GASEOUS EXCHANGE

The uptake of molecular oxygen (O_2) from the environment and the discharge of carbon dioxide (CO_2) to the environment by cells

EXAMINATION TYPE QUESTION

a) **Compare the suitability of air and water as gas exchange media in animals / Comment on the suitability of air and water as media for gaseous exchange in animals.**
   - Air is much richer in oxygen than water, therefore much less volume of air is required to pass over the respiratory surface to satisfy the oxygen demands of the organism, but too much water is required to pass over the respiratory surface to enable the organism to extract oxygen to satisfy the oxygen demands. Therefore, air is suitable for much active animals while water is suitable for less active animals.
   - Air has much lower density and is less viscous than water, therefore much less energy is needed to move air through the respiratory system than is required for water.
   - Air is suitable for organisms without ventilation mechanisms like plants while water requires an actively operated ventilation mechanism like fish.
   - Air has a dehydrating effect on surfaces which slows gaseous diffusion, hence gas exchange surfaces must be folded into the body to reduce water loss. Air is not suitable for organisms whose gaseous exchange surfaces are exposed e.g. skin of frogs, external gills of tadpoles.
   - Slight temperature increase causes oxygen to diffuse out of water hence causing anoxic conditions while oxygen in air remains relatively stable.
   - Water's high density supports and prevents collapse of respiratory structures like gills lamellae while alveolar sacs collapse in absence of lung surfactants.
   - Unidirectional water flow during ventilation in aquatic animals like bony fish is energetically less costly than tidal ventilation in lungs of land animals.
   - Countercurrent flow of water with respect to blood flow over gill lamellae in bony fish improves oxygen extraction efficiency compared to non-directional ventilation of toads with air.
   - CO_2 is highly soluble in water, therefore it is easier to eliminate CO_2 in water than in air. O_2 is 30 time less soluble in water than in air, making water dwelling unfavourable for metabolically very active organisms.

b) **Despite the high efficiency of gills as respiratory structures in aquatic environments, terrestrial animals do not use gills for gaseous exchange. Explain.**
   - **Air is less buoyant than water.** The fine membranous lamellae of gills lack structural strength and rely on water for their support. Although air contains much more oxygen than water, a fish placed out of water soon suffocates because its gills collapse into a mass of tissue which greatly reduces the diffusion surface area of the gills. Unlike gills, internal air passages can remain open, because the body itself provides the necessary structural support.
   - **Water diffuses into air through evaporation.** Atmospheric air is rarely saturated with water vapor, except immediately after a rainstorm. Consequently, terrestrial organisms that are surrounded by air constantly lose water to the atmosphere. Gills would provide an enormous surface area for water loss.

Generalized features of gas exchange

- Involves diffusion of respiratory gases along their concentration gradients.
- Involves ventilation mechanisms to replenish oxygen to maintain a high concentration gradient.

Role of Diffusion in Gaseous Exchange

Diffusion is the only process by which CO_2 and O_2 move across the gaseous exchange surfaces.

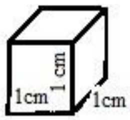
The factors that influence the rate of diffusion, surface area, concentration gradient, and diffusion distance, are described by ***Fick's Law:***

"The rate of diffusion is proportional to the surface area across which diffusion occurs, and inversely proportional to the square of the distance through which molecules must move."

Animals have evolved to maximize the diffusion rate across respiratory membranes by **increasing the respiratory surface area, increasing the concentration gradient across the membrane, or decreasing the diffusion distance**

How surface area to volume ratio affects exchange of substances

Small organisms e.g. amoeba



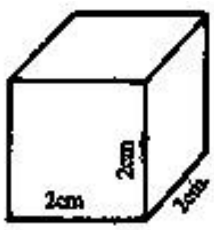
Area (A) of one surface = L x W
= 1 x 1
= 1cm²

Surface area (SA) = area of one surface x no. of surfaces
= 1cm² x 6
= 6cm²

Volume (V) = L x W x H
= 1 x 1 x 1
= 1cm³

SA:V ratio = $\frac{SA}{V}$
= $\frac{6}{1}$
= 6 cm⁻¹

Large organisms e.g. vertebrates



Area (A) of one surface = L x W
= 2 x 2
= 4 cm²
Surface area (SA) = surface of one surface x number of surfaces
= 4 cm x 6
Volume (V) = L x W x H
= 2 x 2 x 2
= 8 cm
SA:VR ratio = $\frac{SA}{V}$
= $\frac{24}{8}$
= 3 cm

SA to V ratio calculations for different-sized organisms

Organism	Length	SA(m²)	Vol.(m³)	SA/Vol
Bacterium	1µm	6 x 10^{-12}	10^{-18}	6,000,000:1
Amoeba	100 µm	6 x 10^{-8}	10^{-12}	60,000:1
Housefly	10 mm	6 x 10^{-4}	10^{-6}	600:1
Dog	1 m	6 x 10^{0}	10^{0}	6:1
Whale	100 m	6 x 10^{4}	10^{6}	0.06:1

Implications:

Bigger organisms have more difficulty in exchanging materials with their surroundings. Diffusion being effective up to a distance of less than 1cm is sufficient to satisfy gas exchange needs of very small organisms while **large organisms** must develop specialized gas exchange structures.

1. **Large organisms surface area to volume:**

   Advantages:
   - A small SA/V ratio decreases the rate of gaining unwanted substances e.g. toxic substances.
   - A small surface area to volume ratio enables slow heat loss during cold weather.

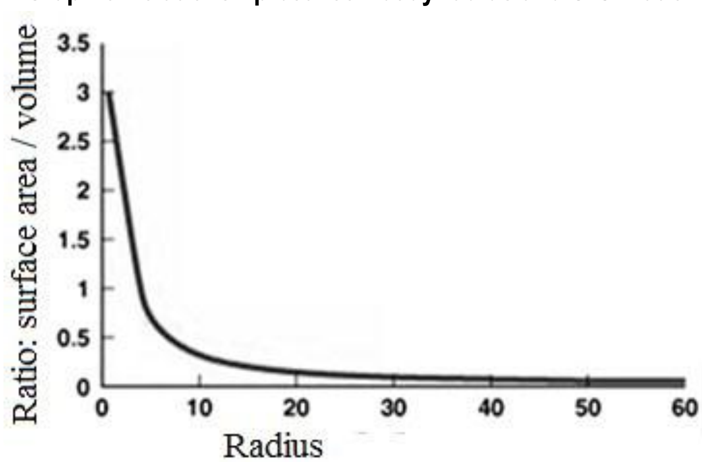
   Disadvantages:
   - A small SA/V ratio causes slow entry of useful substances into the body e.g. oxygen.
   - A small surface area to volume ratio causes slow heat loss during hot weather.

2. **Small organisms have a large surface area to volume ratio**

   Advantages:
   - A large surface area to volume ratio enables fast gaining of useful substances e.g. digested food, oxygen, etc.
   - A large SA/V ratio enables fast loss of toxic substances out of the body e.g. CO_2.
   - A large surface area to volume ratio enables fast heat loss during hot weather.

   Disadvantages:
   - A large surface area to volume ratio causes fast gain of unwanted substances into the body.
   - A surface area to volume ratio causes faster heat loss during cold weather.

Graph of relationship between body radius and SA/V ratio



Observations from the graph:

Increase in body radius from 0 to about 10 decreases surface area to volume ratio rapidly. Radius increase from 10 to 50 decreases gradually SA/V ratio, then remains constant.

In very small organisms, a small change in radius causes a big change in surface area to volume ratio

In very large organisms, big changes in radius cause very small changes in surface area to volume ratio.

Evolution of specialized gas exchange structures

Limitations imposed by the surface area of three dimensional structures led to evolution of specialized gas exchange structures like:

1) Gills (evaginations)
   - External in Tadpoles
   - Internal in Fish
2) Lungs (invaginations) in mammals, reptiles, amphibian and birds
3) Cutaneous in frogs

4) Tracheae in insects
5) Book-lungs in spiders

How organisms minimize the limitations of body sizes

Small organisms

- Living in habitats where harmful substances easily get diluted before harming the body e.g. in fresh water.
- Allowing body enzyme systems to function at varying temperatures

Large organisms

- Development of efficient transport system to speed up transport of O_2 and CO_2
- There is improved oxygen carriage by pigments.
- Development of ventilation mechanisms to ensure rapid gaseous exchange.
- They have high metabolic rate to release heat fast enough to match the rate of heat loss.

Characteristics of efficient gas exchange surfaces

- Have a large surface area relative to the volume of the organism to maximize the rate of gas exchange.
- Thin for gases to diffuse across faster.
- Moist to dissolve respiratory gases to ensure faster diffusion
- Permeable to the respiratory gases to enable their diffusion
- Organized or operated in a way that maintains a high concentration gradient for the diffusion of respiratory gases. *In vertebrates, gas exchange systems operate in tandem with circulatory system to maintain high concentration gradient.*

Gas exchange in unicellular organisms

In unicellular (single-celled) organisms such as protozoa e.g. amoeba, the medium of gas exchange is fresh water and the gas exchange surface is the plasma membrane.

Along their concentration gradients, dissolved oxygen diffuses from the water across the permeable plasma membrane into the cytoplasm while dissolved carbon dioxide diffuses into water.

GAS EXCHANGE IN PLANTS

In plants, different structures (roots, stems, leaves, flowers, fruits) care for their own gas exchange needs; therefore the medium of gas exchange varies depending on environmental location of each plant part.

Plants respire all the time, but photosynthesis only occurs when there is light. This means that **the net gas exchange** from a leaf depends on the light intensity.

$C_6H_{12}O_6 + 6O2 \rightarrow 6CO_2 + 6H_2O$ (aerobic respiration)

$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ (photosynthesis)

Net gas exchange in plants

The net (overall) effect depends on the time of day and the light intensity.

In darkness no photosynthesis occurs, hence in the absence of photosynthesis there is **a net release of carbon dioxide and a net uptake of oxygen**.

In bright light during the day, the rate of photosynthesis is much higher than the rate of respiration hence there is a **net release of oxygen and a net uptake of carbon dioxide**

In Dim light during **early morning** and **evening**, photosynthesis greatly decreases hence the release of oxygen also decreases while respiration occurs normally hence the release of carbon dioxide increases causing c**ompensation point.**

Compensation point is the light intensity at which the photosynthetic intake of carbon dioxide is equal to the respiratory output of carbon dioxide.

Why most plants lack specialized organs for gas exchange

- Each plant part takes care of its own gas exchange needs without dependence on a liquid transport system.
- Roots, stems, and leaves respire at rates much slower than occurs in animals. Only during photosynthesis are large volumes of gases exchanged, and each leaf is well adapted to take care of its own needs.

