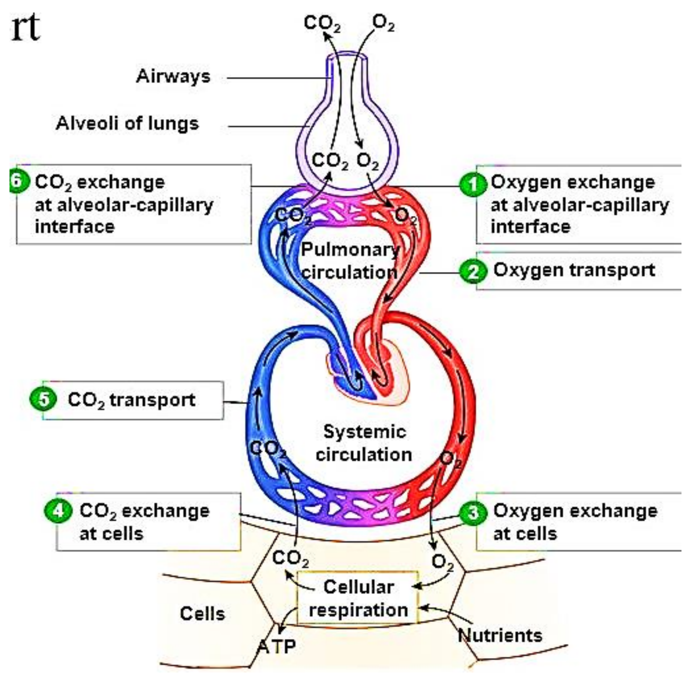
VENTILATION AND GAS EXCHANGE

PART I

Definition of terms:

- **Ventilation**, is the exchange of air between the (alveoli) lungs and the atmosphere/ or movement of gases between gas exchange medium and respiratory system to maintain appropriate concentration of oxygen and carbon dioxide in body fluids/ or is the exchange of O2, and CO2, between the body fluids of an animal and the environment in which that animal lives. Achieved by inhalation and exhalation.
- **Gas (eous) exchange**, is the exchange of oxygen from inhaled air into blood and exchange of carbon dioxide from blood into exhaled air, and exchange of gases that occurs between blood and cells (at tissue level). Thus, two types of gas exchange**, pulmonary gas exchange and tissue gas exchange**.
- **Cellular respiration**, are biochemical reactions that release ATP from organic molecules. Occurs in cytoplasm and mitochondrion.
- **Respiratory surface / gas (eous) exchange surface,** boundary between the external environment and the body interior.
- **Respiratory medium/ gas (eous) exchange medium,** the source of gases (oxygen and carbon dioxide), that is air for terrestrial animals and water for aquatic animals.



The O2 that an animal removes from its environment is used for the production of ATP by the oxidation of foodstuffs. Associated with this is the production and release of **CO2** back into the environment.

This production of ATP is termed metabolic respiration. Virtually all animals depend on such aerobic metabolism to satisfy their resting energy requirements, although it is possible to produce energy, in the form of ATP, by anaerobic metabolism. The advantage of aerobic metabolism, compared with anaerobic metabolism, is that it significantly enhances the amount of ATP which can be made available.

Consider the metabolism of a single molecule of glucose. During aerobic metabolism, 38 molecules of ATP are produced, whereas during anaerobic metabolism only two molecules are produced. Furthermore, it is possible to metabolize other substrates, such as lipids and proteins aerobically, but not anaerobically.

Check progress:

1. **Account for the inefficiency of the anaerobic respiration pathway in metabolism of lipids and proteins?**

GENERALIZED FEATURES OF GAS EXCHANGE

(i) Involves diffusion of respiratory gases along their concentration gradients.
(ii) Sometimes involves Ventilation mechanisms to replenish oxygen to maintain a high concentration gradient.

The exchange of gases between animals and their environments occurs by the process of simple diffusion.

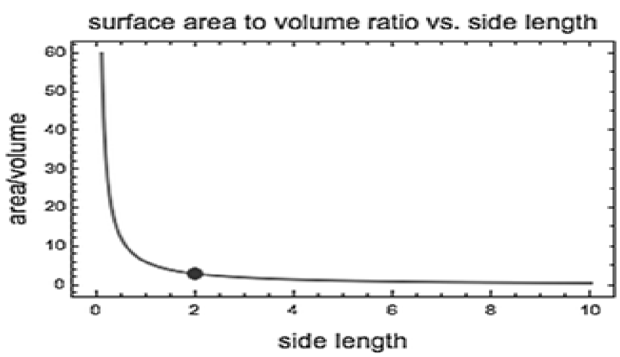
For many animals, small aquatic animals in particular, the exchange of gases across the general body surface is sufficient to meet the demands of the animal.

