sems because:

- Some alveoli are inevitably under-ventilated:
- A proportion of blood that goes to the lungs does not go through any alveolar capillaries and therefore never gets oxygenated. The result is that blood leaving the lungs is not as fully oxygenated as it might be.
- Expired air still contains quite a high proportion of oxygen, enough to save someone's life by **mouth-to-mouth resuscitation.**

Effect of exercise on gaseous exchange:

- Ventilation rate (depth and rate of inspiration) increase from 15 to 45 at the peak of the exercise, to supply more oxygen for muscular contraction.
- Air increased at each breath increases from $0.45dm^3$ at rest to a maximum of $3.5dm^3$ during exercise.
- Expiration is accelerated due to forceful contraction of both intercostal and abdominal muscles, pulling the ribs inwards and the diaphragm upwards. This results into much more expulsion of air.
- Dilation of bronchioles increases the flow of air down to the alveoli:
- Adrenaline dilates arterioles that supply the capillary network around alveoli. This improves blood flow to the lungs and increases the rate of oxygen uptake.

Short-term and long-term effects of smoking on mammalian gas exchange of a mammal:
Short-term effects include:

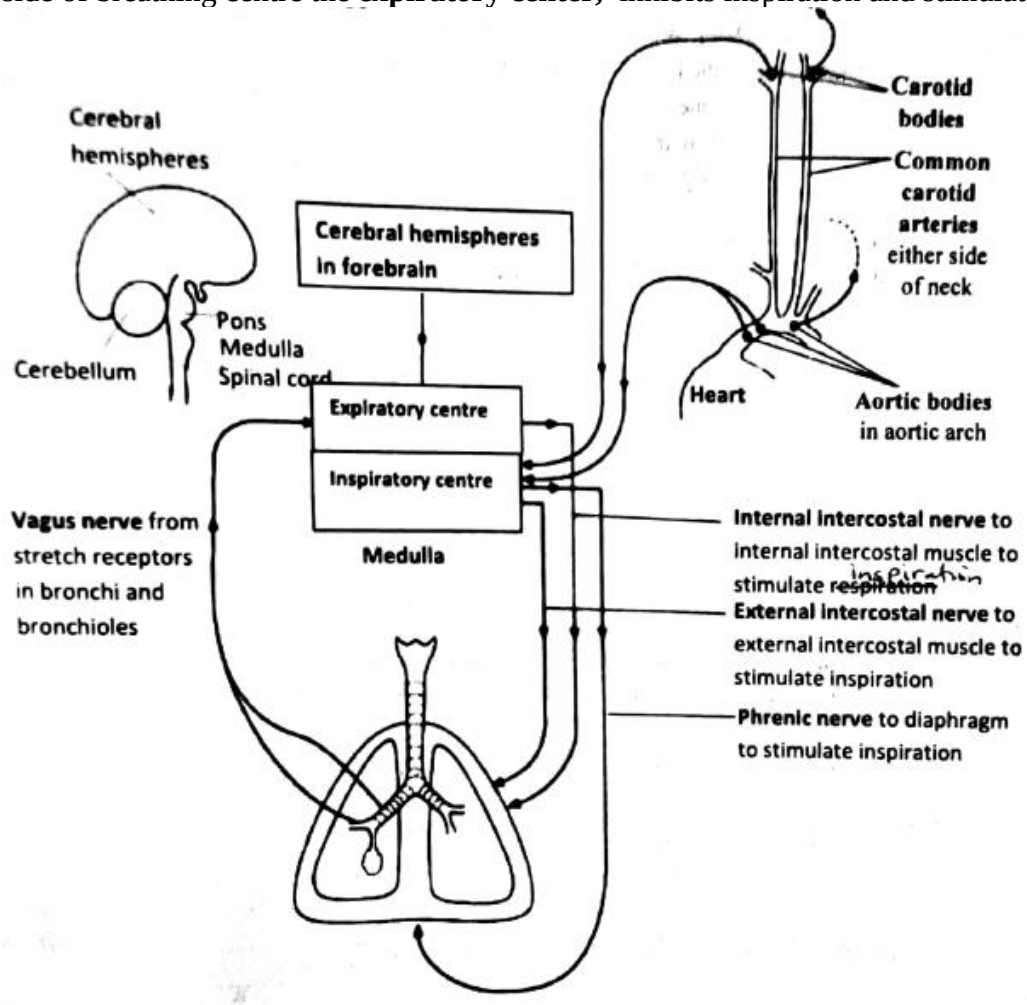
- Releases nicotine that constricts finer bronchioles, increasing resistance to air flow.
- Nicotine may also paralyse cilia such that dirt and bacteria are not eliminated, that accumulate in air passages and restrict air flow.
- Smoke is an irritant, causing secretion of excess mucus from goblet cells that accumulates in airways making it difficult for air to pass through them.
- Carbon monoxide combines permanently with haemoglobin to form **carboxyhaemoglobin,** lowering the ability of blood to transport oxygen from the lungs.

The long-term effects include:

- Cigarette smoke causes emphysema/ gradual breakdown of elastic tissue in alveoli, decreasing surface area for gaseous exchange.
- Chronic bronchitis
- Tars in cigarette contain carcinogens that cause lung cancer.
- Tars may also reduce permeability of alveoli.

Control ventilation in man:

Involuntary/autonomic/reflex control of breathing is carried out by a **breathing centre (respiratory centre)** located in the **medulla oblongata** of the hindbrain. The lower part of the breathing centre, the **inspiratory center,** increases rate and depth of inspiration. While the top side of breathing centre the **expiratory center,** inhibits inspiration and stimulates expiration.



Ventilation in mammals is controlled by the respiratory(breathing) centre in the medulla oblongata; These are Inspiratory center which controls breathing in and expiratory center which controls breathing out.The ventilation movement is initiated by a rise in carbon dioxide levels in blood(low pH) detected by the chemoreceptors in the aortic bodies, carotid bodies. When the level of carbon dioxide is high in blood is high due to increased metabolic activities in the body, the chemoreceptors are stimulated and efferent nerves relay impulses to the inspiratory center which is stimulated to relay impulses along the Phrenic and intercostal nerves to the diaphragm and the intercostal muscles. The impulses cause the internal

intercostal muscles and diaphragm muscles to contract and cause faster inspiration. The lungs become inflated and expand, **stretch receptors (proprioceptors)** in their walls are stimulated and send impulses which pass along the **vagus** nerves to the expiratory center in the medulla. This automatically switches off the inspiratory centre while the expiratory centre is switched on. The external intercostal and diaphragm muscles therefore relax and the elastic recoil of lung tissues occurs. Stimulation of stretch receptors ceases and this causes the expiratory center to switch off and inspiratory centre switched on. The series of events are then repeated.

- Control of breathing depth can occur voluntarily e.g during; speech, forced breathing, singing, sneezing and coughing. When such control is being exerted, impulses originating from cerebral hemispheres pass to the breathing centre in medulla oblongata.
- Control of breathing rate can be increased by increase in levels of adrenaline or thyroxine hormone.

Note:

(i) Inspiratory and expiratory centers are responsible for the basic rhythm of breathing movements. If the phrenic and intercostal muscles are cut, breathing stops immediately.

(ii) At high altitude, the reduced atmospheric pressure makes it more difficult to load the haemoglobin with oxygen. In an attempt to obtain sufficient oxygen, a mountaineer takes very deep breaths. This forces more carbon dioxide out of the body and the level of caron dioxide in blood therefore falls. The inspiratory center is no longer stimulated, and breathing becomes increasingly labored, causing greater fatigue. Given time, the body can adapt to these conditions by excreting more alkali urine. The causes the pH of blood to fall, the chemo receptors are stimulated and so is the inspiratory center.

Breathing cycle and the lung capacity and volumes:

A person breathing normally at rest, takes in and expels, appropriately a half a liter during each respiratory cycle. This is known as tidal volume, and it can be measured by means of a recording **spirometer.**

The rate of respiration can be expressed in terms of **ventilation rate** (volume of air breathed per minute).

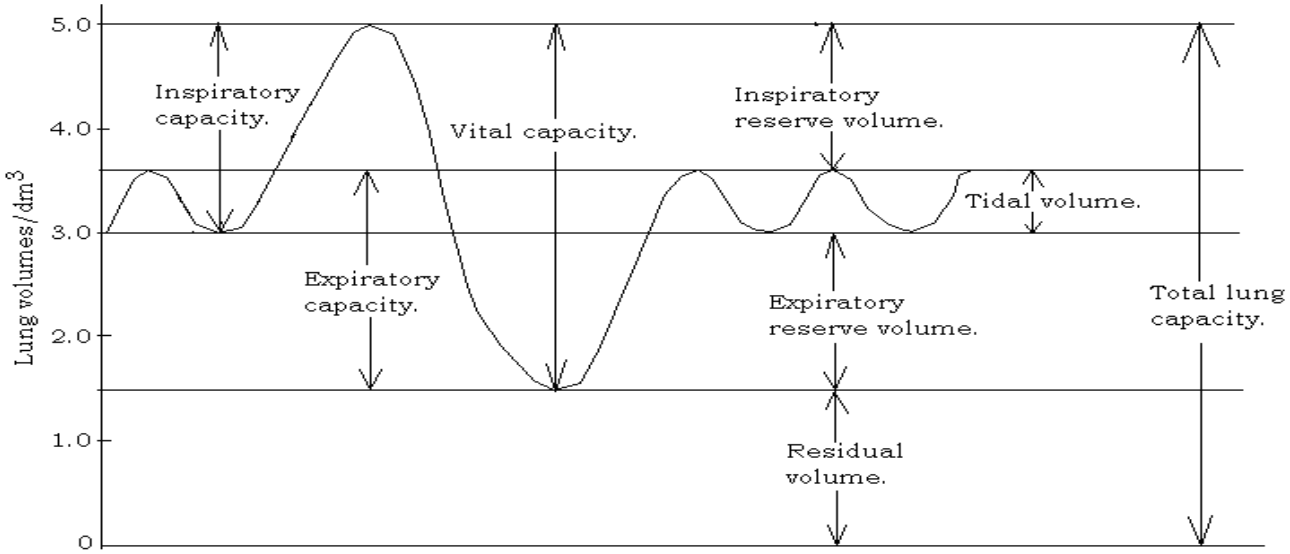
- **Breathing (Ventilation) rate** is the number of breaths taken in one minute.

- **Pulmonary ventilation rate** is the total volume of air that is moved into the lungs during one minute.