- The diffusion distance for gases is very short, even in a large plant because each living cell in the plant is located close to the surface. In stems, middle placed cells are dead while the only living cells are organized in thin layers just beneath the bark.
- The loose packing of parenchyma cells in leaves, stems, and roots provides an interconnecting system of air spaces which exposes one surface of most of the living cells in a plant to air.
- Both the cell walls and plasma membranes are permeable to oxygen and carbon dioxide, enabling diffusion of the gases across. Carbon dioxide diffusion may be aided by **aquaporin** channels inserted in the plasma membrane.

Why most animals have specialized respiratory systems

- Animal bodies are large with a small surface area to volume ratio, which limits the efficiency of diffusion alone in supplying oxygen and exit of carbon dioxide.
- Outermost integuments of most parts on animal bodies are impermeable to respiratory gases.
- Animal bodies are active therefore depend on fast metabolic rates to supply metabolites, which necessitates fast mechanisms for supplying oxygen and disposal of carbon dioxide.
- Animal tissues are thickened layers of cells, for which diffusion alone would be ineffective.

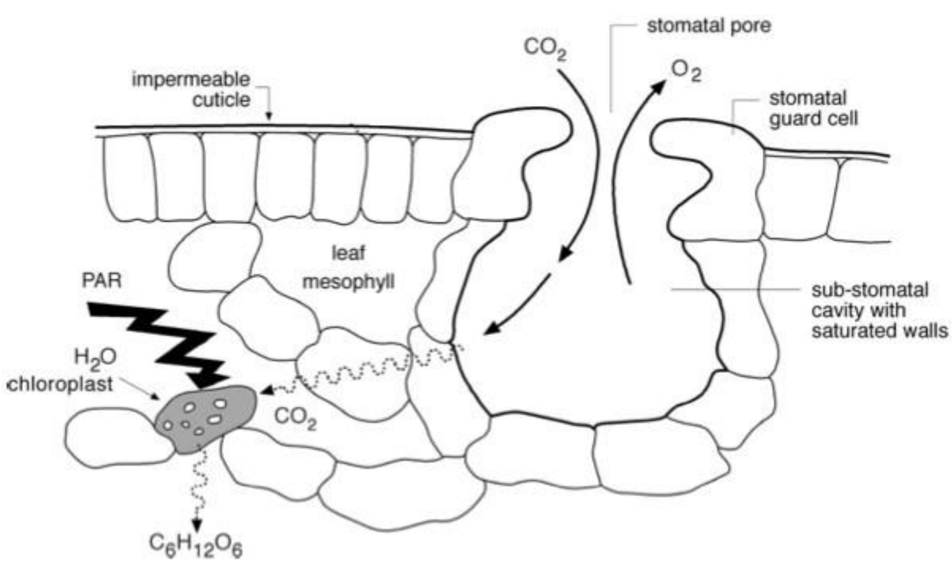
How air enters the plant body

Structure	Explanatory notes
Lenticels	Pores in woody plants that form between the atmosphere and the cambium layer of stems and trunks.
Stomata	Typically found in epidermis of leaves, but can occur on herbaceous stems. Stomata open and close by guard cells, regulated by CO_2 and moisture.

Gas exchange in leaves

The exchange of oxygen and carbon dioxide in the leaf occurs through **stomata** (singular = stoma).

Cross section of part of a leaf



Mechanism of stomata opening and closure

Turgidity of guard cells causes stomata to open, and when guard cells lose water to become flaccid, stomata close.

Main theories of Stomatal Opening and Closure

1. **Theory of photosynthesis in guard cells**

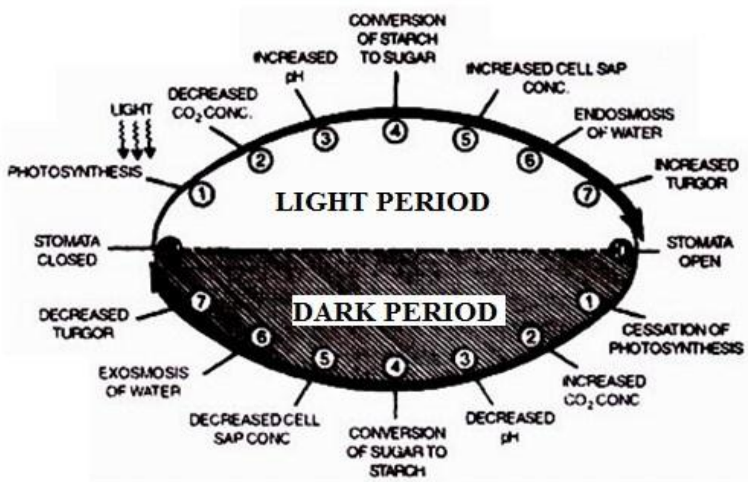
Stomatal opening:

In light, photosynthesis in guard cells forms sugar, which increases the solute concentration of cell sap and decreases water potential. Endosmosis occurs from subsidiary cell to guard cell, to increase turgor pressure in guard cells causing stomata opening

Stomatal closure:

In darkness, photosynthesis in guard cells is inhibited, solute concentration of cell sap decreases causing exosmosis into subsidiary cell from guard cell. Guard cells become flaccid causing stomata to close.

2. **Starch-sugar inter-conversion theory**



3. **Active potassium theory**

Stomatal opening:

During day, blue light activates the conversion of **starch** into **malic acid** and **protons (H^+)** inside guard cells.

In exchange for H^+, guard cells **actively** take up **K+ ions** using **ATP** from light reactions of photosynthesis and **cytokinin** (a plant hormone).

As the concentration of K^+ ions increases in sap of guard cells, the concentration of H+ ions decreases to increase pH above 7 (sap becomes alkaline).

Guard cells increase uptake of Cl^- (anions) to maintain electrical and ionic balance inside and outside.

Malate anions formed in the guard cells are neutralized by K+ ions to form potassium malate, which enters the cell sap of guard cells to increase solute concentration

Stomatal closure:

Darkness inhibits photosynthesis in guard cells, causing increase in CO_2.

Malic acid concentration decreases because of conversion to starch.

Efflux of K^+ ions from guard cells and influx of H^+ ions decreases sap pH below 7 in guard cells.

There is loss of Cl^- ions from guard cells to maintain electrical neutrality.

Solute concentration decreases while water potential increases inside guard cells, which lose water by **exosmosis** to become flaccid.

Loss of turgidity by guard cells causes closing of stomata

Note:

When soil water is insufficient to keep up with transpiration around mid-day, Abscisic acid (ABA) which is a plant growth inhibiting hormone favours closing of stomata by stimulating loss of negatively-charged ions (anions) especially NO_3^- and Cl^-, and K^+ from the cytosol and efflux of H^+ ions from guard cells. Ca^{2+} enter guard cells, which triggers release of Ca^{2+} from vacuole into cytosol, which reduces the solute concentration of the cell and thus turgor, causing stomatal closure.

ABA act as stress hormone during drought condition.

Adaptations of plant parts for gaseous exchange

Leaves:

- Spongy mesophyll cells are loosely packed to accommodate much air which increases the concentration gradient of gases to enable faster diffusion.
- Spongy mesophyll cells are covered by a thin film of water to dissolve respiratory gases to enable faster diffusion
- Palisade mesophyll cells are tightly packed with thin walls to reduce diffusion distance.

- High stomatal density in upper leaf surface increases rate of diffusion of gases
- Differences in thickness of guard cell walls enables the thin outer wall to bulge out and force the thicker inner wall into a crescent shape to open stomata when full turgor develops while regaining of shape when guard cells lose turgor causes stomatal aperture to close.
- Floating leaves (e.g. water lilies) generally lack stomata in lower epidermis but very many stomata in the upper epidermis to maximise gas exchange with air at the upper surface.
- Leaves of hydrophytes have very thin or no cuticle to reduce or prevent any barrier to the diffusion of gases into the leaves
- In land plants, stomata are spread out over leaves, to increase the rate of diffusion of waste gases produced by the leaf, which stops the build-up of excreted products that would slow gas exchange.
- Leaves are thin, which increases diffusion rates of gases.
- Leaves have a very large surface area, which increases diffusion rate of gases.
- Sunken in stomata and sub stomatal spaces enable leaves to minimise stomatal transpiration while maintaining gaseous exchange
- Some plants e.g. water lilies have elongated petioles to enable lamina maintain access to atmospheric air for gaseous exchange

Roots and stem:

- Internally, stems of hydrophytes have large intercellular / air spaces / aerenchymatous tissue to accommodate much air which increases concentration gradient for faster diffusion of gases.
- Black Mangroves which live in oxygen deficient mud have pneumatophores (breathing roots projecting up) with air filled spongy tissue connected to lenticels (pits) for faster diffusion of oxygen to all cells.
- Mangroves which live in oxygen deficient mud water have relatively short roots to remain in close to oxygen rich mud surface to avoid the oxygen deficient deeper layers of mud.
- Red Mangroves which live in oxygen deficient mud have air-rich pneumatophores in prop roots to supplement the oxygen uptake.
- Stems of submerged plants have little or no cuticle to reduce the barrier for gas diffusion.
- Stems of hydrophytes have large air spaces to enable floating to expose leaves above water for access to atmospheric air.
- Some aquatic plants elongate stems to enable stomata access atmospheric air for gaseous exchange.

Gaseous exchange in plant roots and stems

The medium of gas exchange for roots and stems of land plants is air.

For mature roots, dissolved oxygen from soil air diffuses through the loosely attached dead cork cells where there are non-suberized pores called **lenticels**. On reaching inner tissues, O_2 diffuses across the permeable cell walls and plasma membranes of living cells into the protoplasm while CO_2 diffuses from cells into intercellular spaces, then through lenticels into soil air.

For mature stems, atmospheric oxygen diffuses through lenticels to dissolve in the moisture of intercellular spaces of inner tissues, then diffuses across the permeable cell walls and cell membranes of living cells into the protoplasm while carbon dioxide diffuses from cells into intercellular spaces to atmosphere

Role of oxygen in plants

- Facilitates aerobic respiration to release ATP for active transport.
- Decreases toxicity of reduced compounds (e.g. sulfides).
- Supports nitrification and methane oxidation.
- Precipitates metals in soil

EXPERIMENTS ON GAS EXCHANGE

EXPERIMENT I

Five small discs cut from spinach leaves were floated on a small volume of buffered hydrogen carbonate solution in a flask attached to a respirometer. The discs were first exposed to bright light, then to dim light and finally left in the dark. Oxygen release was recorded as positive values and oxygen uptake as negative values as given in the table.