However, as animals have evolved, exchange of gases across the body surface has become inadequate. Several evolutionary changes placed pressure on gas exchange across the general body surface area. For example, metabolic rates have tended to increase as animals have evolved; increasing the oxygen requirements of animals; the evolution of multicellular animals has resulted in specialization of cells; located in the general body surface; the overall effect of these pressures has been to reduce the surface area that is available for gas exchange;. Furthermore, the resultant increase in the complexity of animals has required a progressively more complex and efficient gas exchange mechanism to be developed**;** thus the development of specialized ventilatory and gas exchange structures; such as external gills in tadpoles, lungs, tracheal system in insects, , internal gills in fish,

Check progress:

1. **Why have multicellular organisms evolved a complex gas exchange system?**
2. **Account for the need of a gas exchange system in multicellular organism.**
3. **How have large organism improved efficiency of gas exchange?**
4. **Giving examples, account of the absence of a complex gas exchange system in unicellular organisms.**

$$\text{area} = 6d^2 = 24.000$$
$$\text{volume} = d^3 = 8.000$$
$$\text{area/volume} = \frac{6}{d} = 3.000$$



Graph showing effect of body size (side length) to surface area/ volume ratio

Description of the graph:

1. Increase in side length from 0 to 2 leads to a rapid decrease in SA/V ratio.
2. Increase in side length from 2 to 4 leads to a gradual decrease SA/V ratio, then remains constant from 4 to 10.

Interpretation:

1. In very small organisms, a small change in radius causes a big change in SA/V ratio
2. In very large organisms, big changes in radius cause very small changes in SA/V ratio.

Task: relate the above observations to the nature of the gas exchange system possessed by the organisms of varying sizes from the graph.

GASES IN THE RESPIRATORY/ GAS EXCHANGE MEDIA (AIR AND WATER)

By and large, animals tend to be either air breathers or water breathers.

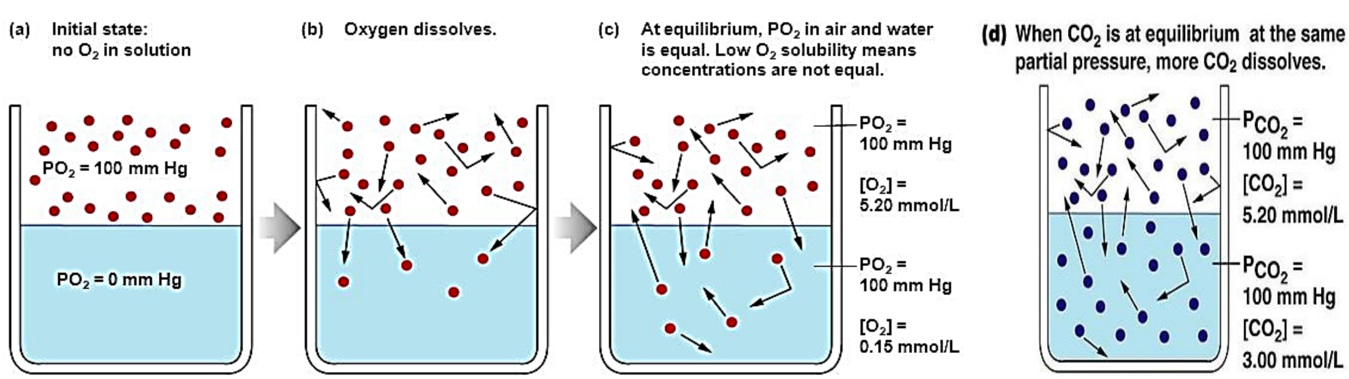
There are a few exceptions to this generalization; for example, larval amphibians (tadpoles) are water breathers, whilst adult amphibians are air breathers, and the common eel (Anguilla) is capable of breathing both air and water.

❖ Before going on to discuss the biology of ventilation, it is necessary to have an understanding of the physical and chemical principles relating to gases in air and water and the process of diffusion.