Clearly **ventilation rate = tidal volume x frequency of inspirations.** In other words **pulmonary ventilation rate = breathing rate x tidal volume.**

$(dm^3\ min^{-1})$ (min^{-1}) (dm^3)

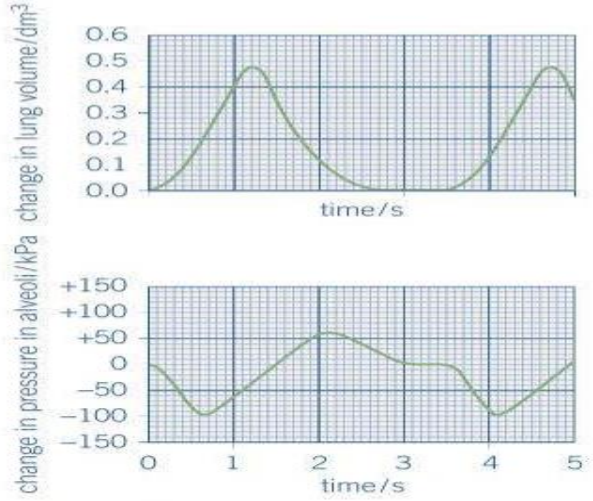
The different lung volumes and capacities in man



1. **Tidal volume.** This is the volume of air breathed in or out per breath. It is about 0.5 dm^3 at rest but varies with each individual; it increases during exercise.
2. **Vital capacity.** This is the maximum volume of air that can be forcibly expired after a maximal intake of air. It varies between 3.5 and 6.0 dm^3 depending on size and fitness of the person.
3. **Residual volume.** This is the volume of air that remain in the lungs after maximum forced expiration. Residual volume is typically 1.5 dm^3. Inhaled air mixes with residual air, keeping the levels of gases in the alveoli relatively constant.
4. **Inspiratory reserve volume.** Maximum volume of air that can be inhaled by a person after normal inspiration.
5. **Dead space volume.** Total amount of air that remains in the air passages and does not take part in gaseous exchange.
6. **Expiratory reserve volume.** Volume of air that can be forced out of the lungs after a normal exhalation.

QUESTION:

Graphs below show volume and pressure changes that occur in the lungs of a person during breathing while at rest.



(a) From the graphs:
(i) Determine the tidal volume of this person
From the graph of change in lung volume, the highest volume of air taken in peaks at 0.48dm3
Therefore, tidal volume of the person was 0.48dm3
(ii) Work out the rate of breathing per minute.
The duration of one breath is the interval of time between two successive corresponding peaks on the volume graph = 4.7seconds – 1.2 seconds = 3.5 seconds
The number of breaths in a minute (60 seconds) is therefore 60 seconds / 3.5 seconds
= 17.14 breaths per minute
(b) If the volume of air n the lungs when this person inhaled was 3000cm3, work out the volume of air in the lungs after the person had exhaled?
$3000cm^3 = 3.0dm^3$
From the graph, exhaled volume
= 0.48dm3 less than the maximum inhaled volume(3.0dm).
The volume of air in the lungs is therefore
$3.0 - 0.48 = 2.52dm^3$ (OR $2520cm^3$)

(c) Explain how muscles create the change of pressure in the alveoli over the period 0 to 0.5 seconds
Diaphragm muscles contract to flatten it; external intercostal muscles contract to move the rib cage upwards and
outwards; thoracic cavity volume increases while alveolar pressure decreases below atmospheric pressure.

EFFECT OF ALTITUDE TO GASEOUS EXCHANGE

The atmospheric pressure becomes lower with increased attitude due to low pressure at high attitudes and the partial pressure of oxygen is decreased and its affinity for haemoglobin is decreased. It is more difficult to load the haemoglobin with oxygen. Thus any one living at high attitude for a period of time overcomes this problem in a condition known as **acclimatization.**
Acclimatization is the period of time during which the person becomes adjusted to the low partial pressures of oxygen at high altitudes. It involves the following changes,

(i) Increased oxygen uptake. Deep breathing and increase in network of blood capillaries leads to absorption of more oxygen.
(ii) The concentration of red blood cells increase. This improves transport of oxygen to the respiring tissues.
(iii) The concentration and amounts of haemoglobin in red blood cells increase. This improves the supply of oxygen to the respiring tissues.

(iv) The concentration of myoglobin in the muscles increase and its affinity for oxygen become higher, this facilitates exchange of oxygen from the blood to the respiring body tissues.

(v) Adjustment of blood pH back to normal. At higher altitudes deep breathing (hyperventilation) occurs, which leads to excessive removal of carbon dioxide and a raised blood pH. In acclimatized individuals the hydrogen carbonate ions are removed by the kidney, restoring blood pH to normal. This is achieved by secretion of more alkaline urine. Chemoreceptors become sensitive to the carbon dioxide present, normal ventilation rates are then maintained at normal pH of blood.

(vi) Haemoglobin molecules with higher affinity for oxygen are manufactured.

UN USUAL CONDITIONS IN VENTILATION.

At high mountains the partial pressure of oxygen and of other gases decrease, therefore mountaineers usually suffer from inadequate oxygenation of the blood a condition known as anoxia or hypoxia.

At high attitude, individuals tend to have an increased rate of ventilation so that more oxygen can be taken in. The increased ventilation expels large quantities of carbon dioxide from the body, resulting into the conditions known as **Alkalaemia.**

The greater pH inhibits the activity of chemoreceptors, as a result pulmonary ventilation is prevented and becomes inadequate causing great discomfort and fatigue. But with time the respiratory and circulatory systems adjust to the low partial pressure of oxygen at high altitude. After some time, bodies chemoreceptors are no longer inhibited and can detect changes in levels of carbon dioxide in blood, pulmonary ventilation do increase.

Such adjustments of respiratory systems of the body to low partial pressure of oxygen at high altitude are known as **Acclimatisation.**

GASEOUS EXCHANGE IN DIVING MAMMALS/ AIR BREATHING ANIMALS LIVING UNDER WATER.

Certain air-breathing organisms can remain submerged in water for long periods of time without resurfacing because of some adaptations,

• Frogs have permeable vascular skins, through which oxygen diffuses, this is sufficient to supply their needs. They also remain inactive while submerged in water.

• Some insects store air in their tracheal systems. For example the larvae of *culex* can remain submerged in this way up to 10 minutes. Larger insects, like the water scorpion can remain submerged up to 30 minutes.

• The water beetle traps atmospheric air beneath their elytra (wing covers). Some beetles trap oxygen bubbles released by photosynthesizing aquatic plants and it supplement their oxygen supplies.

For some other mammals referred to as Diving mammals like seals, whales, and dolphins, they have ability to endure long periods submerged in water due to the following factor,

(i) Blood makes up a greater proportion of the body mass, to increase supply of the oxygen gas in the body. This is accommodated in large sinuses and venacavae. The capacity of oxygen carried in the body increases.
(ii) There is an increased concentration of red blood cells in the blood, increasing capacity of blood to carry oxygen.
(iii) There is a higher concentration of Haemoglobin to increase the amount of oxygen carried to body tissues.
(iv) The heartbeat slows down automatically (Bradycardia), reducing the amount of blood supply and thereby conserving oxygen.
(v) Blood is distributed to the vital organs during a dive by constriction of the veins that drain the less immediately important organs such as the kidney, stomach and muscles, thus conserving oxygen. Such less important organs continue to respire anaerobically. The supply to brain remains unaffected.
(vi) Muscles are rich in myoglobin which acts as an oxygen store.
(vii) Reduced sensitivity to pH. This avoids increase in heart rate and respiratory rate.
(viii) Tolerance to high levels of lactic acid by tissues like the muscles which respire anaerobically during the dive. To avoid severe muscle cramp.
(ix) Larger tidal volume. Few ribs are attached to the sternum, and the lungs become almost collapsed, to allow large exchange of air, for more efficient gaseous exchange
(x) Cartilaginous rings extend further into lungs (bronchioles). This prevents the lung (bronchioles) collapsing under pressures experienced during the deep dive.
(xi) Expulsion of air during the dive. This reduces the danger of excessive nitrogen becoming dissolved in the blood, preventing the narcotic effects of nitrogen.
(xii) The nostrils close during a dive to prevent entry of water into the lungs.

Humans do not have similar adaptations to dive or remain sub-merged under water for a long period of time. So, when humans are under water, they take with them air storage tank to supply oxygen. But this is associated with some problems,

• As one dives deeper, the pressure increases and under these conditions a greater concentration of oxygen and nitrogen may enter into the blood. The oxygen may become toxic and the nitrogen has a narcotic effect.

• Another problem arises if the diver surfaces rapidly. In this case, nitrogen comes out of the solution and forms bubbles. This gives painful symptoms known as "***the bend***". This is avoided when divers spend specified periods of time at certain depth near the surface on their way to the surface. This gives time for the additional nitrogen to be expelled, this is known as ***decompression***.

Common diseases of the respiratory system.

Disease of respiratory system	Key notes:
Bronchitis: *This involves inflammation of the lining of air passages, which may be acute or chronic.*	• **Acute bronchitis** lasts for a few days and is a side-effect of an infection like a cold. • **Chronic bronchitis** is much more serious and is often due to cigarette tars in smoke irritating bronchiole walls and triggering an inflammation response. It is always associated with emphysema in late stages, leading to increased coughing and breathlessness.
Asthma *This is a form of difficult or heavy breathing which is caused by narrowing of air ways due to contraction of smooth muscle in walls of bronchioles. The cause of asthma is due to over-reaction to one of a variety of possible stimuli e.g dust, spore, emotional disturbance*	The contractions of the smooth muscles cause the bronchioles to narrow or close. The person has more difficulty breathing out than breathing in because the pressure from lungs during breathing out squeezes the tubes even more. Asthma is also associated with inflammation of the lining of respiratory pathways, due to release of histamine, it also leads to production of excess mucus, which in along run traps bacteria leading to n infection causing bronchitis.
Emphysema *This is characterized by chronic breathlessness.*	It is caused by a gradual breakdown of the thin walls of alveoli, decreasing the surface area for gaseous exchange. Emphysema is caused by tars in cigarette smoke irritating the lungs for a long period of time . it can also be caused by industrial dust and air pollutants.
Lunger cancer	This usually starts from bronchioles and spreads throughout the lung. Lung cancer is caused exclusively by tars in cigarette smoke. Tars have carcinogens (chemicals which cause cancer.