Light intensity	Time interval in minutes	Oxygen uptake or release in mm^3
Bright light	0 – 3 3 – 6 6 – 9 9 – 12	+57 +64 +58 +60
Dim light	12 – 15 15 – 18	+16 +3
Dark	18 – 21 21 – 24 24 – 27 27 – 30	- 16 - 12 - 15 - 14

a) Present the data in a suitable graphical form

b) (i) Calculate the mean rate of oxygen release in bright light

(ii) Explain the significance of the results obtained from this experiment.

c) Explain the use of the following in the experiment above:

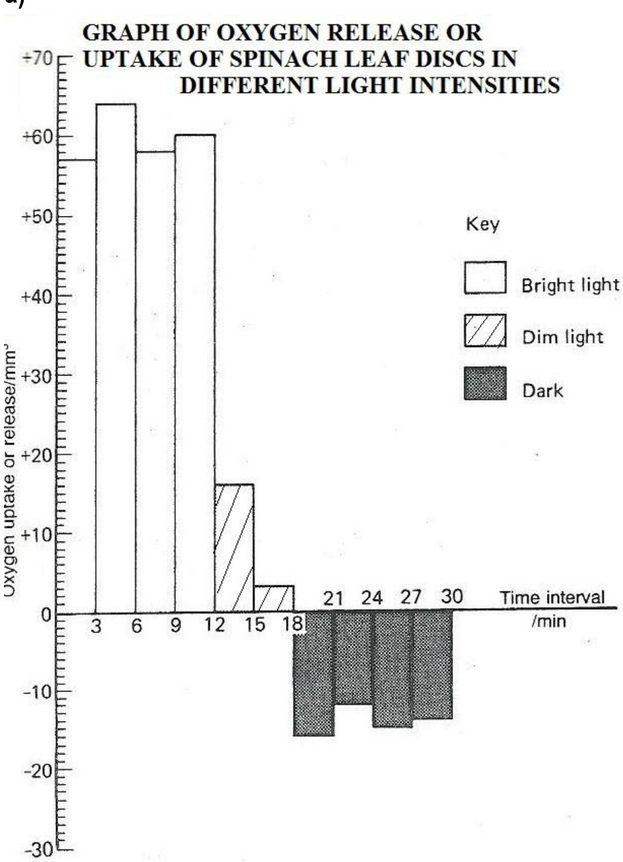
i) Five small leaf discs, not one.

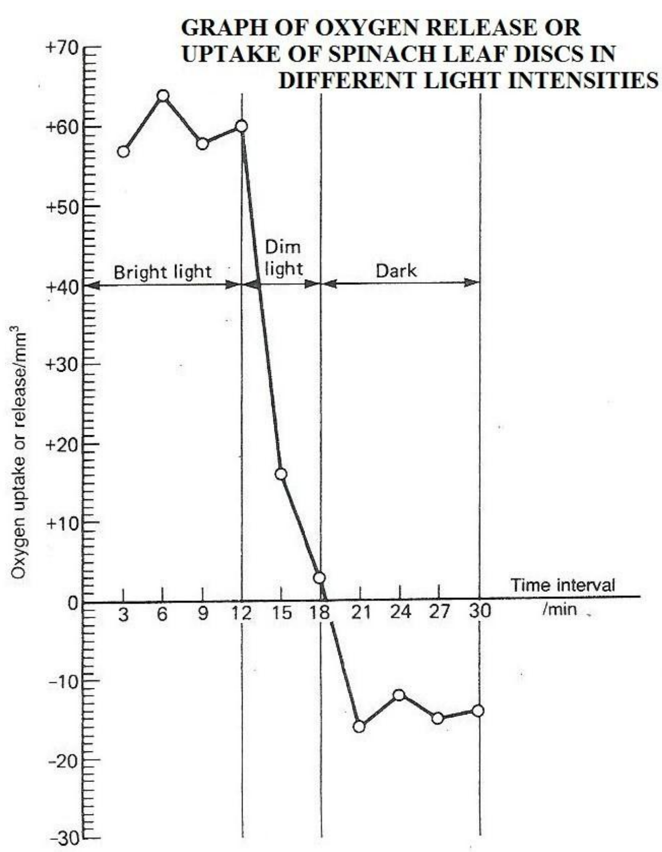
ii) Hydrogen carbonate solution

iii) Buffered hydrogen carbonate solution

Suggested answers:

a)





b) (i) Total oxygen released = 57 + 64 + 58 + 60 = 239 mm^3

Total period of oxygen release = 12 minutes

Rate = $\frac{239}{12}$ = 19.9 $mm^3 min^{-1}$ **OR** 19.9 mm^3/min **OR** 19.9 mm^3 per minute

(ii)

Observations / Description	Explanation
In bright light, rate of oxygen release is rapid and relatively constant.	Oxygen release is a measure of photosynthesis. In bright light photosynthesis is rapid hence releasing oxygen rapidly. The constancy in oxygen release is because some factor other than light intensity is limiting photosynthesis (e.g. carbon dioxide concentration), hence additional light has no further effect.
In darkness, rate of oxygen uptake is slow and relatively constant.	Oxygen uptake is a measure of respiration. In darkness, photosynthesis is inhibited while respiration occurs. The slow uptake of oxygen is because plant leaves respire slowly since energy demands are low. The constancy in oxygen uptake is because of factors limiting respiration.
In dim light, rate of oxygen release decreases rapidly.	In dim light intensity limits photosynthesis and therefore reduction in light intensity produces a great decrease in the rate of photosynthesis. At about 18.5 minutes represents **compensation point** which represents the light intensity at which the oxygen the oxygen released in photosynthesis is exactly counterbalanced by that taken up in respiration**.**

c) (i)
-To minimise errors in the experiment which may be caused by deficiencies in one leaf disc.
-Oxygen released would be very low to be detected.
(ii) To increase on / provide carbon dioxide to the photosynthesizing leaf discs.
(iii) To maintain PH so as to avoid inhibiting the activity of photosynthetic and respiratory enzymes.

EXPERIMENT II

Hydrogencarbonate indicator is used to show carbon dioxide concentration in solution. The table shows the colour that the indicator turns at different levels of carbon dioxide concentration.

Concentration	Indicator turns
Highest	Yellow
Higher	Orange
Atmospheric level	Red
Low	Magenta
Lowest	Purple

A leaf is placed in a stoppered boiling tube containing some hydrogen carbonate indicator solution. The effect of light intensity can then be investigated.
The table shows some typical results.

Condition	Tube 1	Tube 2	Tube 3	Tube 4
Light turned on	✓	✓	✓	✓
Paper on tube	Black paper	Tissue paper	None	None
Leaf	Living	Living	Living	Dead (boiled)
Indicator colour at the end	Yellow	Magenta	Purple	Red
Carbon dioxide concentration	Highest	Low	Lowest	Atmospheric level
Respiration	✓	✓	✓	✗
Photosynthesis	✗	✓	✓✓	✗

- Tube 4 was a control. The results in tubes 3 and 4 show that the leaf has to be alive for the carbon dioxide concentration to change.
- Tubes 1, 2 and 3 show the effect of increasing the light intensity. The black paper stopped light reaching the leaf in tube 1, so only respiration could happen.
- The tissue paper stopped some of the light reaching the leaf in tube 2, and the leaf in tube 3 received the most light.
- Photosynthesis happened as well as respiration in tubes 2 and 3, so there was a net absorption of carbon dioxide.
- The rate of photosynthesis was greatest in the leaf in tube 3, and it had the greatest net absorption of carbon dioxide.

GAS EXCHANGE IN EARTHWORMS

Earthworms exchange oxygen and carbon dioxide with water or air directly through their moist skin. Dissolved oxygen diffuses into tiny blood vessels under the skin surface, where it loosely combines with **haemoglobin** that moves it through bloodstream to tissues. Carbon dioxide released by tissues attaches to haemoglobin then detaches to diffuse out of the skin.

EXAMINATION TYPE QUESTION

Explain how earthworms solely use the skin for gas exchange yet their bodies are quite large.

- Earthworms have low metabolic rate, therefore require relatively low oxygen supply for aerobic respiration.
- Moist surface with dense network of blood capillaries under the skin enable efficient gas exchange between air and blood.
- Earthworm circulatory system contains haemoglobin in blood to increases the oxygen carrying capacity of blood.
- Long, thin body provides large surface area compared to body size, efficient for gas exchange.
- Blood capillaries are very close to the skin surface to reduce the diffusion distance for gases.

GAS EXCHANGE IN INSECTS *Terrestrial insect e.g. grasshopper*

- Increased CO2 is detected by chemoreceptors, causing relaxation of the abdominal muscles, increased volume and lowering of pressure. The spiracle valves open and air rich in oxygen is drawn into the tracheal system.
- Spiracles valves then close and oxygen is forced along the tracheal system into the fluid-filled tracheoles, which are in direct contact with the tissue fluid. Gaseous exchange occurs along concentration gradients of oxygen and carbon dioxide.
- Air is expelled out when muscles contract and flatten the insect body, decreasing the volume of the tracheal system.
- During increased metabolic activity, the water potential of tissue lowers (hypertonic) due to accumulation of wastes like lactic acid, causing osmotic efflux of water from the tracheoles into tissues. Air fills the tracheoles and oxygen diffusion through tracheoles is faster.
- In resting tissues, the water potential of tissue fluid increases (hypotonic), causing the fluid to fill the tracheoles

NOTE:

When water leaves body cells to fill the trachea, it reduces water's effective surface area when asleep or dormant hence reducing chances of evaporation because the spiracle valves will be closed.

In some insects like grasshopper, there is a one-way flow of air, which increases the efficiency of gas exchange as CO_2-enriched air can be expelled without mingling with the incoming flow of fresh air.

Spiracle valves are opened and closed in a particular order which allows the insect to suck air into the tracheal system at one end of the body and to circulate the air through the system and pass it out at the other end of the body.

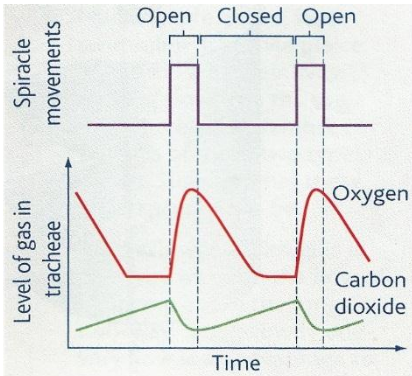
Gas exchange in aquatic insects

- Aquatic insects also use tracheal system for gas exchange.
- Some insect larvae ("wigglers") like mosquito, have a siphon/breathing tube that connects the tracheal system to the water surface for obtaining oxygen and disposal of carbon dioxide.
- Some insects that can submerge for long periods carry an air bubble from which they breathe.
- Some insects have spiracles at the tips of spines. When the spines pierce the leaves of underwater plants oxygen is obtained from the bubbles formed by photosynthesis within the leaves.

- Some aquatic insect larvae have gills into which oxygen diffuses from the water, then into a gas-filled tracheal system for transport through the body.