NOTE:

- **Normal, dry atmospheric air has the following composition: 20.95% O_2, 0.03% CO_2, and 78.09% N_2. The remainder of the volume is made up of the noble gases (e.g. argon, krypton, neon) which, together with N_2, are considered to be physiologically inert.**
- **Gases are soluble in water. When a sample of air and water are allowed to equilibrate with each other, the partial pressure of the gases in water will be the same as those in air. The solubilities of different gases in water vary considerably. For example, CO_2, is approximately 30-times more soluble in water than is o. It has been said previously that the partial pressure of gases in water is the same as that in the gas phase when the system is at equilibrium. However, the concentration of the gases in the water will not be the same.**

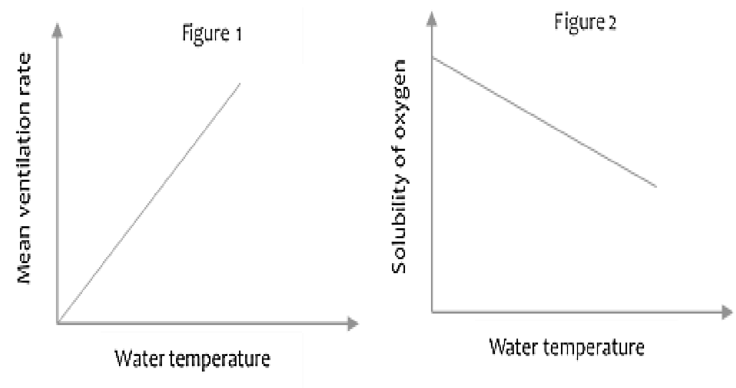
Thus, for the same partial pressure, the amounts of O_2, and CO_2, dissolved in water will not be the same because the solubility of the two gases is different.



Other factors influencing the gas content of water include temperature and the presence of other solutes. Increasing temperature decreases the amount of gases dissolved in water; for example, there is a 40% reduction in the O2, content of water as temperature increases from 10°C to 30°C. In a similar manner, the presence of solutes in water also decreases the gas content. At the same temperature, there is a 20-30% reduction in the amount of O2, dissolved in seawater when compared to freshwater.

Check progress:

1. **Describe three factors that affect the oxygen content in water as a gas exchange medium for water breathers.**
2. **In an investigation to determine the effect of water temperature on the rate of ventilation of gills in fish in a thermostatically controlled aquarium. Results obtained are shown on figures 1 and 2. Ventilation rate was measured by counting the movements of the gill covers. Changes on oxygen concentration in water was also monitored.**



a) **Describe the relationships between water temperature, oxygen concentration and ventilation rate.**

b) **Explain the relationship between water temperature, oxygen concentration and ventilation rate.**

Diffusion:

The movement of gases, across the general body surface or from alveoli to pulmonary capillary blood in the human lung occurs by the process of diffusion. That **is,** molecules of gas move from a region of high partial pressure to one of lower partial pressure down a concentration gradient. It is possible to attempt to quantify the process of diffusion by the use of **Fick's law**. In its simplest form, Fick's law defines the movement of a gas from one region to another in a single dimension; for example, a molecule of O2, passing from water across the body surface into an animal.

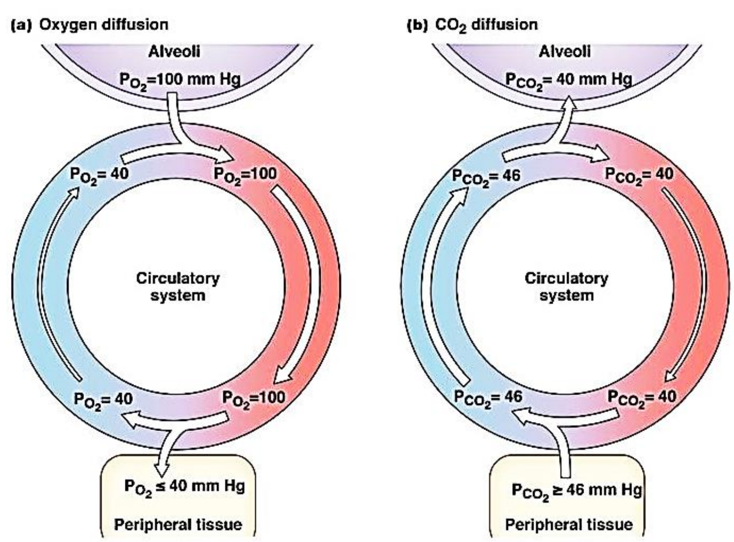
Fick's law is stated as: **"diffusion of a gas id directly proportional to the product of body surface area and difference in concentration of gas in the two regions and inversely proportional to the thickness of the membrane across which the gas diffuses**.