Note: Ageing causes gradual loss of elastic tissue in the respiratory system and the chest wall becomes incapable of expansion. Vital capacity of lungs also decreases with age.

Comparison of gaseous exchange in man and bony fish:

Similarities

- Both have internal respiratory surfaces connected to the external medium by a respiratory tract.
- In both, the ventilation mechanism brings the external medium into contact with a respiratory surface.

- In both, muscular contractions expand the cavities that contain the respiratory surfaces during inspiration.
- In both, gas exchange is between external medium and blood.
- In both, respiratory medium moves along a pressure gradient.
- In both, gaseous exchange occurs by diffusion.
- Both possess respiratory surfaces which have a large surface area to volume ratio, are moist, have rich blood supply.

Differences.

Gaseous exchange in man	**Gaseous exchange in bony fish**
Air is a medium for gaseous exchange	Water is a medium for gaseous exchange
Air enters and leaves via the same pass way I,e nose or mouth	Water enters via the mouth and leaves via the opercular opening
Involves back and forth type of ventilation	Involves one-way types of ventilation
Respiratory surface is the alveolar membrane	Respiratory surface is the epithelium of gill plates
Respiratory surface id found and protected within the ribcage	Respiratory surface is found protected by operculum and wall of pharynx
Ventilation involves adjustments in the thoracic cavity i.e ribs, intercostal muscles and diaphragm	Ventilation is by adjustments of the buccal cavity, pharynx and opercular cavity.

Comparison of gaseous exchange in amphibians and man:

Similarities:

- In both, back and forth type of ventilation is used
- In both, air is respiratory medium
- In both, lungs are respiratory organs and alveolar membrane are respiratory surfaces.
- In both, internal respiratory surfaces connect to the external medium by a respiratory tract.
- In both, ventilation mechanism brings the external medium into contact with a respiratory medium.
- In both, during respiration, muscular contractions occur to expand the cavities that contain the respiratory surfaces.
- In both, gaseous exchange is between the external medium and blood.
- In both, respiratory medium moves along a pressure gradient.
- In both, gaseous exchange occurs by diffusion.
- In both, respiratory surfaces have a large surface area to volume ratio, are moist, have rich blood supply.
- In both, ventilation is maintained rhythmically by a control mechanism in the respiratory center in the hind brain.

Differences

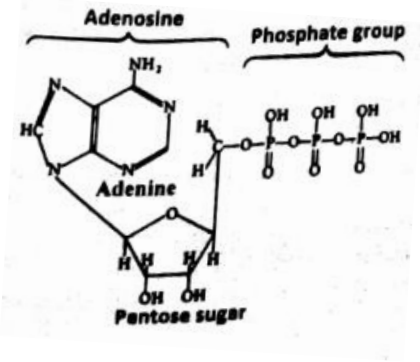
Gaseous exchange in man	Gaseous exchange in amphibians
Respiratory medium is air	Respiratory media are both air and water
Respiratory surface is the alveolar membrane only.	Respiratory surfaces are; buccal cavity lining, epithelium of skin and alveoli
Muscular diaphragm is involved in ventilation	Lacks a diaphragm
Ventilation is continuous and rhythmic	Ventilation is not always continuous though rhythmic

CELLLULAR RESPIRATION:

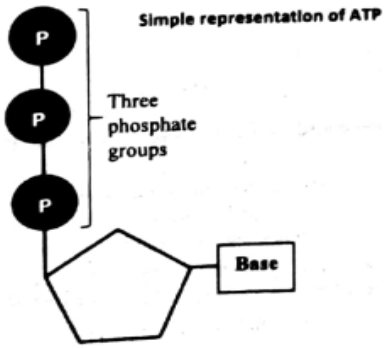
Cellular respiration is the process by which organic food materials are broken down in a cell to release energy in form of ATP. The food substance oxidized is called a respiratory substrate, which may be glucose (major respiratory substrate), fats and proteins may also be used. The energy is made available to cells in form of ATP.
The respiratory substrates are broken down gradually by a series of enzyme controlled reactions. Each releases a small amount of energy, some of which is transferred into ATP (energy carrier of cells). The rest of the energy is lost as heat. The energy in the ATP can be used when required in reactions in the cell which require energy.

ATP (Adenosine Triphosphate)

Structure of ATP



Simple representation of ATP



ATP is a molecule made up of a nitrogen base adenine, a ribose sugar and three phosphate groups. Adenine is attached to carbon 1 of ribose sugar while the chain of phosphate groups is attached to carbon 5 of ribose.

Significance of ATP.

ATP is a temporary energy store compound which releases energy when thr bonds between the phosphate groups is broken during hydrolysis. All cells require energy and all cells in every kind of living organism use ATP as their source of energy when performing their work. ATP is therefore known as the 'the universal energy carrier' or energy currency of cells.

More energy is obtained from the hydrolysis of ATP to ADP and ADP to AMP than from hydrolysis of AMP. This explains why hydrolysis of AMP to release energy isn't feasible.
Hydrolysis of ATP TO Adenosine Diphosphate and inorganic phosphate (Pi) is catalyzed by ATPase enzyme.
Equation:

$$ATP + H_2O \underset{\text{Condensation}}{\overset{\text{Hydrolysis}}{\rightleftharpoons}} ADP + Pi + 30.6\ KJ\ per\ mole\ of\ ATP$$

ATP is formed by a process called phosphorylation in which a phosphate is added to ADP. There are three types of phosphorylation;

i. ***Substrate level phosphorylation:*** this involves the transfer of phosphate group directly from a high energy compound to ADP to form ATP. Examples of high energy compounds include 1, 3-bisphosphoglycerate, creatine phosphate.
ii. ***Oxidative phosphorylation;*** is the process of ATP synthesis using energy from oxidation of compounds such as NADH and $FADH_2$.
iii. ***Photophosphorylation:*** is the process by which ATP synthesis takes place in a cell using energy from light. E,g during photosynthesis.

ATP is preferred to other high energy compounds to provide energy for cell metabolism because;

- ATP is mobile and can carry energy to energy consuming processes anywhere in the cell.
- ATP can release energy quickly. (Only one hydrolysis is required)
- The rate at which can be reformed from ADP and inorganic phosphate can be varied quickly according to the energy demand.

Note;
Brain cells only have few minute supply of ATP and thus must be continuously supplied with oxygen to regenerate it.
Muscle cells however store creatine phosphate which is a source of phosphate for rapid regeneration of ATP.

USES OF ENERGY FROM ATP IN CELLS

- Used for loading and unloading of sugars in plants
- Used for translocation of organic food materials in phloem of plants
- Used in movement of cilia and flagella
- Used for contraction of muscles
- Used for active transport of molecules across cell membrane
- Used for synthesis of compounds and structures e.g. DNA and protein synthesis
- For activation of chemical compounds, to make them more reactive. E.g. phosphorylation of glucose during glycolysis
- For Contraction of microfilaments during cell division
- Powers movement of a sperm cell toward the secondary oocyte
- For Transmission of nerve impulses

- For secretion of substances such as hormones that are formed in cells

SITES FOR CELLULAR RESPIRATION:

CELL	SITE
Prokaryotic cell	Cytoplasm, Mesosome
Eukaryotic cell	Cytoplasm, mitochondrion

STAGES OF RESPIRATION

Cellular respiration involves three stages.

STAGE	*SITE*	*CONDITION*
GLYCOLYSIS	*CYTOPLASM*	*BOTH AEROBIC & ANAEROBIC*
KREBS CYCLE /TRICARBOXYLIC ACID CYCLE/CITRIC ACID CYCLE	*MITOCHONDRIAL MATRIX*	*AEROBIC*
ELECTRON TRANSPORT SYSTEM	*CRISTAE*	*AEROBIC*

There are two types of respiration:

- Aerobic respiration
- Anaerobic respiration

AEROBIC RESPIRATION:

This is the oxidative breakdown of glucose to yield energy in the presence of oxygen. Glucose is the main respiratory substrate.

Aerobic respiration goes through three stages;

(i) Glycolysis
(ii) Krebs cycle or tricarboxylic acid cycle (TCA) or citric acid cycle
(iii) Electron Transport system(ETS) of hydrogen transport system

GLYCOLYSIS:

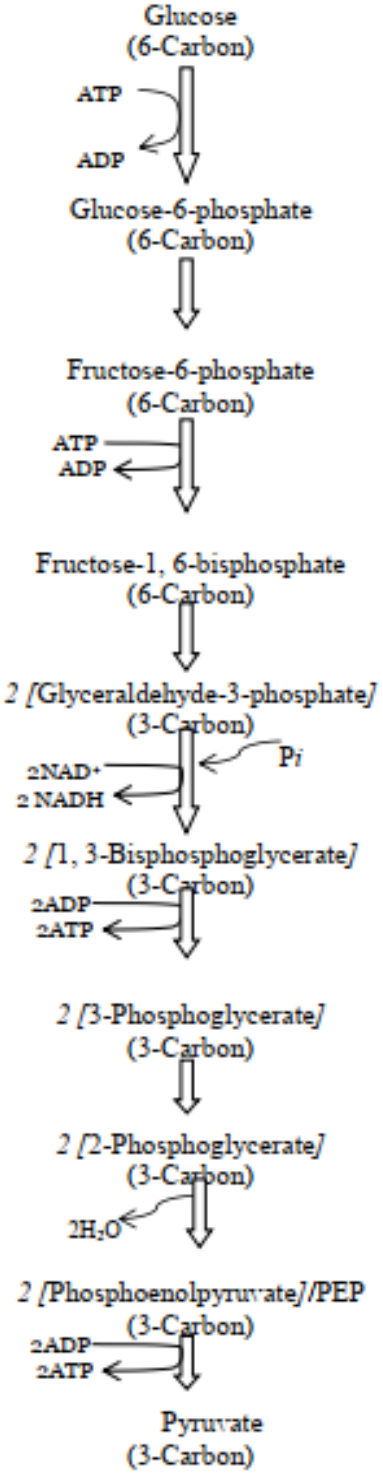
This is the splitting of a 6-carbon sugar (glucose) into two molecules of pyruvate(pyruvic acid), a 3-carbon compound.

Glycolysis occurs in all cells of aerobes and anaerobes. In anaerobic respiration, glycolysis is the only stage that occurs.

DESCRIPTION OF THE PROCESS OF GLYCOLYSIS.