TYPICAL EXAMINATION QUESTION

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.
When spiracles are open the level of oxygen in the tracheae increases rapidly to a maximum; while the level of carbon dioxide decreases rapidly;
When spiracles close the level of oxygen immediately decreases rapidly; and thereafter remains constant; while the level of carbon dioxide increases gradually;

b) Explain the pattern of level of gases in tracheae in relation to spiracle movements.
Opening of spiracles enables rapid entry of oxygen until the tracheae fill up. This is because of relaxation of abdominal muscles which increases abdominal volume while abdominal pressure decreases below atmospheric pressure.
When spiracles close oxygen rapidly diffuses along a concentration gradient into respiring cells until the gradient can no longer allow any more diffusion into cells hence oxygen level in the tracheae later remains constant.
Opening of spiracles enables rapid exit of carbon dioxide from tracheae along a concentration gradient.
When spiracles close carbon dioxide gradually diffuses along a concentration gradient from respiring cells into the closed tracheae

c) (i) From the information provided by the graph suggest what causes the spiracles to open
The increasing level of carbon dioxide
(ii) What is the advantage of the observed spiracle movements to a terrestrial insect?
Observation: Interval of spiracle opening is very short while interval of spiracle closure is relatively long. Advantage: Longer spiracle closure period conserves water because water vapour does not diffuse out continually.

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?
The earlier atmosphere contained more oxygen than the present atmosphere

MODES OF VENTILATION IN VERTEBRATES

1) **Non-directional:** Respiratory medium flows past gas exchange surface in an unpredictable pattern e.g. in earthworms.
2) **Directional:** Respiratory medium flows in a particular direction. Directional ventilation is of two categories:
   a) **Bidirectional (tidal) ventilation:** Occurs when the external medium moves in and out of the respiratory chamber in a back-and-forth movement e.g. alveoli of mammalian lungs.
   b) **Unidirectional ventilation:** Medium enters the chamber at one point and exits at another causing the medium to flow in a single direction across the respiratory surface.

   Unidirectional ventilation includes: concurrent, countercurrent and crosscurrent flow.

i) **Concurrent:** Blood flows in the same direction as the medium. Concurrent flow allows the pO_2 of the blood to equilibrate with the pO_2 of the respiratory medium e.g. dog fish shark.

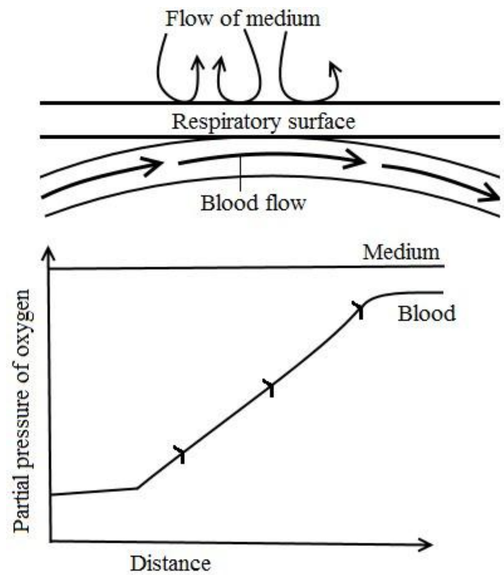
ii) **Countercurrent:** Blood and the respiratory medium flow in opposite directions e.g. bony fish. The pO_2 of the blood leaving the gas exchange surface can approach that of the inhaled medium.

iii) **Crosscurrent:** Blood flows at an angle relative to the flow of the external medium.

PATTERNS OF FLOW AT GAS EXCHANGE SURFACES

1. NON-DIRECTIONAL VENTILATION

Partial pressure of oxygen (PO2) in the blood leaving the gas exchanger can approach the PO2 in the medium. Anything that increases diffusion distance, will decrease oxygen exchange efficiency and reduce the pO_2 in the blood leaving the gas exchanger.



2. DIRECTIONAL (BIDIRECIONAL VENTILATION)

Tidal Ventilation

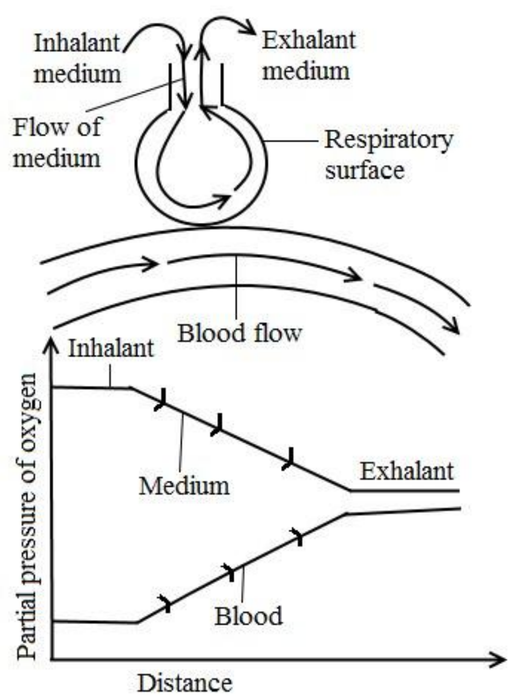
Respiratory cavities do not fully empty.

Fresh air mixes with oxygen-depleted residual air.

pO_2 of blood equilibrates with the PO2 of the respiratory cavity.

Tidal ventilation is much less efficient, with humans only extracting about 25% of the oxygen inhaled.

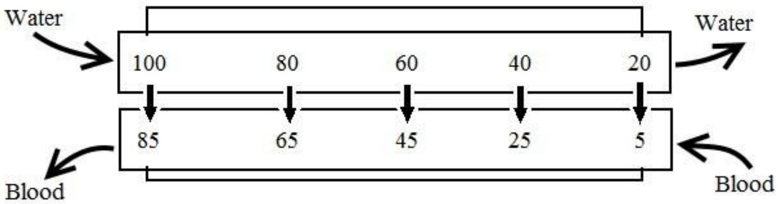
Tidal flow suits terrestrial animals because they have the problem of water loss.

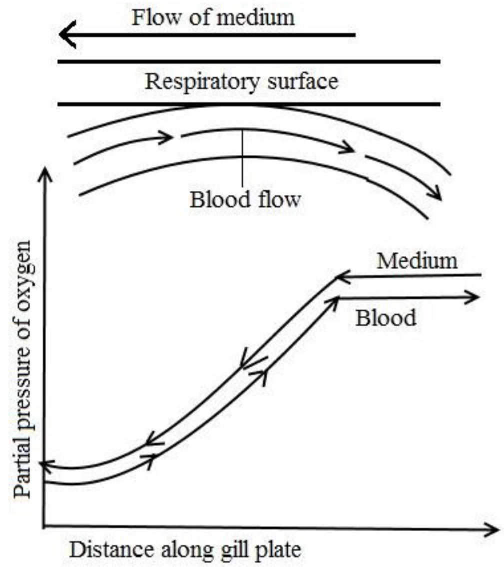


3. DIRECTIONAL (UNIDIRECIONAL)

Countercurrent Ventilation

- Water flows across the gill lamellae in an opposite direction to the blood flow, enabling much of the oxygen (80-90%) from the water diffusing into the blood.
- Although dissolved oxygen levels in water drop as the water flows across the gill lamellae, the blood has lower levels; therefore a sustained diffusion gradient is maintained throughout.
- Countercurrent flow maintains high O2 gradient between water and blood, such that O2 diffusion into blood occurs even after blood acquires more than 50% of the water's O2 content.





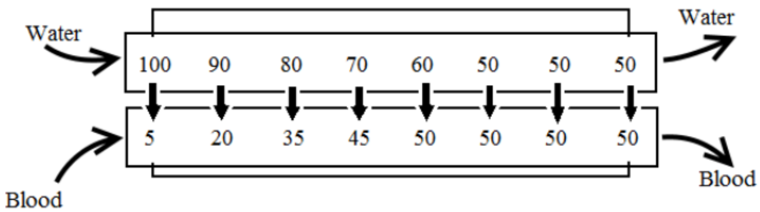
Advantages of counter flow

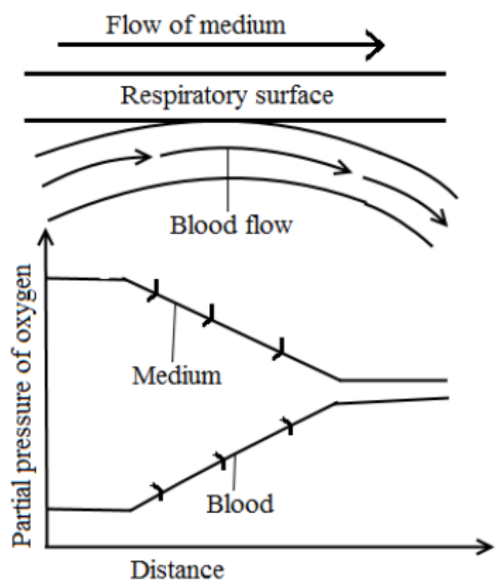
- Enables blood of the gill lamellae to extract maximum oxygen from the water for the entire period the water flows across the gill filaments.
- Under conditions permitting adequate oxygen uptake, the counter-current fish expends less energy in respiration compared to parallel flow.

4. DIRECTIONAL (UNIDIRECIONAL):

Concurrent flow / Parallel flow

- Blood in the gill lamellae flows in the same direction and at the same speed as the water passing it, resulting in only half (50%) of the available oxygen from the water diffusing into blood. The blood and water reach equilibrium in oxygen content and diffusion stops.
- During parallel flow, initially large amounts of oxygen diffuse but the efficiency reduces when the fluids start to reach equilibrium.
- The concentration of oxygen gained from this system does not meet the physiological needs of the fish.





How to improve parallel flow:

When the flow of water is very rapid compared to blood flow rate, to ensure a higher saturation of the blood by the time it leaves the respiratory surface.

How countercurrent is prevented in a dogfish:

The vertical septum deflects the water so that it tends to pass over rather than between the gill plates, hence flowing parallel to the lamellae through the gill pouches.

RESPIRATORY PIGMENTS

A **respiratory pigment** is any molecule that increases the oxygen carrying capacity of blood.

While the transport of respiratory gases in insects occurs directly with body cells without any respiratory pigment getting involved, many other animals use respiratory pigments.

Respiratory pigments are necessary:

- Because O_2 has low solubility in aqueous solution.
- To enable pickup of molecular O_2 at sites of high O_2 tension and deposition at sites of low O_2 tension.
- To enable blood to carry a much greater quantity of O_2
- To enable quick removal of O_2 from respiratory surfaces, thus maintaining a concentration gradient down which O2 can diffuse.