E.g**. Diffusion rate of a gas** $\propto \frac{\textbf{surface area of respiratory surface} \times \textbf{difference in concentration of the gas}}{\textbf{thickness of the membrane of respiratory surface}}$

Role of diffusion in gas exchange

Factors that affect diffusion of gases along a gas exchange surface if membrane permeability remains the same.

a) **Surface area** – diffusion rate is proportional to available surface area.
b) **Concentration gradient** – diffusion rate is proportional to concentration gradient.
c) **Membrane thickness** – diffusion rate is inversely proportional to membrane thickness. Thus higher in thin walled membranes.
d) **Diffusion distance** – diffusion rate is inversely proportional to distance across the membrane. Another reason for which the membrane is thin.
e) **Pressure gradient** – drives gas flow
f) **Solubility** – gas must be able to dissolve in liquid, diffusion will continue until it reaches equilibrium, increased pressure may dissolve some gas if solubility is low.
g) **Temperature** – temperature is constant so it may not play a role in the body unless there is pathology.



Check progress:

1) **The diameter of capillaries is smaller than the diameter of the red blood cells passing through them resulting into increased efficiency of gas exchange. Explain.**
2) **The table below summarizes the features of gills in three species of 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) **Comment on the relationship of thickness of the lamellae and distance between blood and surrounding water.**
b) **Account for the relationship between lamellae thickness and level activity of the fish species.**

A Comparison of Air and Water as Respiratory Media.

As stated previously, animals generally breathe air or water.

Property	Air	Fresh water	Ratio: air / water
Oxygen volume/cm^3L^{-1}	210	8	26:1
Oxygen composition/ %	21	Variable, but much less than in air	
Diffusion coefficient of oxygen (arbitrary units)	0.198	0.000025	8000:1
Dynamic Viscosity (cP)	1	0.02	50:1
Density (kg/ liter)	0.0013	1.000	1:800
Heat capacity/ Cal / s cm °C	0.31	1000	1:3000
Stability of oxygen to temperature increase	Stable	Decreases	
Gas exchange surface needs suppo	Yes	No	

NB: the values may differ depending on the source.

What are the advantages and disadvantages of utilizing either of these substances?

1) **Water is much more dense and viscous than air**; some 800-times denser and 50-times more viscous.
This means that water is, in metabolic terms, much more expensive to pass through or over a respiratory structure. Such is the metabolic cost of breathing that a fish may expend up to 10% of its resting metabolism simply passing water over its gills. Obviously, when the fish becomes more active, the cost of ventilation increases even more.
However, to be offset against this is the fact that air-breathing animals must expend energy to overcome the effects of gravity (aquatic animals do not have this problem).
In order to limit the metabolic cost of ventilating gill structures, animals that breathe water usually have a unidirectional flow of water through the gills.
2) Water's high density supports and prevents collapse of respiratory structures like gills lamellae while alveolar sacs collapse in absence of lung surfactants.
3) **Oxygen content of water is much reduced when compared to air**; water contains 10 ml of O2, per liter, whereas air contains approximately 200 ml per liter.
4) Water has a **higher CO2 solubility 20-30 times greater than that of air**. Thus, aquatic animals have very little problem in excreting the CO_2, produced during aerobic metabolism.
The significance of this is that for aquatic animals O2, is the primary stimulus for breathing, whilst in air breathers it is CO2, simply because these are the 'rate-limiting' gases. The fact that in air-breathing animals CO2, levels in the body are much higher has implications for acid-base balance, since CO2, is an acidic **gas.**
5) Unidirectional water flow during ventilation in aquatic animals like bony fish is energetically less costly than tidal ventilation in lungs of land animals.
6) Air breathing is associated with dehydration, as it is associated with loss of water vapour; thus slowing down gaseous diffusion. Therefore the gas exchange system must be enclosed within the body reduce water loss.
7) **Water has a higher thermal capacity than air** (i.e. water is an effective heat sink), and the consequence of this is that aquatic animals have tremendous problems when it comes to thermoregulation, as any heat that is produced is rapidly dissipated to the water.

It is difficult for such animals to do anything other than conform to the temperature of the surrounding water. Conversely, air has a poor thermal capacity, so it is possible for air-breathing animals to utilize the heat of respiration (i.e. the heat which is produced as a by-product of biochemical reactions) for the process of thermoregulation. This tends to give air the advantage over water as a respiratory medium.

Certainly, air-breathing animals tend to have higher metabolic rates than aquatic animals and this presumably confers the animal with some advantage over those with lower metabolic rates, although in, **turn,** this also produces potential problems - for example, the continual requirement for large amounts of oxygen, and the possible problems of overheating.

Explain the following observation.

- **Despite the high efficiency of gills as respiratory structures in aquatic environments, terrestrial animals do not use gills for gaseous exchange.**

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.