DESCRIPTION OF THE PROCESS OF GLYCOLYSIS

Description through reactions



Glycolysis starts with phosphorylation of glucose by ATP to form glucose-6-phosphate. This process **(1)** chemically reactivates glucose **(2)** traps glucose in the cell because the phosphate group bears a negative charge yet the cell membrane is impermeable to ions.

Glucose-6-phosphate isomerizes to form fructose-6-phosphate to ease another Phosphorylation.

Fructose-6-phosphate is phosphorylated by ATP to form fructose-1, 6-bisphosphate

Fructose-1, 6-bisphosphate splits at once into two glyceraldehyde-3-phosphates (3-phosphoglyceraldehyde/3-PGAL), each with three-carbons.

Each 3-PGAL is dehydrogenated by nicotinamide adenine dinucleotide (NAD+) to form reduced nicotinamide adenine dinucleotides (NADH)
Each 3-PGAL molecule is phosphorylated by phosphates present in the cytoplasm to form 1, 3-bisphosphoglycerate, which later donates the phosphate to ADP to form ATP and 3-phosphoglycerate, which has 3-carbons.

Each 3-phosphoglycerate isomerizes to form 2-phosphoglycerate,

Each 2-phosphoglycerate loses a water molecule to form 3-phosphoenolpyruvate (PEP).

Each 3-phosphoenolpyruvate (PEP) loses a phosphate to ADP to form ATP and pyruvate which has three-carbons

Total input	Total output
1 molecule of glucose (6C)	2 molecules of pyruvate (2x 3C)
2 ATPs	4 ATPs
2x NAD^+	2X ($NADH + H^+$)
Overall profit	2 ATP + 2($NADH + H^+$)

Overall equation of glycolysis.

$$\text{Glucose} + 2NAD^+ \longrightarrow 2\text{pyruvate} + 2ATP + 2NADH + 2H^+$$

Note:

(i) In the presence of oxygen, each pyruvate molecule diffuses into the mitochondrion, and is converted into a 2-carbon compound, **acetyl coenzyme A,** which enters the Krebs cycle. The NADH(reduced NAD) can feed electrons into the electron transport system.

(ii) The NADH produced during glycolysis must be oxidized back to NAD^+ to be used again in glycolysis. Failure to happen, NAD would soon run out and ATP production would halt.
In the presence of oxygen, NAD^+ is regenerated when NADH releases hydrogen into the mitochondria. The hydrogen enters the electron transport system and generates six molecules of ATP. If however oxygen is unavailable, NAD^+ is regenerated by fermentation, a process in which no more ATP molecules are generated.

(iii) NAD is regarded as a coenzyme because it assists dehydrogenases in removing hydrogen from substrates.

SIGNIFICANCE OF GLYCOLYSIS:

- Formation of ATP used to power cell activities
- Formation of ($NADH + H^+$) from which more energy is extracted during electron transport system.
- Formation of pyruvate from which more energy can be extracted either in anaerobic conditions or aerobic conditions during Krebs cycle.

LINK REACTION AND THE KREBS CYCLE:

In the presence of oxygen, the pyruvate molecules formed from glycolysis, diffuse or actively move into the matrix of the mitochondria, where the lin link reaction and Krebs cycle occur.

LINK REACTION:

The link reaction involves conversion of pyruvate molecules into carbon dioxide and a 2-carbon molecule called ***acetyl coenzyme A. (Acetyl CoA.*** It occurs in he matrix of the mitochondria, in the presence of oxygen.

The conversion of each pyruvate molecule to a 2-carbon fragment (acetyl CoA), Involves the following steps:

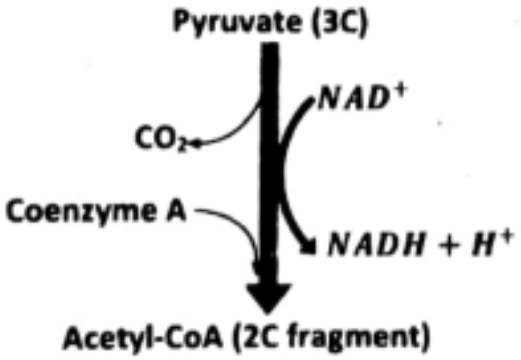
(i) Removal of carbon dioxide (decarboxylation), under the catalysis of **pyruvate decarboxylase.**

(ii) Dehydrogenation (oxidation) of the pyruvate, under the catalysis of pyruvate dehydrogenase. This process is called oxidative decarboxylation. The

hydrogen atoms released from dehydrogenation, reduce NAD to (NADH + H^+). The $NADH_2$ passes the hydrogen atoms through the carrier system, with the formation of 3 ATPs.

(iii) The 2-carbon molecule (acetyl group), formed as a result of decarboxylation and dehydrogenation, combines with a cofactor called coenzyme A (**CoA)** to produce acetyl coenzyme A.

THE LINK REACTION:



Overall equation for link reaction:

Pyruvate + NAD^+ + CoA ⟶ acetyl-CoA + reduced NAD + CO_2

Since the link reaction yields two molecules of acetyl-CoA, the link reaction occurs twice for every glucose molecule. So link reaction of one glucose molecule yields $2NADH_2$ (and so 6ATPs) via the **ETS)** and $2CO_2$.

SIGNIFICANCE OF THE LINK REACTION:

It makes acetyl-CoA, which carries acetyl groups made from pyruvate, into the Krebs cycle. Acetyl-CoA is the from in which all energy containing compounds, including fats and proteins are converted before entering the Krebs cycle.

THE KREBS CYCLE/TRICARBOXYLIC ACID CYLE/CITRIC ACID CYCLE.

Krebs cycle involves introduction of acetyl coenzyme A into a cycle of many reactions that yield some ATP and a large number of electrons.

Krebs cycle involves the following main steps.

(i) Each of 2-carbon acetyl-CoA, from the link reaction combines with 4-carbon compound oxaloacetate (oxaloacetic acid), to produce a 6-carbon molecule citric acid (citrate)

(ii) Coenzyme A is reformed and may be used to combine with another acetate molecule from pyruvate.

(iii) Citrate isomerises to form isocitrate, a more reactive molecule by addition and removal of a water molecule.

(iv) The isocitric acid is decarboxylated and dehydrogenated to produce a 5-carbon compound α-ketoglutarate or glutaric acid, carbon dioxide and reduced NAD.

(v) The α-ketoglutarate loses a carbon dioxide molecule and oxidized by (NAD^+), the remaining product reacts with coenzyme A to form a 4C

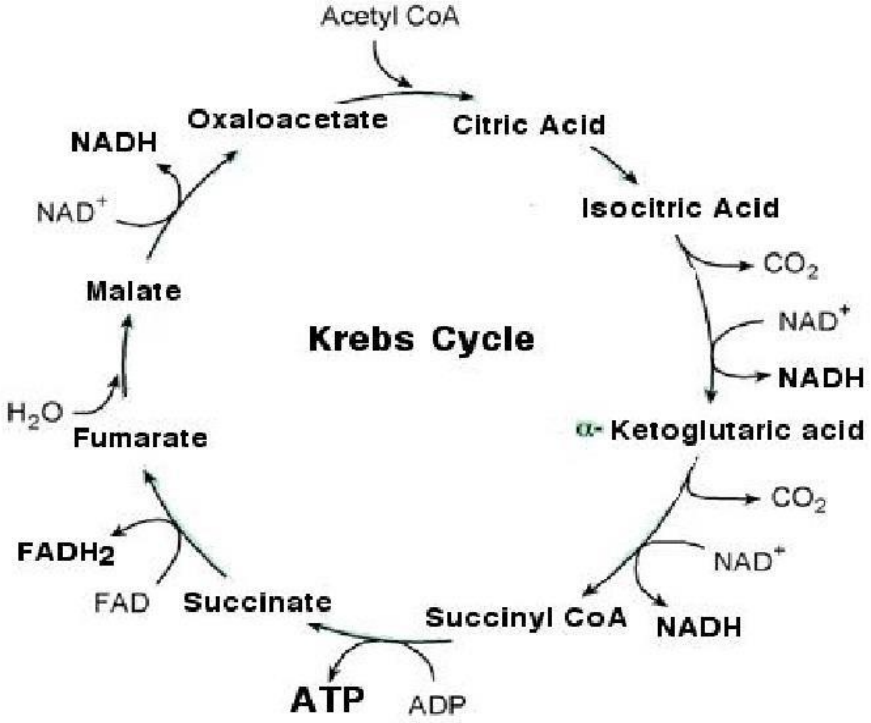
compound, succinyl CoA, which is unstable.

(vi) The CoA is displaced, ATP is formed and a more stable 4C compound, succinate (succinic acid) forms.

(vii) The succinate is oxidized by removal of two hydrogen atoms by (Flavine Adenine Dinucleotide) FAD, to form FADH2. Fumarate is formed.

(viii) Addition of a water molecule to the fumarate results into formation of malate, a 4C compound.

(ix) Malate is oxidized by NAD^+ to regenerate oxaloacetate. ($NADH^+H^+$) is also formed



Krebs cycle results into the formation of 3 molecules of NADH and one molecule of FADH2

From the Krebs cycle, one ATP molecule is made directly by substrate level phosphorylation from each pyruvate molecule that enters the cycle. For one glucose molecule thus, two ATP molecules are formed.

Role of coenzyme A

• Activates acetate so that more energy can be obtained from it

• Transfers the acetyl group formed from pyruvate to combine with 4C compound oxaloacetate, forming 6C compound citrate. This reaction is catalysed by the enzyme citrate synthetase.

• Provides a pathway by which fatty acids and proteins can be used as respiratory substrates via a central link of acetyl coenzyme A.

IMPORTANC OF KREBS CYCLE:

- Breaks macromolecules into simpler ones for example pyruvate to carbon dioxide.
- Produces hydrogen atoms that are carried by NAD to electron transport chain for oxidative phosphorylation, and the production of ATP by chemiosmosis, which provides metabolic energy for the cell.
- Regenerates the starter material (oxaloacetate), which would otherwise be completely used up.
- Source of intermediate compounds used by the cell to manufacturer other important substances, e.g fatty acids, amino acids.