Pigment	Example of organism	Explanatory notes
Haemoglobin	Mammals, invertebrates like annelids, molluscs, echinoderms, flatworms, and some protists.	• **Fe-containing protein** structurally similar to cytochromes, thus also found in plants • Contains four haem groups, each of which can combine with one O_2 molecule. • **Dark red** when deoxygenated, **bright red** when oxygenated. • May occur within RBCs or in suspension in blood.
Haemocyanin	Invertebrates like gastropods and cephalopods, crustaceans, arachnids, and horseshoe crabs	• **Copper** dissolved in the circulating fluid (haemolymph) • One haemocyanin molecule contains two Cu atoms and can combine with one O_2 molecule. • **Blue** when deoxygenated, **colorless / white** when oxygenated
Haemerythrin	Polychaetes	• **Fe-containing protein** • One Haemerythrin molecule contains several Fe atoms and each O_2 molecule can combine with 2 or 3 Fe atoms • **Brownish** in deoxygenated state, **purple** in oxygenated state • Occurs within coelomocytes that circulate in coelomic fluid

GAS EXCHANGE IN FROGS

Gaseous exchange in the frog takes place in three main parts of the body:

(1) Skin (cutaneous) - especially during low activity when hibernating **(2)** Mouth [buccal cavity] **(3)** the lungs

Frog Cutaneous gaseous exchange:

Oxygen from atmospheric air dissolves in moisture / mucus at the outer skin surface, then diffuses through the thin skin into the underlying dense capillary network while carbon dioxide diffuses out of the skin.

Cutaneous respiration is actually more significant than pulmonary (lung) ventilation in frogs during **winter**, when their metabolisms are slow while lung function becomes more important during the **summer** as the frog's metabolism increases.

Frog Mouth (Buccal cavity) gaseous exchange:

The muscles of the mouth contract to lower the surface of the mouth hence reducing its pressure than that of the atmosphere.

Air rich in oxygen is inhaled through the nostrils into the mouth cavity. Oxygen diffuses into the dense capillary network under the buccal cavity lining and is transported by the red blood cells. Carbon dioxide diffuses from the blood tissues to the buccal cavity; then exhaled through the nostrils when the mouth floor is raised.

Frog Lung (Pulmonary) ventilation:

Amphibians use **positive pressure breathing** to force air into their lungs by creating a greater-than-atmospheric pressure **(positive pressure)** in the air outside their lungs.

Inhalation:

- Mouth and glottis close while nostrils open
- Sternohyoid muscles contract while petrohyoid muscles relax.
- Floor of buccal cavity lowers to increase buccal cavity volume while decreasing pressure below atmospheric pressure.
- Atmospheric air rushes to fill the buccal cavity via open external nostrils.

- Nostrils close, then floor of buccal cavity is raised by simultaneous contraction of petrohyoid muscles and relaxation of Sternohyoid muscles, which decreases buccal cavity volume while increasing pressure above lung pressure, which forces air into lungs via open glottis.
- O_2 diffuses into lung capillaries along concentration gradient while CO_2 diffuses from lung capillaries into alveolus

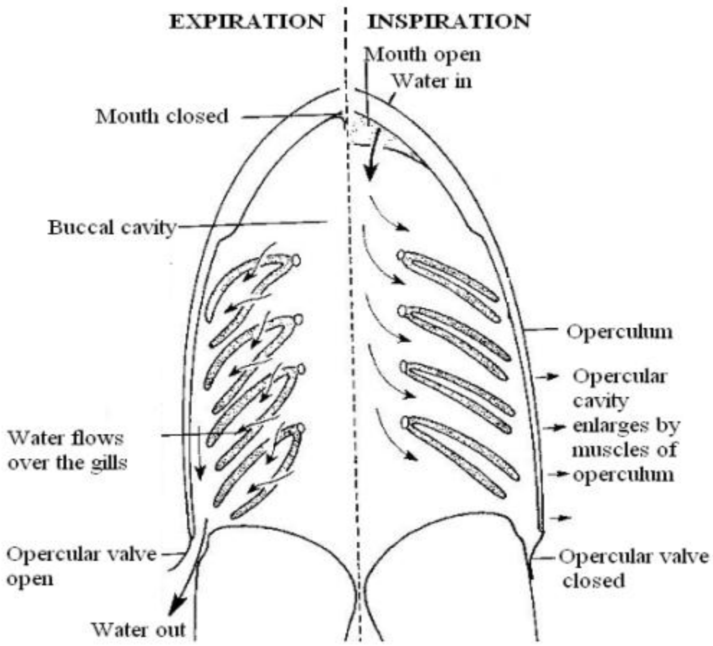
Exhalation:

- Sternohyoid muscles contract while petrohyoid muscles relax.
- Floor of buccal cavity lowers to increase buccal cavity volume while decreasing pressure below lung pressure.
- Air rich in CO_2, from lungs is forced out into the buccal cavity through glottis. At the same time, atmospheric air enters the buccal cavity via external nostrils
- Thus during pulmonary respiration, the buccal cavity receives mixed air, which is again pushed into the lungs.
- Therefore, oxygenation of amphibian blood by the lungs being inefficient is supplemented by cutaneous respiration—the exchange of gases across the skin

GAS EXCHANGE IN BONY FISH

Description of respiratory system in bony fish

Horizontal section through pharynx and gill region



Adaptations of the gill filaments for gaseous exchange

- Gill filaments have folds called ***secondary lamellae*** that increase the surface area for gas exchange.
- The gill lamellae contain a network of capillaries for carrying away oxygen or bringing in Carbon dioxide for expulsion.
- There is counter current flow i.e. water and blood in the gills flow in opposite directions to maintain a favourable concentration gradient for diffusion of respiratory gases.
- Gill filaments are moist to enable dissolution of respiratory gases for efficient diffusion.
- Gills filaments are ***thin-walled*** to provide a short distance for diffusion of respiratory gases.
- Tips of adjacent gill filaments overlap = increases the resistance to the flow of water over gill surfaces and slows down the movement of water= more time for gaseous exchange to take place

Mechanism of ventilation in bony fish

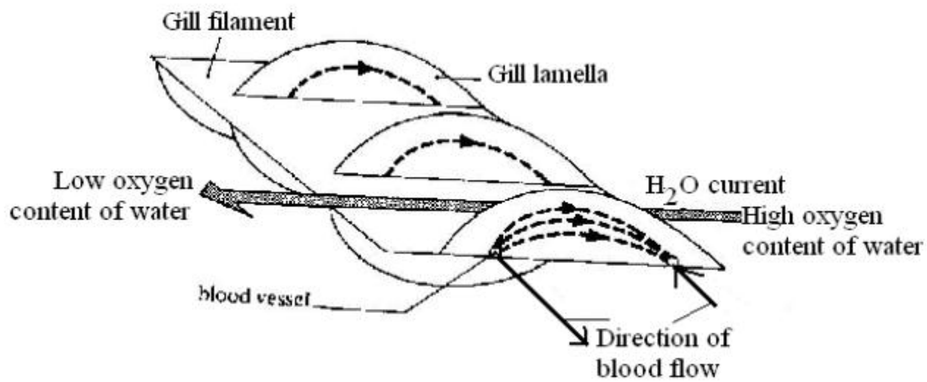
INHALATION

- Contraction of the mouth muscles lowers the floor of the mouth, increasing buccal cavity volume as pressure decreases.
- Water rushes to fill the buccal cavity, and at the same time, water's pressure outside presses against and closes opercular valves.

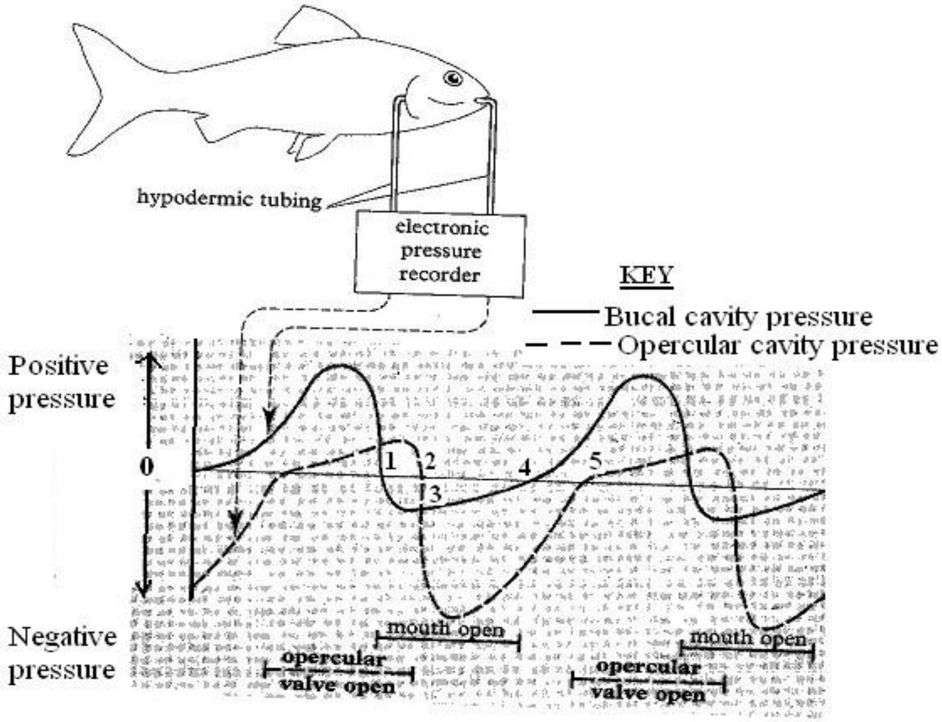
- Operculum muscles contract; causing operculum to bulge; and increase opercular volume but decreases opercular cavity pressure.
- Mouth contracts to decrease buccal cavity volume while increasing pressure, which forces/sucks water into opercular cavity which is at lower pressure.
- As water flows over gill filaments in opposite direction to flow of blood (**countercurrent flow)** O_2 diffuses into blood capillaries to combine with haemoglobin while CO_2 diffuse into the flowing water along concentration gradients.

EXHALATION

- Mouth muscles are fully contracted with mouth valve tightly closed.
- Opercular muscles relax to decrease opercular cavity volume and increase pressure.
- Pressured water in opercular cavity forces opercular valves to open as water exits.



Pressure changes in buccal and opercular cavities in bony fish ventilation



Observations and explanations from the graph

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

At 2, opercular cavity is expanding, 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 buccal cavity to opercular cavity.

At 5, opercular cavity is contracting to decrease the volume as pressure increases above atmospheric pressure **(acquires positive pressure)**; opercular valve opens and water is expelled

NOTE:

i) ***Water almost flows in one direction from the buccal cavity to the opercular cavity.***
<u>EVIDENCE:</u> *Throughout the ventilation cycle, except for one short period when the buccal cavity expands* ***(see 1 above),*** *the pressure in the buccal cavity is higher than that in the opercular cavity forcing water to flow from the buccal cavity to the opercular cavity along the pressure gradient. Expansion of buccal cavity lowers the pressure below atmospheric pressure, causing the water to enter the buccal cavity but at the same time the opercular valves close to prevent entry of water.*

ii) *The buccal cavity acts as a force pump while the opercular cavity acts as a suction pump*

WORKED EXAMPLES

Qn. 1. (a) Explain why when fish are taken out of the water, they suffocate.