RESPIRATORY/ GAS (EOUS) EXCHANGE SURFACES.

This is the general body or part of the body's surface over which gas exchange by diffusion occurs.

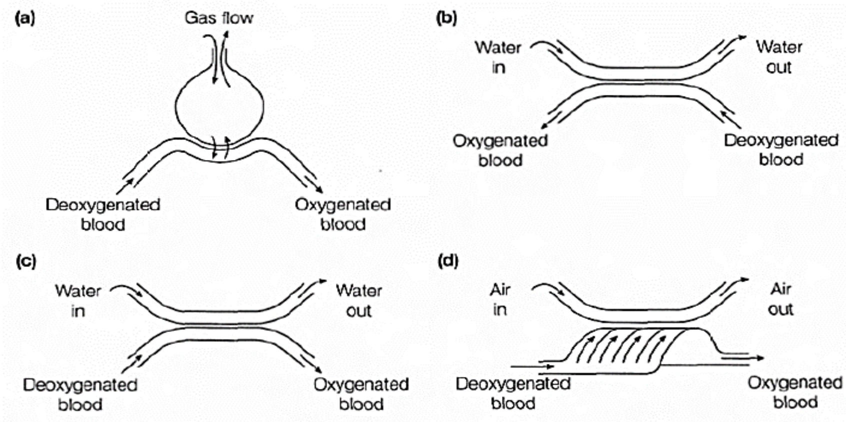
The evolution and design considerations of gas exchange organs.

It is apparent that gas exchange across the body surface will only meet the requirements of small animals or those with very low metabolic rates. Some of the evolutionary pressures on the development of gas exchange surfaces were discussed in already.

Before the organs/ surfaces themselves are discussed, it is necessary to appreciate the functional requirements/ features/ characteristics of such organs/ surfaces.

- **Large surface area (: volume ratio);** this may be the general body surface area for small organism or the infoldings of the surface such as lungs and gills in larger organism. To increase amount of gas that can be moved from the environment to the animal and vice versa.
- **Permeable;** to allow exchange of gases with minimal resistance.
- **Thin;** to minimize distance between blood of organism and water or air. Such as thickness of a single plasma membrane separating body fluids and respiratory medium ensures a path of least resistance in terms of diffusion across it.
- **Moist;** to dissolve respiratory surfaces to enable diffusion.
- **Efficient transport system;** such as the circulatory system in vertebrates which operates in tandem with the gas exchange system to maintain a high concentration gradient through consistent blood supply for example in gills and lungs.
  NB: the gas exchange system-the tracheal system in insects is independent of the circulatory system, so the above consideration does not work.
- The final aspect of the design of gas exchange organs is **good ventilation design** (**physical arrangement between the respiratory medium and the body fluids**). The following ventilation designs are possible.
  a) **Uniform pool arrangement**, the prime example of which is the **mammalian respiratory system**. In this situation, the respiratory medium (i.e. air) does not flow in any particular direction in relation to the flow of blood through the lungs. An equilibrium is established between gas concentrations in air and blood.
  b) **Countercurrent arrangement**, as seen in **fish gills.** Here, the flow of the respiratory medium (i.e. water) and blood are in opposite directions. This is a particularly good arrangement, in that the entire length of the gas exchange surface is utilized. At any point along the gill, gas concentration in the water is greater than that in the blood, so there is continual movement of gas from water to blood.
  c) **Cocurrent arrangement,** where the respiratory media and blood flow in the same direction. Such a system is less efficient. Maximal theoretical gas concentrations in the blood are never achieved because gas concentrations equilibrate before blood has had a chance to perfuse the entire length of the respiratory organ/surface.

d) **Crosscurrent flow,** this is the arrangement found in **bird lungs**. Here, blood and respiratory medium flow almost at right angles to each other. Once again, this ensures maximal transfer of gases between blood and the respiratory medium.



NB: Bearing in mind all the requirement of gas exchange organs, evolution has provided animals with three possibilities: gills, lungs and tracheal systems. Each of these will now be discussed.