SIMILARITIES BETWEEN GLYCOLYSIS AND KREBS CYCLE

- In both, NADH+H+ is formed
- In both, ATP is formed
- Both involve reduction in number of carbon atoms of initial substrate
- Both are enzyme catalysed
- Both occur in living cells

DIFFERENCES BETWEEN GLYCOLYSIS AND KREBS CYCLE

GLYCOLYSIS	**KREBS CYCLE**
Electron acceptor FAD not involved	Electron acceptor FAD involved
Carbon dioxide not formed	Carbon dioxide formed
Occurs in cytoplasm of cell	Occurs in mitochondrial matrix
Doesn't require oxygen availability to occurs	Requires oxygen to occur
Doesn't involve coenzyme A	Involves coenzyme A

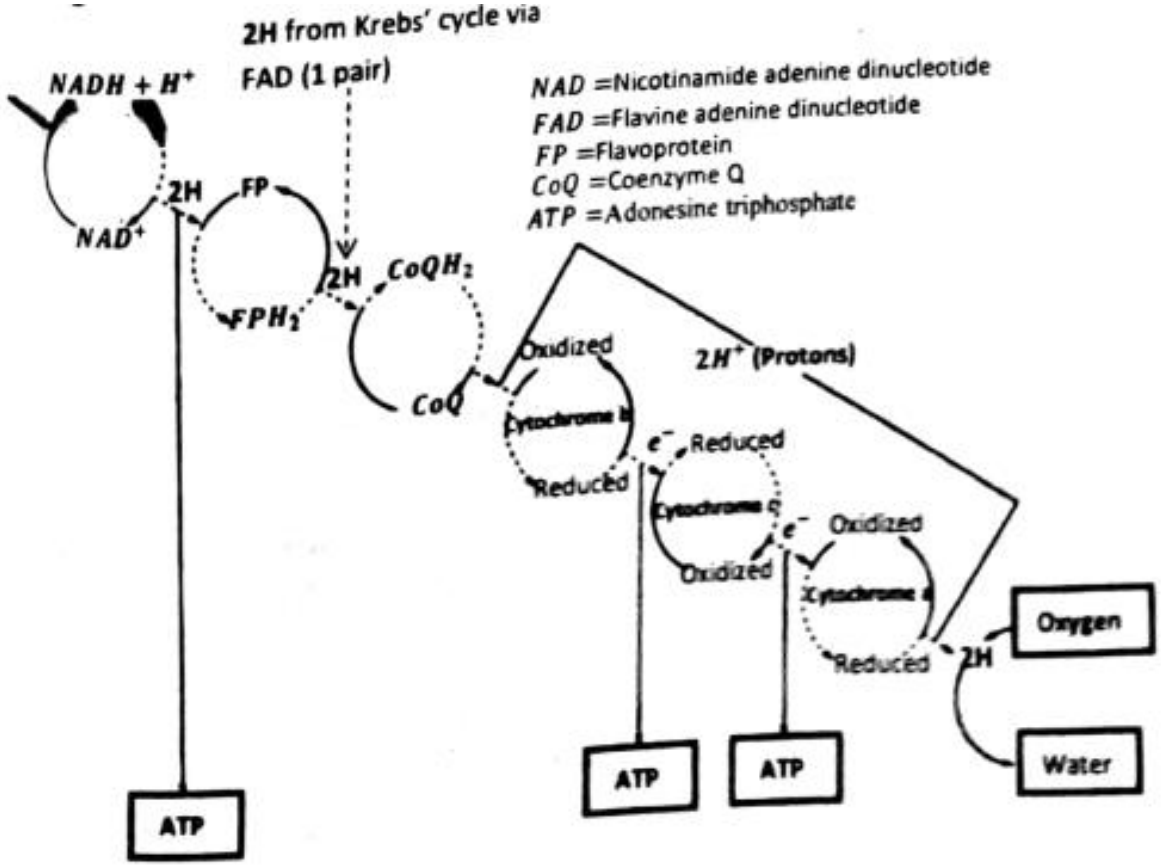
THE ELECTRON TRANSPORT SYSTEM (ETS)

The ETS is a series of hydrogen and electron carriers ending with oxygen. Hydrogen or electrons are passed from one carrier to the next, moving downhill in energy terms, until they reach oxygen, which is reduced to water as a result. As electrons flow downhill in energy terms, energy is lost and is used to synthesis ATP mainly come from the Krebs cycle, though some comes from glycolysis. The hydrogen atoms carried by $NADH_2$ and $FADH_2$ are the main source of electrons which are passed along a chain of carrier molecules (the electron transport system/ETS), electron transport occurs on or in the inner mitochondrial membrane and cristae.

Overall equation of reaction:

$$12H_2 + 6O_2 \longrightarrow 12H_2O + 34ATPs$$

THE ETS.



The hydrogen atoms, carried as 10NADH and 2 $FADH_2$, enter the inner mitochondrial membrane. NADH and $FADH_2$ pass on electrons when they donate hydrogen to the next carrier in the respiratory chain, so a redox reaction takes place. For example NADH becomes oxidized by losing hydrogen and its electron whereas the next carrier becomes reduced by gaining the hydrogen and the electron.

At one point the ETS, hydrogen atoms are split to form protons (H^+) and electrons (e^-). The ETS concludes with reduction of oxygen (the final acceptor of protons and electrons) which forms water.

Each redox reaction in the ETS releases energy which can be used to synthesise ATP, from ADP and inorganic phosphate. This oxygen-dependent synthesis of ATP within the mitochondrion using energy released from redox reactions is called **oxidative phosphorylation.**

At the end of the respiratory chain, the reduced **cytochrome oxidase,** a copper containing enzyme transfers electrons back to the protons, reforming the hydrogen atoms. These hydrogen atoms reduce oxygen to form water. The role of oxygen in the ETS is therefore to act as the final acceptor of hydrogen atoms. In the absence of oxygen, only glycolysis stage of respiration occurs.

Note:

(i) Some chemicals such as cyanide or carbon monoxide, inhibit the last stage of ETS by inhibiting action of cytochrome oxidase. Cyanide may combine with copper in cytochrome a t the end of the respiratory chain. This leads to accumulation of

hydrogen atoms and electrons at the carriers, bringing Krebs cycle to a halt and leaving pyruvate from glycolysis to accumulate. This causes aerobic respiration to cease.

(ii) 34 ATPs are produced in the ETS. The total of 38 ATPs is produced in complete aerobic respiration, which represents the maximum possible yield. The actual yield may be different depending upon the condition in one cell at a time.

(iii) The respiratory ETS includes **cytochromes,** iron-containing pigments which give muscles rich in mitochondria a brownish colour.

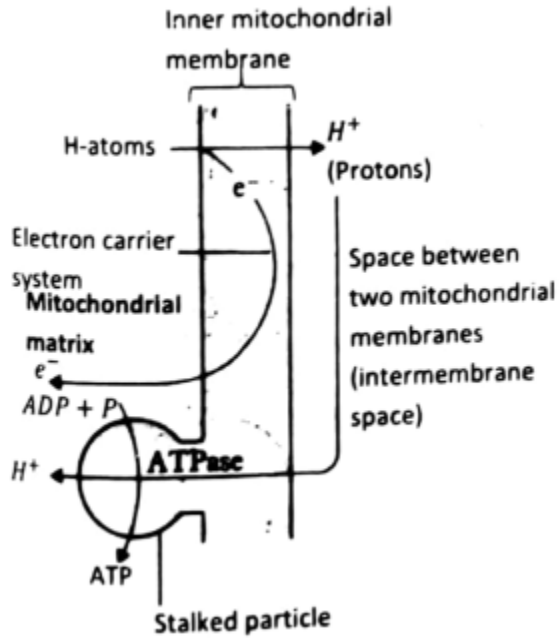
(iv) If oxygen is unavailable, the ETS cannot work. This in turn stops the Krebs cycle, because the reduced NAD and reduced FAD cannot be re-oxidised. Consequently, anaerobic respiration results in a gross production of only 4ATPs for each molecule of glucose with a net production of only 2ATPs.

(v) Theoretically, complete aerobic respiration of one glucose molecules results into production of 38ATPs.

BUDGET FOR THE RESPIRATORY CHAIN.

No. of hydrogen atoms entering	**No. of oxygen molecules used**	**No. of products**	
$10H_2$ in the form of 10NADH + H^+	**$5O_2$**	**30 ATPs + $10H_2O$**	
$2H_2$ in the form of 2FAD + H^+	**O_2**	**4ATPs + $2H_2O$**	
$12H_2$ in the form of 10NADH + H^+ and 2FADH + H^+	**$6O_2$**	**34ATPs + $12H_2O$**	**Total**

CHEMIOSMOTIC THEORY BY P. MITCHELL:



(i) Hydrogen ions are actively transported from the mitochondrial matrix into the intermembrane space. Energy for pumping these protons comes from the flow of electrons in the electron transport system.

(ii) The H^+ ions accumulate in the intermembrane space so that a steep concentration (and pH) gradient is developed.

(iii) The hydrogen ions diffuse into the matrix via the **chemiosmotic channels** in the stalked particles. Diffusion of H^+ is only possible via these channels as the inner mitochondrial membrane is impermeable to H^+.

(iv) As H^+ move from higher energy level to lower energy levels within the chemiosmotic channels, energy is lost which is used to combine inorganic phosphate with ADP to form ATP.**(Oxidative phosphorylation).** This phosphorylation is catalysed by **ATPase** in the bulbous ends of the stalked particles.

Note:

(i) H^+ pumped from the matrix are formed from dissociation of hydrogen atoms accepted by coenzyme Q. Proton pump actively pumps these H^+ from the matrix into the intermembrane space, using energy from the electron transport system in the mitochondrial membrane.

(ii) Chemiosmosis and oxidative phosphorylation also occur in the chloroplast as follows.

Electrons flow along the electron transport chain. As a result protons are pumped out of the stroma into the thylakoid space. Energy for pumping comes from electron flow between photosystem I and photosystem II. This generates an **electrochemical proton gradient** across the inner membrane, exerting a proton **motive force.** Protons move back into the stroma by diffusion, hence operating ATPase system located in the thylakoid membrane which generates ATP.

Assignment

Comparison between oxidative phosphorylation and photophosphorylation

Account of ATP molecules formed directly and indirectly during aerobic respiration of one glucose molecule.

Respiratory process	**No. of reduced hydrogen carriers**	**ATPs formed indirectly (from reduced hydrogen carriers via ETS)**	**ATPs formed directly**	**Total ATPs**
Glycolysis	**2NADH + H^+**	**2 X 3 = 06**	**2**	**08**
Link reaction	**2NADH + H^+**	**2 X3 =06**	**0**	**06**
Krebs cycle	**6NADH + H^+** **2FADH + H^+**	**6 X 3 = 18** **2 X2 = 04**	**2 X1**	**24**
Total	**10$NADH_2$ + 2$FADH_2$**	**34**	**04**	**38**

Evidence of ATP synthesis:

(i) If the content of cell's cytoplasm are centrifuged, a fraction containing mitochondria is obtained. If these are supplied with oxygen and glucose, they produce ATP.