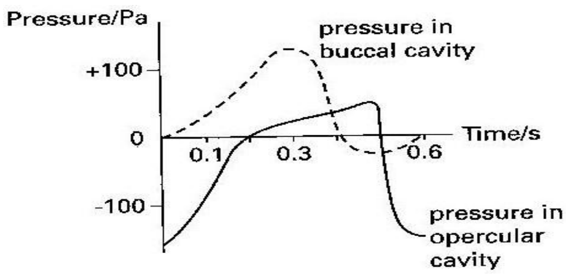
This is because ***(1)*** *their gill lamellae collapse and there is not enough surface area for diffusion to take place.* ***(2)*** *the gill lamellae surface dries and oxygen in air fails to dissolve and diffuse into blood.*

Note: There are actually some fish that can survive out of the water, such as the walking catfish because they have modified lamellae, allowing them to breathe air.

b) Under what circumstances do fish suffocate in the water?

- *When the oxygen in the water is depleted by another biotic source such as bacteria/decomposers.*
- *When oxygen greatly diffuses out of water due to increase in water temperature.*

Qn. 2. The graph below shows the changes in pressure in the buccal cavity and in the opercular cavity during a ventilation cycle.

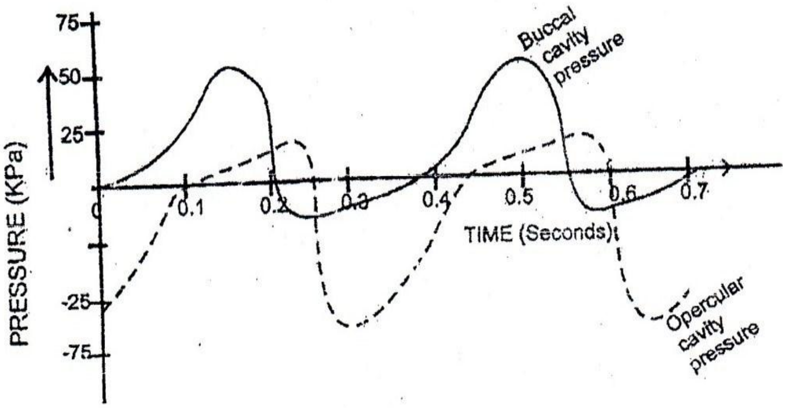


a) **Calculate the rate of ventilation in cycles per minute**
Since the duration of one cycle is 0.6 seconds, therefore ventilation rate

b) **With evidence from the graph, explain why water almost flows in one direction over the gills**.
The pressure in the buccal cavity is higher than opercular cavity pressure in the first 0.4 seconds, therefore water moves from buccal cavity over the gills to opercular cavity along the pressure gradient. After 0.3 seconds, the buccal cavity expands and lowers the pressure, causing the water to enter the mouth but at the same time the opercular valves close to prevent entry of water

c) **How does the fish increase buccal cavity pressure?**
The mouth closes, the floor of buccal cavity is raised and the buccal cavity pressure increases

Qn 3: The figure below shows the pressure changes in the buccal and opercular cavities of a teleost fish obtained by using hypodermic tubing connected to a pressure recorder. Negative pressure indicates expansion while positive pressures mean contraction of the cavities.



The table below summarizes the features of gills in three species of teleost fish A, B and C.

Fish Species	**Thickness of lamellae / µm**	**Distance between lamellae /µm**	**Distance between blood and surrounding water / µm**
A	35	75	6
B	15	40	3
C	5	20	1

a) Describe the pressure changes in the buccal cavity for the first 0.5 seconds. (10 marks)
b) Compare the pressure changes in the buccal cavity and opercular cavity in the first 0.4 seconds. (06 marks)
   i) Explain the observed changes in the buccal cavity and opercular cavity from 0.2 seconds to 0.6 seconds. (06 marks)
   ii) What is the physiological significance of the differences between the pressure in the buccal and opercular cavities? (02 marks)
   iii) Comment on the relationship of the thickness of the lamellae and distance between blood and surrounding water. (02 marks)
c) Explain the significance of the features of the gills in the table in gas exchange. (04 marks)
d) State other structure features of the teleost fish which are important in breathing and gas exchange. (06 marks)
e) Blood in the lamellae of the teleost fish flows in opposite direction to that of water. Comment on the efficiency of this mechanism in gas exchange. (04 marks)

a) Comparison of pressure changes in buccal cavity and opercular cavity for the first 0.4 seconds (8 marks) *Similarities*

- *Both Increase from 0 second to 0.15 second and from 0.3 second to 0.4 second;*
- *Both have positive pressure from 0.1 second to 0.2 second;*
- *Both have negative pressure from 0.25 second to 0.4 second;*
- *Both are equivalent at 0.2 second and 0.25 second;*

Differences

*From 0 second to 0.1 second, opercular cavity pressure is negative **while** buccal cavity pressure is positive; From 0 second to 0.1 second, opercular cavity pressure increases rapidly **while** buccal cavity pressure increases slowly;*
*From 0.1 second to 0.15 second, opercular cavity pressure increases slowly **while** buccal cavity pressure increases rapidly;*
*From 0.15 second to 0.2 second, opercular cavity pressure increases **while** buccal cavity pressure decreases;*
*From 0.25 second to 0.3 second, opercular cavity pressure decreases **while** buccal cavity pressure increases;*
*The maximum buccal cavity positive pressure is **higher** than the maximum opercular cavity positive pressure;*
*The minimum buccal cavity negative pressure is **lower** than the minimum opercular cavity negative pressure;*

b) Account for the observed changes in pressure in the buccal and opercular cavities from 0.2 seconds to 0.6 seconds (14 marks)

From 0.1 second to 0.25 second, opercular valves are open while mouth valve is closed;
*From 0.1 second to 0.15 second, the buccal cavity expands, the pressure decreases below atmospheric pressure (acquires negative pressure)**;** mouth valve opens and water enters from outside.*
From 0.25 second to 0.4 second mouth valve is open while opercular valves close; opercular cavity expands, pressure reduces below atmospheric pressure (acquires negative pressure); Pressure in opercular cavity decreases below that of buccal cavity which has begun to contract, resulting in water being sucked into opercular cavity from buccal cavity;
At 0.4 second, floor of buccal cavity is elevated to reduce buccal cavity volume as buccal cavity pressure rises above atmospheric pressure (acquires positive pressure); mouth valve closes and water is forced from buccal cavity to opercular cavity;
*At 0.45 second, opercular cavity contracts to reduce opercular volume and increase opercular pressure above atmospheric pressure (acquires positive pressure)**;** opercular valve opens and water is expelled via operculum*

c) Physiological significance of the differences in pressure between opercular and buccal cavity pressure (6 marks)

The pressure in the buccal cavity is higher than that in the opercular cavity forces water to flow in one direction from the buccal cavity to the opercular cavity along the pressure gradient.
Expansion of opercular cavity lowers the pressure below that of buccal cavity, causing the water to flow over gills in the opercular cavity but at the same time the opercular valves close to prevent entry of water. The buccal cavity acts as a force pump while the opercular cavity as a suction pump.

d) How lamellae thickness relates to fish's activities (7 marks)

***Fish A** is the **most sluggish/slow;** because has the thickest lamellae; which increases the diffusion distance for oxygen from blood capillaries into lamellae; reducing the rate of **aerobic respiration**; ATP energy is released **slowly** for muscle contraction;*
***Fish C** is the **most active;** because has the **thinnest lamellae**; which offer **very short** diffusion distance for oxygen from blood capillaries into lamellae; enabling **very fast** rate of **aerobic respiration**; ATP energy is released fast for muscle contraction;*
***Fish B** is **moderately fast;** because has **relatively thin lamellae**; which offer **moderately short diffusion** distance for oxygen from blood capillaries into lamellae; enabling moderately fast rate of **aerobic respiration**; ATP energy is moderately fast released for muscle contraction;*

e) Blood in the lamellae flows in opposite direction to that of water. Comment on the efficiency of this mechanism in gaseous exchange (5 marks)

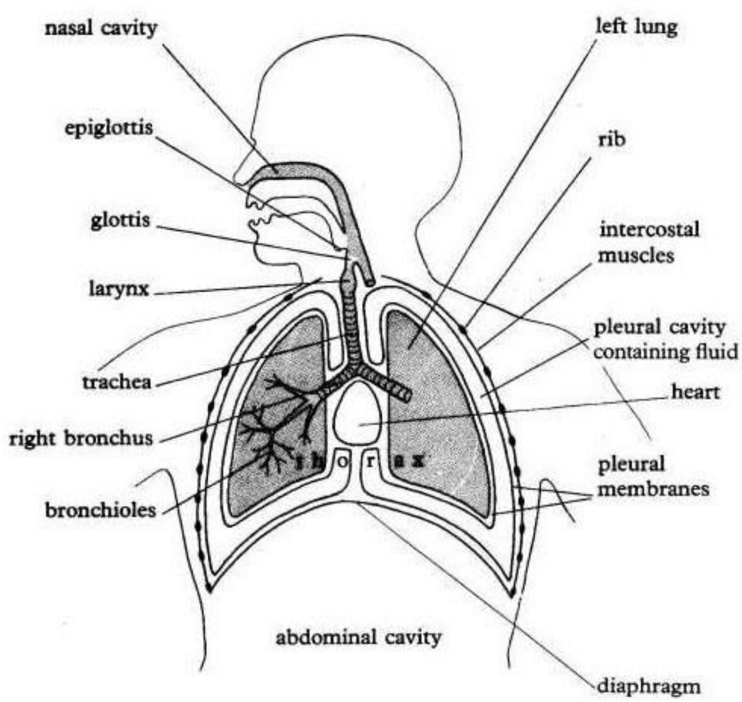
Enables blood of the gill lamellae to extract maximum oxygen from the water (80-90%) for the entire period the water flows across the gill filaments. Although dissolved oxygen levels in water drop as the water flows across the gill lamellae, the blood has lower levels; therefore a sustained diffusion gradient is maintained throughout.
Because, the gradient is always such that the water has more available oxygen than the blood, and oxygen diffusion continues to take place after the blood has acquired more than 50% of the water's oxygen content.
Under conditions permitting adequate oxygen uptake, the counter-current fish uses low energy in respiration

GAS EXCHANGE IN HUMANS

Humans have a high metabolic rate which necessitates a fast rate of gas exchange. This is enabled by two key features the human system has evolved:

- A blood transport system with red blood cells containing haemoglobin
- A mechanism of ventilation to get the gases to and from the gas exchange surface.