Check progress:

1) **Explain the functional requirements/ design of an efficient gas exchange surface.**

2) **Describe the ventilatory structural designs/ forms in living organisms, giving example of gas exchange surfaces and the organism in each case.**

3) **Describe the major gas exchange surfaces that developed due to evolutionary pressures.**

TYPES OF VENTILATION;

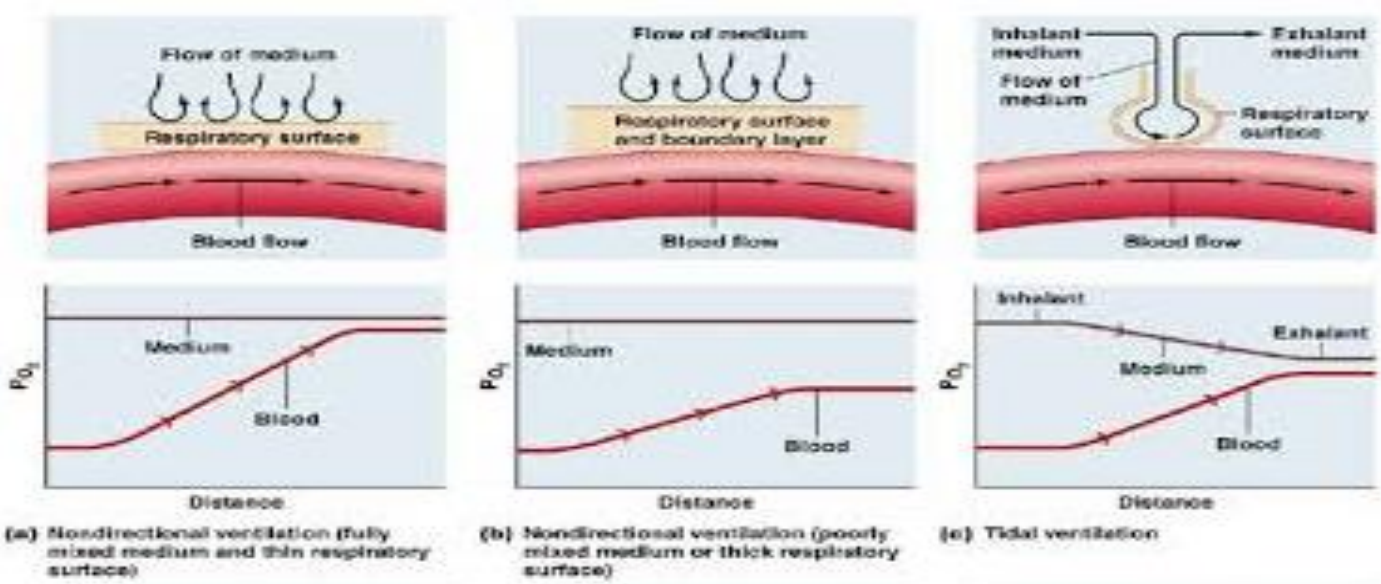
1. Non directional ventilation.

This is a passive mechanism by which respiratory medium flows past gas exchange surface in an unpredictable pattern. Passive ventilation relies on water and air currents. For example in skin breathers like **toad**, e**arthworm, flat worms**.

- More oxygen dissolves into blood when medium is fully mixed and with a thin respiratory surface.
- Less oxygen dissolves in blood when medium is poorly mixed and with a thick respiratory medium.

Represent the above saturation variations graphically.

2. Directional ventilation/ current flow.



a) Bidirectional ventilation.

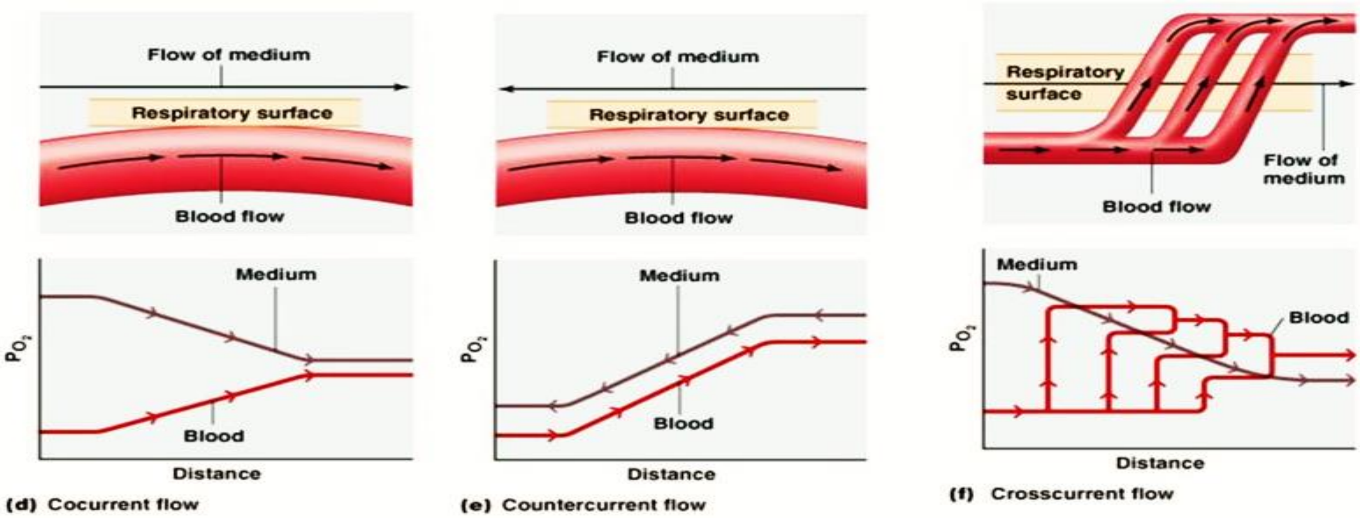
This is an active mechanism by which external medium moves in and out of the respiratory chamber in a back and forth movement. Such as the **Tidal ventilation** in **lung breathers** like **mammals**, amphians, reptiles etc. requires energy expenditure by respiratory muscles.