(ii) High powered electron micrographs show the surface of the inner membrane of mitochondrion having closely packed stalked particles. These provide a greatly increased surface for enzymes to work.

(iii) Stalked particles and part of membrane associated to it, when separated from the mitochondria produce ATP.

Adaptations of the mitochondrion to its function:

- The cristae have proteins involved in the electron transport chain, to allow oxidative phosphorylation
- Proton pump pumps H^+ into te intermembrane space to create a concentration gradient between the inner membrane and matrix, needed for ATP synthesis.
- The matrix has phosphate granules to store inorganic phosphate.
- The inner membrane is folded into cristae that increase surface area for action of respiratory enzymes to form more ATP.
- The outer membrane is permeable to allow entry of respiratory substrates e.g oxygen and exit of products e.g carbon dioxide.
- Mitochondrion envelope is thin for faster exit of respiratory products and entry of respiratory substrates by diffusion.
- Head of the stalked particles are associated with ATPase enzyme that catalyses the synthesis of ATP in the respiratory chain.
- Matrix contains most of the enzymes of the Krebs cycle.
- In some mitochondria, cristae may be so close, hence further increasing surface area for ATP production.

FATE OF OTHER RESPIRATORY SUBSTRATES (FATS AND PROTEUINS) IN RESPIRATION.

- **Respiration of lipids (fats and oils)**

Mammalian liver and seeds of many plants contain stores of fats and oils that may be used in aerobic respiration. Fats are utilized when the energy demand is too great or when carbohydrates are in short supply.

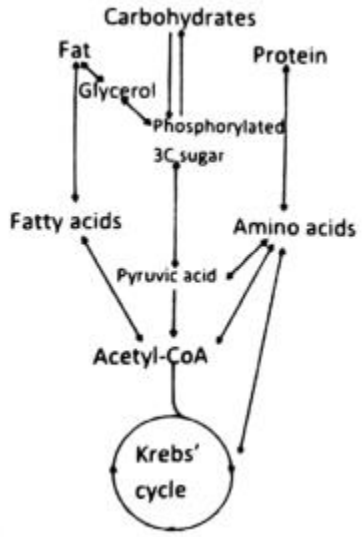
Lipase catalyses the hydrolysis of fats and oils into glycerol and fatty acids. Glycerol is phosphorylated with ATP dehydrogenated with NAD, and converted to a triose phosphate (**TP**), which is converted into pyruvic acid (glycolysis pathway). The pyruvic caid then enters the Krebs cycle. There is a net yield 19ATPs from oxidation of TP, and $NADH_2$ is formed. On the other hand, fatty acids are oxidised by successive removal of 2-carbon fragments, in the form of acetyl-CoA, a process called **B oxidation.** Which occurs in the mitochondrial matrix. The acetyl Coenzyme A is then oxidised to carbon dioxide and water, by Krebs cycle and the electron transport pathway, and the coenzyme is unavailable for re-use.

Note:

The number of ATPs produced from a fatty acid depends on its number of carbon atoms. A fatty acid with a long chain of carbon atoms will obviously produce more acetyl-CoA in the Krebs cycles, and so more ATPs will be formed. For example, complete oxidation of a single molecule of stearic acid with 16 carbon atoms, yields about 180ATPS, much more than what is given from complete oxidation of a single molecule of sugar.

RESPIARTION OF PROTEINS:
These are used as respiratory substrates by carnivorous mammals. During starvation, carbohydrate stores, lipid stores and excess dietary proteins become depleted, and so tissue proteins may be respired.
Proteins are first hydrolysed to amino acids by ***proteases***. The individual amino acids are deaminated, and the amino group is excreted as ammonia, uric acid or urea. The residual carbon compound (keto acid) then enters the respiratory pathway as; pyruvic acid, acetyl-CoA or as a Krebs cycle acid such as oxaloacetic acid or α-ketoglutaric acid.

Interconversion between carbohydrate, fat and protein metabolism



It can be observed that with the exception of conversation of pyruvic acid to acetyl-CoA, all other reactions are reversible. This allows interconversion of carbohydrate to fat for storage or for synthesis of certain fatty acids. It also allows synthesis of amino acids from carbohydrates, and carbohydrates from amino acids.

Control of respiration:
Because the principle function of respiration is to produce ATP, it must be regulated so that ATP is generated
only when needed. This occurs in a number of ways:
1. At cellular level, the rate at which respiration occurs is regulated mainly by the energy state of the cell (i.e. the ratio of ATP to ADP), acting via regulatory enzymes. High levels of ATP (high energy level of the cell) inhibit the enzyme **hexokinase** that catalyses phosphorylation of glucose at the start of glycolysis while low energy levels (high ADP levels) stimulate **hexokinase** enzyme. Highly active cells utilize ATP very fast breaking it to ADP. This has the effect of enhancing the rate of respiration. Such cells include **liver cells, striated muscle cells, spermatozoa** and **nerve cells**. They are characterized by presence of numerous mitochondria. Less active cells utilize ATP slowly and hence respiration in them is slow e.g. **fat cells**.
2. At the level of the whole organism, the respiratory rate is influenced by **environmental factors** e.g. temperature, **structural factors** e.g. body size and **physiological factors** such as level of activity, growth and dormancy.

Temperature: generally, very low temperature slows down respiration in both homoiotherms and poikilotherms, although it can be observed that homoiotherms need increased respiration rate to generate much heat for maintaining body temperature. In poikilotherms temperature near to that of the body increases the respiration rate. *This partly explains why mosquitoes and tsetse flies are only found in the tropics where environmental temperature is close to their optimal temperature.* High temperature slows down the respiration rate in homoiotherms. This explains why such animals tend to be sluggish during hot weather. However, excessively high temperatures trigger increased respiration rate and finally stop as a response by enzymes to temperature.
Body size: small organisms with a large surface area to volume ratio lose heat faster and therefore respire faster than large organisms.
Level of activity: animals engaging in vigorous physical exercise require much energy and so experience faster respiration rate e.g. sprinting, flying, etc.
Growth: actively growing organisms e.g. young animals and germinating seeds respire faster to generate much energy required to drive metabolic processes
Dormancy during extreme cold and hot seasons: respiration rate is always slow to avoid depleting food reserves before the unfavourable season ends.

Comparison of aerobic respiration and photosynthesis
Similarities

- Both are energy converting process
- Both are enzyme-catalysed reactions
- Both process occur in living cells
- Both require mechanisms for exchange of carbon dioxide and oxygen
- Both occur in special organelles
- Both involve flow of electrons along a chain of electron carriers
- Electron carriers must be organized on a membrane coupling reaction to occur
- In both phosphorylation occurs.

Differences

Aerobic respiration	Photosynthesis
Catabolic process/ carbohydrate broken	Anabolic process/carbohydrate synthesised
Energy is incorporated into ATP for immediate use	Energy is accumulated and stored in carbohydrates.
Oxygen is used up	Oxygen is released
Carbon dioxide and water are given off	Carbon dioxide and water re raw materials
Leads to decrease in dry mass	Leads to increase ion dry mass
Does not need the presence of chlorophyll	Occurs in the presence of chlorophyll
In eukaryotic cells, it occurs in the mitochondria	In eukaryotic cells, it occurs in the chloroplasts
Occurs continuously throughout the life of living cells	Occurs in the presence of light

ANAEROBIC RESPIARTION / FERMENTATION (ANAEROBIOSIS)

This involves deriving energy from the breakdown of sugars in absence of oxygen. So the organisms that can respire anaerobically are called **anaerobes.**

There are two types of anaerobes recognized.

(i) Obligate/complete anaerobes

These survive in permanently oxygen deficient conditions and do not require oxygen at all. Indeed, in some cases they may e poisoned by oxygen, even in small concentrations. Examples of obligate anaerobes include;

- *Clostridium botulinum*
- *Clostridium tetani*

(ii) **Facultative /partial anaerobes.**

These respire aerobically when oxygen is present but respire anaerobically if oxygen is absent or in short supply

Example include;

- *Yeast (unicellular fungus)*
- *Escherichia coli (E.coli)*

Examples of circumstances which lead to aerobic respiration in selected organism.

In yeast	In flowering plants	In mammals
• Stagnant solutions • When in center of decomposing fruits and other organic matter.	• Young seeds • Seeds at the center of the fruit; • Roots in water logged soils • Aquatic plants in stagnant water. • Roots in compact soils • Center of large stems where oxygen cannot reach easily	• When lungs are inefficient e.g Emphysema; • Decrease in blood pressure e.g when there is haemorrhage, pressure on artery etc. • Low oxygen carrying capacity of blood e.g anaemia, bone marrow disease. • Low cardiac out put e.g slow heart beat, coronary thrombosis. • High oxygen demands e.g strenuous exercise, pregnancy, etc. • Hibernation • Sperm in oviduct • High

Depending on the metabolic pathway within thr organisms or cells themselves, the end product of anaerobic respiration will either be ethanol and carbon dioxide in yeast and plants, or lactic acid (lactate) in animals. Therefore the process of anaerobic respiration is either **alcoholic fermentation or lactate fermentation.**

Note:

Some species of anaerobic bacteria can produce both ethanol and lactate. Bacteria which sour milk also make lactic acid when oxygen is not available.

Formation of lactic acid and ethanol in anaerobic respiration:
Like aerobic respiration, the first part of aerobic respiration is ,glycolysis. This produces pyruvate (3C) acid from glucose, and produces a profit of 2ATPs and $2NADH_2$. Since oxygen is absent during anaerobic respiration, $2NADH_2$ formed is not oxidised to form water in the ETS.

ANAEROBI RESPIRATION IN YEAST AND PLANTS (ALCOHOLIC FERMENATTION).