Description of respiratory system in man



Main features of the respiratory system

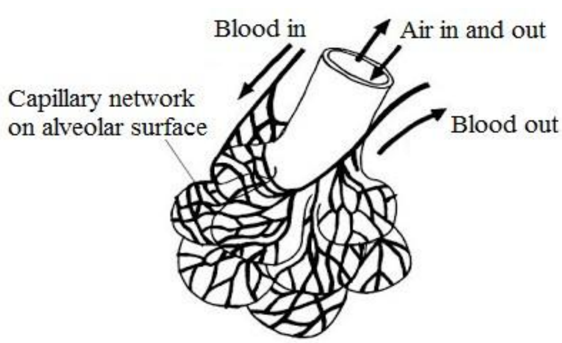
Trachea (wind pipe), the two bronchi and the bronchioles: They are held open (without collapsing) by the **C-shaped cartilaginous rings**. Epithelium is **ciliated**, have goblet cells that secret **mucus**, and have smooth muscle; there is also connective tissue with **elastic** and **collagen fibres.**

Lungs:

- They are spongy and elastic - are capable of expanding and contracting
- Consist of air sacs and the alveoli
- Have blood vessels that are the branches of the pulmonary artery and veins
- Each is enclosed by two membranes called the outer and the inner pleural membrane. The membranes enclose a space called the **pleural cavity** that contains a **fluid that lubricates** free lung movement**.**

Alveolar ducts and alveolar sacs: lack cartilage, are non-ciliated and lack goblet cells. There is connective tissue with elastic and collagen fibres

Alveoli: lack cartilage, are non-ciliated and lack goblet cells. Epithelium is **squamous** (thin flattened cells) with **liquid surfactant** on **inner surface** and blood capillaries on **outer surface**



Lung surfactant

Lung surfactant is a detergent-like substance formed by type II alveolar cells, which **adsorbs** to the air-water interface of alveoli with the hydrophilic head groups in the water and the hydrophobic tails facing towards the air.

Functions of lung surfactant

1) It greatly reduces alveolar surface tension, increasing compliance allowing the lung to inflate much more easily, thereby reducing the effort needed to breathe in air. ***Compliance is the ability of lungs and thorax to expand.***
2) It speeds up the diffusion of oxygen and carbon dioxide between the air and the liquid lining the alveoli.
3) It kills bacteria that reach the alveoli
4) It lowers pressure when the radius is small, and therefore stabilizes the alveoli to prevent collapse.

Ventilation and gaseous exchange in man

INSPIRATION:

Inhalation is an **active** process brought about by several muscles. ***The inspiratory muscles*** (major muscles which cause active increase in lung volume) include: Diaphragm and external intercostals

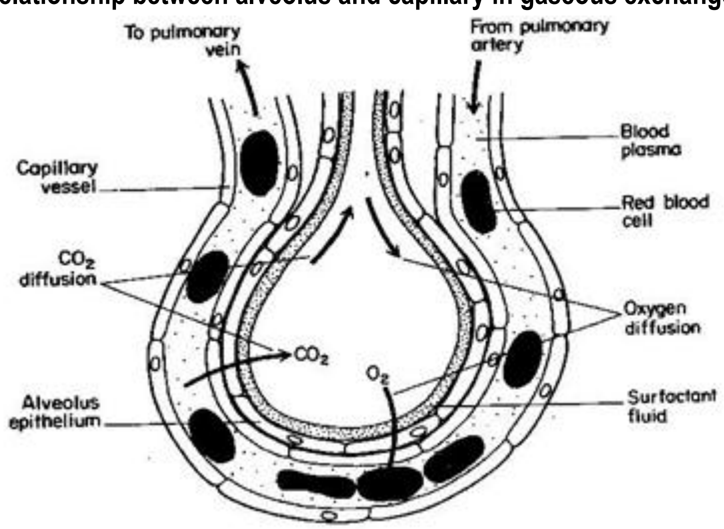
- The external intercostal muscles contract while the inner intercostals relax at the same time causing the rib cage to move upwards and outwards.
- Diaphragm muscles contract and flatten / move downwards.
- These movements increase the volume of the thoracic cavity; and lung volume.
- Alveolar lung pressure decreases below atmospheric pressure causing air to rush into lungs through the nostrils, into nasal passages, pharynx, larynx, trachea, main bronchi, bronchioles, alveolar ducts, and into alveoli.
- Air dissolves in the moisture lining the alveolar epithelium, oxygen then diffuses into blood capillaries while carbon dioxide diffuses from blood capillaries into alveolar air along the concentration gradients

EXPIRATION:

Exhalation in mammals is mainly **passive**, although some muscles are involved. ***The expiratory muscles*** (major muscles which cause active decrease in lung volume) include: Abdominal rectus and internal intercostals

- Internal intercostal muscles contract while external intercostals muscles relax causing the rib cage to move downwards and inwards.
- Diaphragm muscles relax to move upwards / assume its dome shape.
- The volume of thoracic cavity and lungs decreases; causing increased lung pressure above atmospheric pressure.
- **Carbon dioxide-rich air** but with **low oxygen** is then forced out of the lungs

Relationship between alveolus and capillary in gaseous exchange



Physical changes that occur to air during gas exchange

Air is:

(1) Warmed by the capillary blood in the nostrils
(2) Moistened by mucus lining the trachea, bronchi and bronchioles
(3) Filtered and cleaned of particles and dust by hair (whiskers) in the nostrils, cilia and mucus in the trachea, bronchi and bronchioles.
(4) The composition of air changes as indicated in the table below:

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 and carbon dioxide in expired air is intermediate between the inspired and alveolar values	Some of the oxygen in alveolar air diffuses into blood capillaries while carbon dioxide from blood diffuses into alveolar air. The air that remains in the alveoli mixes with the fresh air in alveolar ducts hence lowering the percentage of oxygen in alveolar air

TYPICAL EXAMINATION QUESTIONS:

1. The table below shows the rate and depth of breathing in a group of students during rest and during strenuous exercise.

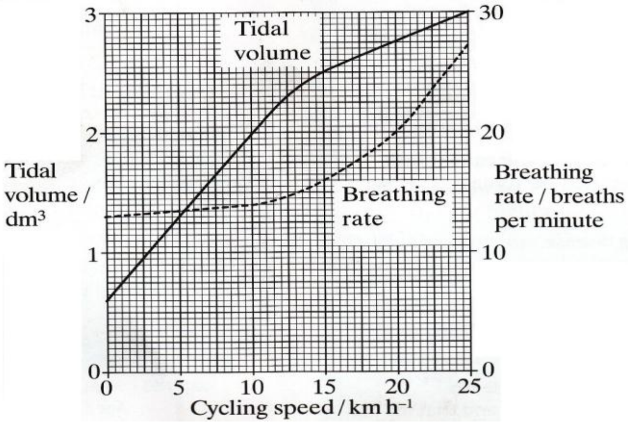
Student	Breathing during rest		Breathing during exercise	
	Volume of inspired air (cm^3)	Number of inspirations per minute	Volume of inspired air (cm^3)	Number of inspirations per minute
1	480	13	2300	19
2	508	12	2250	20
3	496	12	2290	21
4	515	11	2340	20
5	490	12	2280	20

i) Calculate the average number of inspirations per minute during rest and during exercise.
   During rest: 12; during exercise: 20

ii) Calculate the average tidal volume during rest and during exercise
   During rest: 497.8cm³; during exercise: 2292cm³

iii) Explain how the oxygen requirements of a mammal are met under different conditions of physical activity.

2. The volume of air breathed in and out of the lungs during each breath is called tidal volume. The breathing rate and tidal volume were measured for a cyclist pedaling at different speeds and the results are given below:

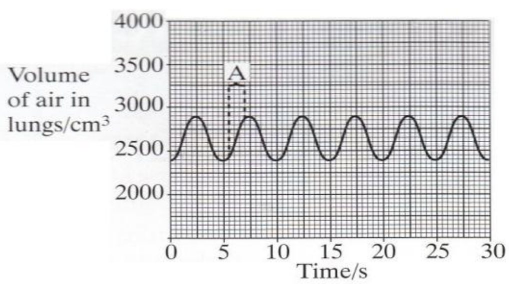


(a) Describe the changes in:

(i) Tidal volume

(ii) Breathing rate

(c) Calculate the pulmonary ventilation when the cyclist is cycling at 20 kmhr-1. Show your working

3. The figure below shows the changes in the volume of air in the lungs during each normal breath of a resting person.  	a) Calculate the pulmonary ventilation rate of the person whose pattern of breathing is shown in the graph. (Volume of air taken into the lungs in one minute) b) Give two ways in which a change in the pattern of breathing may increase pulmonary ventilation rate during a period of exercise. c) Describe the part played by the diaphragm in bringing about the movement of air over the part of the graph labelled **"A"**

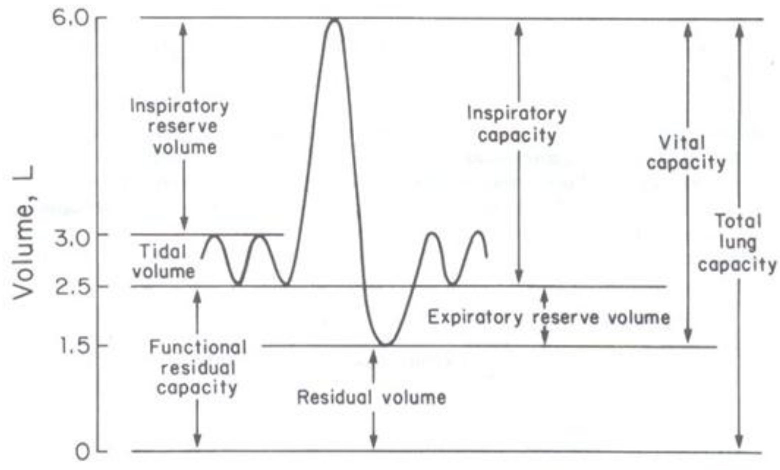
(a) Explain the need for ventilation of the lungs in humans. ***4 marks***

(b) Distinguish between ventilation and gas exchange in humans. ***4 marks***

Ventilation	Gas exchange
• Air moves	• Carbon dioxide and oxygen move
• Air moves in and out of lungs	• Oxygen moves from lungs/alveoli to blood and carbon dioxide moves from blood to lungs/alveoli.
• Brought about by muscle.	• Brought about by concentration gradients.
• Active process	• Passive process/diffusion
• Involves flow along air passages	• Occurs across a surface

NORMAL LUNG VOLUMES AND LUNG CAPACITIES IN RESTING ADULTS

Lung volumes and **lung capacities** refer to the volume of air associated with different phases of the respiratory cycle. Lung volumes are directly measured. Lung capacities are determined from lung volumes. Lung capacities are subdivisions of total volume that include two or more of the 4 basic lung volumes. ***Lung volumes and capacities as shown by a spirometer***



Terms describing lung volumes and lung capacities

Volume or capacity	***Description***
Total lung capacity	The volume of air contained in the lung at the end of maximal inspiration. The total volume of the lung.
Vital capacity	The amount of air that can be forced out of the lungs after a maximal inspiration.
Tidal volume	Volume of air normally breathed in when the body is at rest.
Residual volume	The amount of air left in the lungs after a maximal exhalation can't be expired
Expiratory reserve volume	The amount of additional air that can be pushed out after the end expiratory level of normal breathing.
Inspiratory capacity	The maximal volume that can be inspired following a normal expiration.
Alveolar dead space	The volume of inspired air that is not used for gas exchange as a result of reaching alveoli with no blood supply
Anatomical dead space	Space within the airways that does not permit gas exchange with blood.