- Difference in partial pressures drive movement of respiratory fluid (air).

b) Unidirectional ventilation/ flow.

This is an active mechanism by which a respiratory medium flows enters the chamber at one point and exist at another. Requires energy expenditure by muscles/ or cilia.

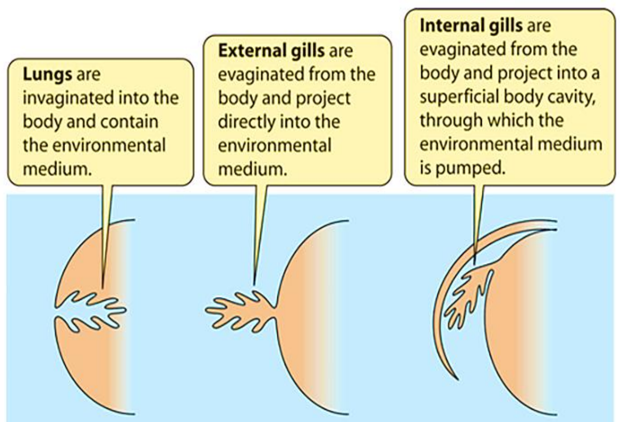
- Medium and blood may flow in **same direction** that is **concurrent flow/ parallel flow**; in **dog fish/ teleost fish or shark**.
- Medium and blood may flow in **opposite direction** that is **countercurrent flow**; in **bony fish**.
- Medium and blood may flow at an **angle that** is crosscurrent flow; **in bird lungs**.



NOTE: air breathers use bi-directional ventilation since air has low density and is less viscous while water breathers use unidirectional flow to save respiratory energy that would be expended in moving the more viscous water across the gas exchange surface.

Check progress:

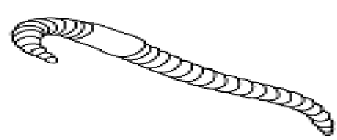
1) **Describe the different types of ventilation, giving examples in each case.**



TYPES OF RESPIRATORY / GAS EXCHANGE SURFACES IN ORGANISMS

- **Integuments,** outermost surfaces, which must be thin, moist and permeable e.g. skin for gas exchange.
- **Evaginations,** (external and internal gills in tadpole and fish respectively), specialized, extensive epidermal outgrowths suspended in respiratory medium.
- **Invaginations,** (lungs), internal infoldings in which the respiratory medium is drawn forth and back.

1) **Cell surface membrane in unicellular organisms;** such as amoeba
2) **Entire/ general body surface in Porifera, Coelenterates, majority of Platyhelminthes, Nematodes, Rotifers and some Annelids** such as earthworm, **some fish** such as eel; **some amphibians** such as the hairy frog (*Asylosternus robustus*) which develop vascularized hairs to increase surface area for gas exchange; **in some mammals** such as bats where 10% -15% of their carbon dioxide is excreted across the skin of the wing.



3) **Gills:**

Gills are the gas exchange organs of aquatic animals. They are outgrowths of the body surface which are highly folded or convoluted in order to maximize the surface area available for gas exchange. They may be secondarily enclosed in a protective structure, such as the opercular cavity in bony fish. In order for them to be ventilated, water must pass over their surface. This can be achieved in one **of** two ways: either the gill passes through water or water passes over the gill. The latter is only feasible for small organisms (e.g. some aquatic insect larvae), because of the excessive energy requirements that are required. Gills are present in both invertebrates and vertebrates.

a) **Invertebrate gills.**

Gills are present in marine polychaete worms (eg. ***Arenicola).*** In these animals, the gills are modifications of the parapodia, which are lateral appendages. In the case of ***Arenicola,*** water is moved over the gills as a consequence of the general body movements of the animal. In other polychaetes, **cilia** may be present on the gill to ensure the flow of water. There is considerable diversity in the morphology of gills in the polychaetes which suggests that, in this group at least, gills have evolved several times. Molluscs also have gills and, although there is much variation in the gill, in all cases they are ciliated and this is the mechanism by which water passes over them. In some molluscs (e.g. the lamellibranch ***Mytilus),*** the gills have a secondary function in that they are involved in filter feeding.