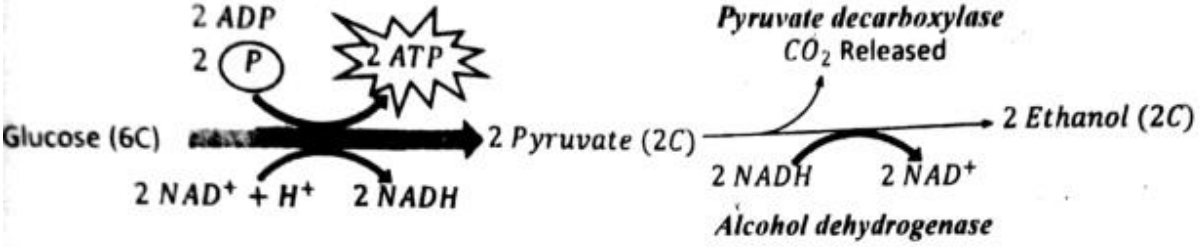
Overall equation: $C_6H_{12}O_6 \longrightarrow CH_3CH_2OH + 2CO_2 + 210\ KJ$

Apart from the two ATPs formed per glucose molecule, in glycolysis, no more ATP is made during alcoholic fermentation.

Note.

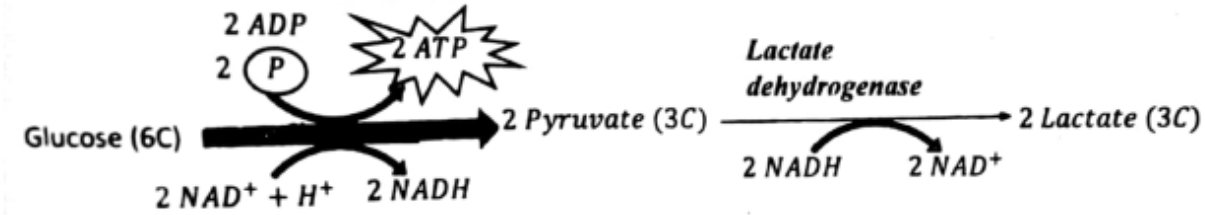
Ethanol is a waste product that still contains a lot of energy. The energy in ethanol is unavailable in the absence of oxygen. However, plants cannot make use of ethanol. Plants cannot convert ethanol to carbohydrate, nor can it be broken down in the presence of oxygen. As it is toxic, it is not allowed to accumulate and this is the main reason why very few plants can be complete anaerobes. Many plant parts can indulge into anaerobiosis for a short period of time, but before the concentration of ethanol reaches a certain level they must revert to aerobic respiration. On returning to aerobic conditions, plants metabolize ethanol to Acetyl-CoA, which is then involved in reactions of established pathways. On the other hand, yeasts are unable to metabolize the ethanol they produce during fermentation, so when ethanol accumulates yeasts cells are killed.

Alcoholic fermentation



ANAEROIBIC RESPIRATION IN ANIMALS (Lactate fermentation in muscles)

Lactate fermentation:



In anaerobic respiration, oxygen is absent to accept hydrogen atoms from reduced NAD. The pyruvate becomes the acceptor of hydrogen atoms from reduced NAD. The pyruvate becomes reduced and lactate is formed. A part from the 2ATPs formed per glucose molecule, in glycolysis, no further ATP is produced during lactate fermentation.
Accumulation of lactic acid in muscles contributes to sensation of fatigue and can contribute to muscle fatigue.

OTHER ALTERNATIVE RESPIRATORY SUBSTRATES.

Fructose

Availed from fruit diet and the digestion of sucrose. In muscles and kidneys, fructose is phosphorylated to form fructose-6-phosphate which joins glycolysis, reaction catalysed by hexokinase enzyme.

In liver cells, fructose is phosphorylated to form fructose-1-phosphate, catalysed by fructose kinase enzyme. The fructose-1-phosphate splits to form glyceraldehyde-3-phosphate and dihydroxyacetone phosphate both of which join the glycolysis pathway.

Galactose

Mostly obtained from digestion of lactose. Galactose is phosphorylated to form Galactose-1-phosphate which is then converted to glucose-1-phosphate which then joins glycolysis pathway.

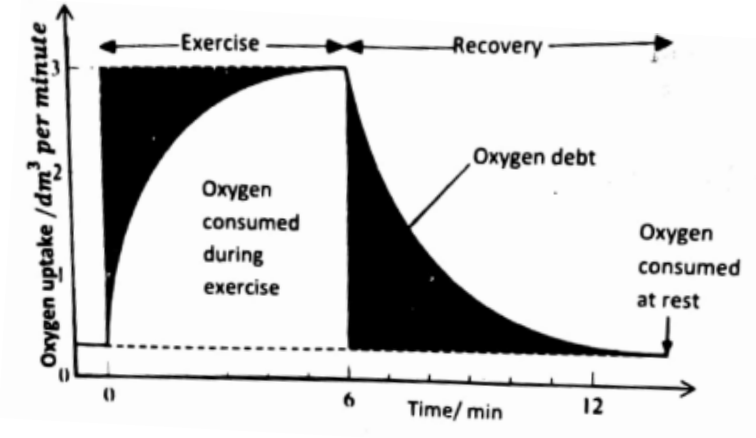
This is part of Galactose pathway and inability to metabolize Galactose thus results into **galactosaemia.**

OXYGEN DEBT AND THE IMMEDIATE EFFECTS OF EXERCISE:

During the exercise:

- The oxygen uptake increases, to form energy for the increased muscular contractions. Initially, the oxygen is supplied to the respiring muscles by oxyhaemoglobin, which soon becomes depleted and the oxygen reserve, oxymyoglobin, now supplies the oxygen to the contracting muscle, in order to sustain energy supply.
- The amount of ATP in muscle is sufficient only for about three seconds of maximal muscle contraction. When ATP in muscles is depleted, the energy reserve, phosphocreatine (creatine phosphate) donates a phosphate group which combines with ADP to form enough ATP, to sustain muscle contraction.
- When oxygen reserves (oxymyoglobin) are depleted, oxygen becomes insufficient to sustain aerobic respiration, so the muscle switches to anaerobic respiration (lactate fermentation). Anaerobic respiration uses glycogen as a source of glucose, and supplies energy more rapidly compared to aerobic respiration, though it provides energy for about 80 seconds maximum muscular activity.

Oxygen uptake during and immediately after the exercise



Overall it can be seen that creatine phosphate and anaerobic respiration systems can provide energy rapidly, but for short periods of time.

Note:

(i) Sports or activities which rely on short explosive bursts of activity, such as 100m race or weight lifting, use mainly creatine phosphate system. Additional energy would be used in a 200m race. Most of the energy in a 400m race would come from anaerobic respiration, and ports like tennis and soccer would rely almost entirely on anaerobic respiration during active phases of the game. Endurance sports such as marathon running, jogging and cross-country are almost entirely aerobic.

(ii) The amount oxygen that was needed, but not supplied by breathing is called **oxygen debt.**

During recovery:

Immediately after the exercise, the rate and depth of breathing first remain high to supply extra oxygen. This oxygen debt is needed for the following:

- Replacing the oxygen reserves (oxyhaemoglobin) in the muscles, and the normal oxygen levels in the lungs, tissue fluids and haemoglobin.
- Restoring the energy store of muscles (creatine phosphate). After the exercise, the creatine combines with the phosphate again, using energy from aerobic respiration. The replacement of creatine phosphate and oxygen reserves takes place rapidly, which explains the steep down ward part of the curve in the first few minutes of recovery.
- Aerobic respiration of lactate that was formed during anaerobic respiration. This is shown by the slow part of recovery.

Lactic acid id transported from the muscles to the liver, where it is reconverted to pyruvate and reduced NAD. Some of the pyruvate enters the normal aerobic pathway through the Krebs cycle to e oxidised, yielding many more ATPs. Alternatively, the pyruvate(75%) can be converted back into glucose by reverse of glycolysis using energy from ATP.

Notes:

(i) The heart can also convert lactic acid back to pyruvate ad reduced NAD as an extra energy source during heavy exercise.

(ii) In some organisms e.g parasitic worms where food supply is abundant, the lactate is just excreted and hence eliminating the need to repay an oxygen debt.

(iii) The level of lactic acid in blood continues to raise after exercise when anerobic respiration has ceased. This is because lactic acid is diffusing from muscles into blood to be transported to the liver.

(iv) A considerable amount of energy remains in lactic acid. Thus just like alcoholic fermentation, lactic fermentation is insufficient compared to aerobic respiration.

(v) Conversion of pyruvate to lactate or ethanol, due to acceptance of hydrogen atoms from reduced NAD, prevents hydrogen ions from accumulating, and causing acidity within the cell. This would undoubtedly happen otherwise, for anaerobic respiration takes place at a much higher rate than aerobic respiration.

EFFICIENCY OF ENERGY IN AEROBIC AND ANAEROBIC RESPIRATION:

Not all the energy present in the high-energy hydrogen atoms is conserved as ATP. Part of the energy is released as heat used for the maintenance of body temperature, but if it is in excess then it can be dissipated to the external environment.

The efficiency of energy conserved in aerobic respiration, alcoholic fermentation and lactic acid fermentation to ATP are thus as follows:

Aerobic respiration	**Alcoholic fermentation**	**Lactic acid fermentation**
A total of 38 molecules of ATP are formed while the amount of energy released is 2880KJ. To form 1 molecule of ATP requires 30.6kj. Thus the amount of energy used to form 38 molecules of ATP is equal to 38 x 30.6 = 1162.8KJ.	Alcohol fermentation releases 210KJ with the formation of 2ATP. To form 1 molecule of ATP requires 30.6kj. Thus the amount of energy used to form 2 molecules of ATP is equal to 2 x 30.6 = 61.2KJ.	Lactic acid fermentation releases 150KJ with the formation of 2ATP. To form 1 molecule of ATP requires 30.6kj. Thus the amount of energy used to form 2 molecules of ATP is equal to 2 x 30.6 = 61.2KJ.
Efficiency of energy conserved= (38ATP x 30.6KJ) x 100 / 2880 = 40.375 ≈ 40.4%	*Efficiency of energy conserved* = (2ATP x 30.6KJ) x 100 / 210 = 29.1%	*Efficiency of energy conserved* = (2ATP x 30.6KJ) x 100 / 150 = 40.8%
The remaining 1717.2KJ(59.6%) is released as heat	The remaining 148.8KJ(70.9%) is released as heat	The remaining 88.8KJ(59.2%) is released as heat
However, considering that glucose on complete oxidation releases 2880KJ of energy, the yield from anaerobic respiration is given by: $\frac{(2ATP \times 30.6KJ)}{2880} \times 100 = 2.1\%$ Therefore, on a whole anaerobic respiration is 2% efficient.		