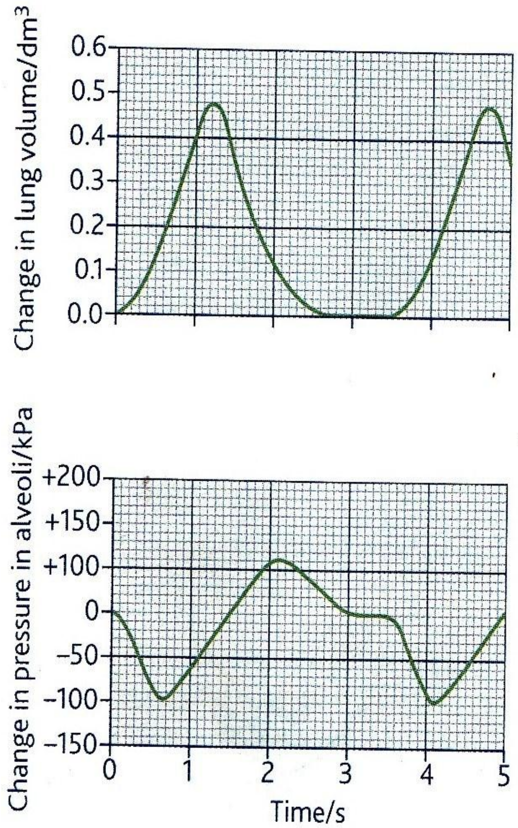
VENTILATION RATE

Ventilation (Breathing rate): The number of breaths taken in one minute. This is normally 12 – 20 breaths in a healthy adult.

Pulmonary ventilation is expressed as $dm^3 min^{-1}$

Pulmonary ventilation (dm^3 min^{-1}) = tidal volume (dm^3) x ventilation rate (min^{-1})

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 0.48dm^3 Therefore, tidal volume of the person was 0.48dm^3

(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 = 4.7 seconds – 1.2 seconds

= 3.5 seconds

The number of breaths in a minute (60 seconds) is therefore $\frac{60 \text{ seconds}}{3.5 \text{ seconds}}$

= 17.14 breaths per minute

(b) If the volume of air in the lungs when this person inhaled was 3000cm^3, work out the volume of air in the lungs after the person had exhaled?

3000cm^3 = 3.0dm^3

From the graph, exhaled volume

= ***0.48dm^3 less than the maximum inhaled volume.***

The exhaled volume is therefore

3.0 - 0.48 = 2.52dm^3 (OR 2520cm^2)

(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.

Factors affecting volumes

Several factors affect lung volumes; some can be controlled and some cannot.

Larger volumes	Smaller volumes
taller people	shorter people
non -smokers	smokers
athletes	non-athletes
people living at high altitudes	people living at low altitudes

Effect of altitude

At high altitudes (e.g. mountains), there is low atmospheric pressure and therefore a low partial pressure of oxygen while at lower altitudes (e.g. deep sea), atmospheric pressure is high. Rapid ascent of high heights causes **mountain sickness** while **diving** into **deeper water** causes difficulties in breathing.

Altitude Sickness (Mountain Sickness): An illness that develops when the rate of ascent into higher altitudes outpaces the body's ability to adjust to low partial pressure of oxygen.

Altitude sickness generally develops at elevations higher than 8,000 feet (about 2,400 meters) above sea level and when the rate of ascent exceeds 1,000 feet (300 meters) per day.

Symptoms: Fatigue, Headache, Dizziness, Insomnia (sleeplessness), Shortness of breath during exertion, Nausea, Decreased appetite, Swelling of extremities, Social withdrawal.

Effects of changes in altitude can be avoided by **acclimatization;** *a period of time during which the body physiologically and physically adjusts to changes in partial pressure of oxygen.*

Adjustments to minimise altitude sickness

(i) Increased number of red blood cells
(ii) Increased haemoglobin content
(iii) Increased ventilation rate
(iv) Increased cardiac frequency

Adaptations of diving animals

(i) Oxygen carriage by having greater blood volume e.g. man's blood is about 7% of body weight while in diving marine mammals it is about 15% of the body weight.
(ii) Enlarged blood vessels to work as reservoirs of oxygenated blood.
(iii) High concentration of myoglobin
(iv) Slower heart beat to conserve use of oxygen
(v) Reduction of blood supply to organs and tissues tolerant to oxygen deficiency e.g. digestive system, muscles, etc
(vi) Compression of air spaces to reduce unnecessary body bends e.g. lungs, middle ear, etc.
(vii) Higher proportion of red blood cells
(viii) Respiratory centers do not function automatically to cause breathing at a certain concentration of CO_2

Explain why a person who is born and lives at sea level will develop a slightly smaller lung capacity than a person who spends their life at a high altitude.

This is because the partial pressure of oxygen is lower at higher altitude which, as a result means that oxygen less readily diffuses into the bloodstream. In response to higher altitude, the body's diffusing capacity increases in order to process more air.

Adaptations of lung system for gas exchange

- Large surface area in lungs provided by numerous alveoli;
- Thin alveolar epithelial lining shortens diffusion distance for gases
- Elastic fibres in lungs permit optimum extension during inhalation
- Highly vascularized alveoli maintain high diffusion gradient for gases.
- Moist alveolar epithelial lining dissolves gases before diffusion can occur
- Trachea and bronchi walls are supported by rigid cartilage rings are permanently open for uninterrupted air flow.
- Trachea and bronchi inner walls are lined with mucus to trap to clean air to avoid damaging alveoli
- Stretch receptors in alveolar walls enable initiating breathing reflex.
- Alveolar inner lining is covered by surfactant, which lowers surface tension differentially to prevent lung collapse

Involuntary control of breathing in man

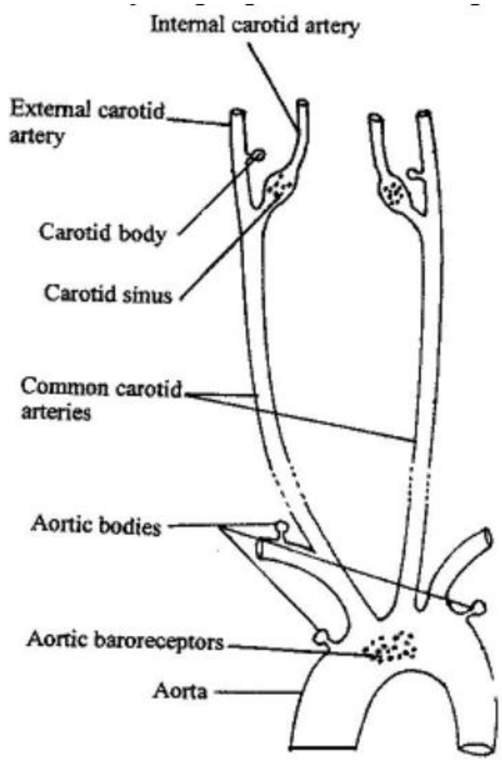
The rate of breathing is controlled by the **respiratory centre**, in the medulla oblongata comprising of the **inspiratory** and **expiratory centres.**

Many factors can modify the rate and depth of breathing e.g. low oxygen partial pressure, hormone Adrenaline, but the strongest factors are the levels of carbon dioxide and hydrogen ions (H^+) in arterial blood.

Central chemoreceptors (cells that respond to chemical stimuli) in the medulla oblongata of the brain detect changes in the concentration of carbon dioxide (CO_2) in blood by monitoring the PH of cerebrospinal fluid while Peripheral chemoreceptors in the carotid and aortic bodies monitor both carbon dioxide and oxygen concentrations in blood of carotid arteries and aorta respectively.

High CO_2 lowers pH

Location of the *peripheral chemoreceptors*



Description of the nervous control of breathing

Respiring tissues release CO_2 from aerobic respiration which is transported to lungs in three different ways

- As dissolved CO_2 in plasma;
- As carbamino compound bound to haemoglobin in RBCs;
- As bicarbonate ions HCO_3^- and H^+ from RBCs:
  $CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$;

HCO_3^- ions in pulmonary capillaries react with hydrogen ions (H^+) to form carbonic acid (H_2CO_3);

Carbonic acid dissociates into water (H_2O) and carbon dioxide gas (CO_2); which diffuse into alveoli

Increased H^+ (acidity) **stimulates central chemoreceptors** in the **medulla oblongata** while Increased blood CO_2 stimulates **peripheral chemoreceptors** in **carotid and aortic bodies** to send impulses via **glossopharyngeal nerve** and **vagus nerve** respectively to the **inspiratory centre** in medulla oblongata;

Inspiratory centre sends impulses via **phrenic nerve** to the diaphragm **and intercostal nerves** to the intercostal muscles;

Diaphragm and external intercostal muscles contract to increase thoracic volume while thoracic pressure decreases below atmospheric pressure;

Air rushes to inflate lungs and stimulate **stretch receptors** in lung walls, which send impulses via the vagus nerve to expiratory centre in medulla oblongata;

Inspiratory centre is inhibited / switched off, causing relaxation of external intercostal muscles and diaphragm;

Thoracic volume decreases while thoracic pressure increases above atmospheric pressure, forcing lungs to deflate and expel air rich in carbon dioxide;

Effect of oxygen variation

Breathing air with low Oxygen:

- Under conditions of low oxygen levels, e.g. at higher altitude, the partial pressure of oxygen in arterial blood drops significantly from about 100 mm Hg to about 60 mm Hg.
- Chemoreceptors in carotid and aortic bodies are stimulated to send impulses to the inhalation centre of the medulla, causing increased breathing rate.
- As more air is drawn into the alveoli, oxygen diffuses into alveolar capillaries until breathing returns to normal.

Breathing air with excess Oxygen (Hyperoxia):

- It is **dangerous** to breathe air with **pure** O_2 because blood's ability to carry it away is exceeded, causing binding of free O_2 to surface proteins of lungs, interfering with the operation of the central nervous system and also attacking the retina; all of which can be **toxic/poisonous**.
- Prolonged exposure to above-normal oxygen partial pressures, or shorter exposures to very high partial pressures, can cause:
  i) Oxidative damage to cell membranes,
  ii) Collapse of the alveoli in the lungs.
  iii) Retinal detachment, and seizures.