Note:

Anaerobic respiration is far a less efficient type of respiration compared to aerobic respiration. This is because a great deal of energy remains locked within lactate and ethanol. The energy in ethanol is permanently unavailable to yeast, which clearly indicates that alcoholic fermentation is an inefficient energy producing process. However, the energy locked up in lactate can be liberated in the presence of oxygen.

COMPARISON BETWEEN AEROBIC RESPIRATION AND FERMENTATION
Similarities:

- Both process are catalysed by enzymes
- Both occur only in living cells
- In both carbon dioxide is produced
- Both release energy stored in form of ATP
- Both involve breakdown of organic substrates mainly glucose

Differences.

Aerobic respiration	Anaerobic respiration
• Common method of respiration in animals and plants	• Very rare in plants and animals and is limited to a few plants, animals, yeasts, bacteria
• in higher animals, it goes on throughout life	• In higher animals, it may occur temporarily in active muscles
• Liberates a lot of energy (38ATPs per glucose molecule)	• Liberates less energy (2ATPs per glucose molecule)
• Supplies energy for a longer period of time	• Supplies energy for a shorter period of time
• Liberates energy slowly	• Liberates enrgy faster
• Requires oxygen	• Occurs in absence /limited oxygen
• Involves glycolysis, TCA and ETS	• Involves glycolysis only
• Occurs in the cytoplasm and mitochondrion of cells	• Occurs only in the cytoplasm
• Complete oxidation of glucose	• Incomplete oxidation of glucose occurs i.e intermediates are produced that can be oxidised further e.g lactate
• Produce CO_2 water and energy as products	• Produces; ATP and lactate in animals, or ethanol, CO_2 and ATP in plants and fungi.

Economic importance of fermentation/anaerobic respiration

- Used in production of alcoholic drinks like wine, beer and spirits
- Used in production of raised bread using yeast
- Manufacture of milk products like sour milk, yoghurt and cheese. Theses are manufactured using anaerobic bacteria, lactobacilli that produce lactic acid
- Anaerobic microorganisms are also used in disposal of sewage. Biogas is produced in the process.
- Manufacture of organic acids e.g citric acid, oxalic acid and butyric acid
- Ethanol is used to make gasohol a fuel that is used for cars in Brazil.

Role of Vitamin B complex in cellular respiration

- Vitamin B_1 in involved in the formation of Krebs cycle enzymes, and also forms part of acetyl coenzyme A.
- Vitamin B_2 forms part of the hydrogen carrier flavoproteins **(FP)**
- Vitamin B_5 forms part of acetyl coenzyme A.
- Vitamin B_3 is used in the synthesis of NAD.

Note;

A dietary deficiency of vitamin B_3 results into a disease known as **pellagra**. The provision of energy in the brain is impaired in sufferers of pellagra, resulting into nervous disorders.

Basal Metabolic Rate (BMR):

This is the minimum rate of energy conversion required just to stay alive during complete rest or sleep. The energy needed at rest is for maintenance of basic breathing, beating of the heart, peristalsis, biosynthesis of proteins and other important molecules, temperature regulation, etc. in other words the energy is needed to maintain life of a cell.

Before the BMR of human subjects, they undergo a standard rest period of 12 to 18 hours physical and mental relaxation. No meal is eaten during this time.

FACTORS AFFECTING BMR:

- Size
- Surface area to volume ratio
- State of health
- Sex
- Age

VARIATION OF METABOLIC RATE WITH AGE IN MALE AND FEMALE HUMANS:

In infancy and childhood, the BMR is relatively high as much as much energy is required for biosynthesis of cellular components necessary for growth. When we mature, BMR levels off until middle age. In old age, there is a gradual fall in BMR as metabolism begins to slow down. Throughout life, men usually have a higher BMR than women. This is because men generally have less fat per unit body mass and surface area.

RESPIRATORY QUOTIENT (RQ):

This is the ratio of amount carbon dioxide produced to amount of oxygen used in respiration during the same period of time.

$$RQ = \frac{Volume\ of\ carbon\ dioxide\ evolved}{Volume\ of\ oxygen\ taken\ in}$$

Importance of RQ values

- Indicate the kind of substrate respire
- Indicates type of respiration.

Summary of different RQ values and their possible explanations.

RQ Value:	Possible explanation of RQ value:
>1.0	Anaerobic respiration of carbohydrates e.g in seeds with inadequate oxygen supply
1.0	Aerobic respiration of carbohydrates like glucose
0.90	Aerobic respiration of proteins
0.70	Aerobic respiration of fats/lipids
0.50	Aerobic respiration of fats associated with carbohydrate synthesis/ photosynthesis where part of CO_2 released is used and hence not available for measurement. Construction of calcareous shells may only lead to this.
0.30	Aerobic respiration of carbohydrates but part of the CO_2 released is not available for measurement because it is used in organic acid synthesis.

Note:
High RQ values may also result from the conversion of carbohydrates to fats because carbon dioxide is being produced in the process. This is most common in organisms that are laying down extensive food reserves e.g in mammals preparing to hibernate of fattening livestock.
High RQ values greater than 1.0 also result from a mixture of aerobic and anaerobic respiration.

- A low RQ on the other hand may mean that some or all of the carbon dioxide released in respiration is being used by the organism e.g for photosynthesis in plants or for construction of calcareous sells in animals.
- Most resting animals have a
  N RQ of between 0.8 and 0.9, e.g 0.85 for humans. Although these values would suggest that protein was being respired, we know that protein is used only in extreme situations such as starvation. We must assume therefore that these values are due to a mixture of carbohydrate (1.0) and lipid (0.7) being respired.
- In anaerobic respiration, carbon dioxide is produced but no oxygen is taken in, in this case, the RQ will be infinity.

QUESTONS.

1) Table **1** shows the relative contribution of aerobic and anaerobic respiration to the total energy output in an individual during exercise.

TABLE 1

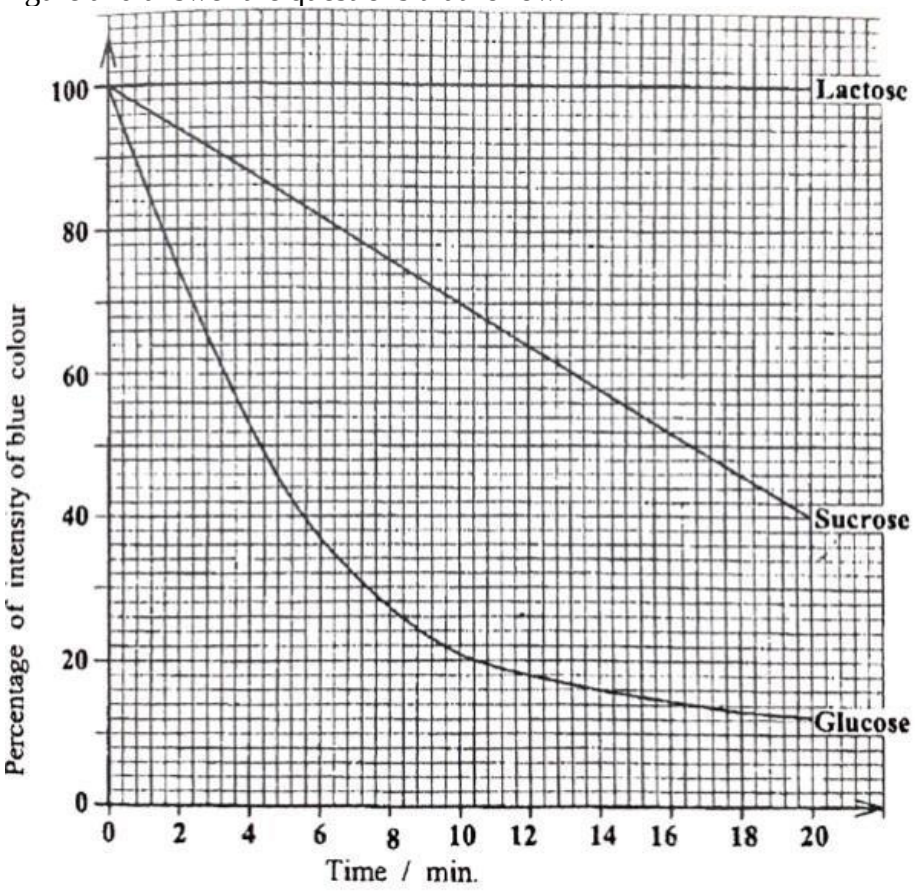
Duration of exercise (min)	Relative contribution of energy (%)	
	From aerobic respiration	From anaerobic respiration
0.5	**83**	**17**
2.0	**40**	**60**
10.0	**9**	**91**
60.0	**1**	**99**

a) Compare the relative contribution of aerobic and anaerobic respiration to the total energy output, with duration of exercise (03 marks)
b) Explain the changes in relative contributions of aerobic and anaerobic respiration with

duration of exercise. (04 marks)
c) Explain why diving mammals have a reduced heart beat rate. (03 marks)

2) a) Differentiate between aerobic and anaerobic respiration. (05 marks)
b) Describe what happens to end products of glycolysis in absence of oxygen. (10 marks)
c) Why is it important to produce ATP during cellular respiration? (05 marks)

3. An experiment was carried out to investigate the rate of respiration in yeast cells mixed with three different carbohydrates (glucose, sucrose and lactose), using methylene blue as an indicator. (Methylene blue is blue in alkaline conditions and colourless in acidic condition) 1cm3 of 0.1M methylene blue was added to a mixture of 5cm3 of a suspension of yeast in 10cm3 of 0.5% glucose solution in a boiling tube. The boiling tube was placed in a water bath at 30oC for 20 minutes. The rate of respiration was measured as a percentage of the intensity of the blue colour at the beginning of the experiment at intervals of 2 minutes. The experiment was repeated using 0.5% sucrose and lactose. The results are shown in the figure below. Study the figure and answer the questions that follow.



a) Calculate the average rate of respiration of yeast in glucose solution during the first four

minutes in terms of percentage intensity of the blue colour. (03 marks)

b) Describe the changes in the intensity of the blue colour with time, for each carbohydrate. (05 marks)

(c) Explain the relationship described in (b) for each carbohydrate.

(i) Lactose (03 marks)

(ii) Sucrose (05 marks)

(iii) Glucose (08 marks)

(d) Suggest what would happen to the colour for glucose and sucrose if the experiment continued for 10 more minutes. Give an explanation in each case. (10 marks)

(e) Explain why the boiling tubes were;

(i) Kept covered during the experiment (03 marks)

(ii) Placed in a water bath at 30^0C. (03 marks)