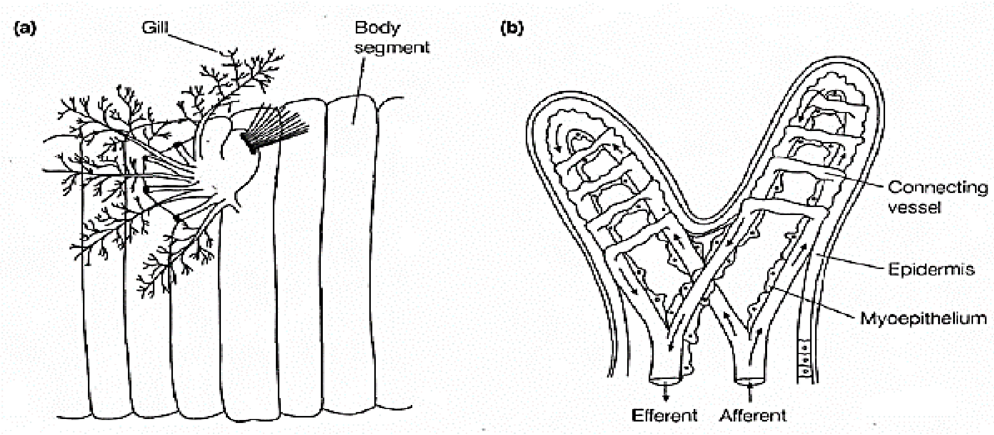
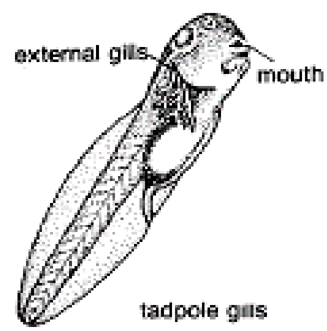


Figure (a): the body all of Arenicola sp. Showing respiratory structures. Branching of the gills maximizes the surface area available for gas exchange. Figure (b) shows an enlarged view of the gill. Arrows show direction of blood flow.

In the case of crustaceans, it is mainly the malacostraca (crabs, lobsters etc.) which have gills. In these animals, the gills are usually derived from the thoracic or, occasionally, abdominal appendages and are usually enclosed within the carapace. The nature and number of gills is related to the environment in which the animal lives; for example, aquatic crabs tend to have larger gill areas than land crabs. Although water flow over the gills is usually unidirectional, many crustaceans have the ability to reverse this flow. The significance of this maneuver is that it rids the gills of accumulated debris.

As will be seen later, insects have developed a tracheal system to ensure adequate gas exchange, but many aquatic insects and aquatic larvae of terrestrial insects rely upon gills. Once again there are many variations on insect gills. In some cases they have developed from abdominal appendages, such as those found in Ephemeroptera larvae. Other variants include the development of gills within the lumen of the rectum, so-called **anal gills**. In such a situation, the gills are ventilated by the movement of water in and out of the rectum. This arrangement **is** seen in some dragonfly larvae.



b) **<u>Vertebrate gills.</u>**

Many aquatic vertebrates depend, to differing degrees, upon gas exchange across the general body surface area. However, such a mechanism is virtually always insufficient to meet the needs of the animal concerned. Gills in vertebrates may be of two types, **<u>external filamentous gills</u>** and **<u>internal lamellar gills,</u>** the latter being most common.

Many vertebrates only have external gills during certain stages of development (e.g. fish and amphibian larvae/ tadpole).

Internal gills are much more common. Gills are best developed and understood in teleost fish**.** They consist of several gill arches from which extend **two** rows of gill filaments. Upon each filament are rows of gill lamellae, which is the site of gas exchange. Water and blood flow in opposite directions, i.e. there is a countercurrent arrangement which maximizes O2 uptake into blood. Water is moved over the gills by the pumping action of the mouth and the opercular cavity**.**

Water is drawn into the mouth when the floor of the mouth is lowered**.** The mouth then closes and water is forced over the gills, aided by the opening of the

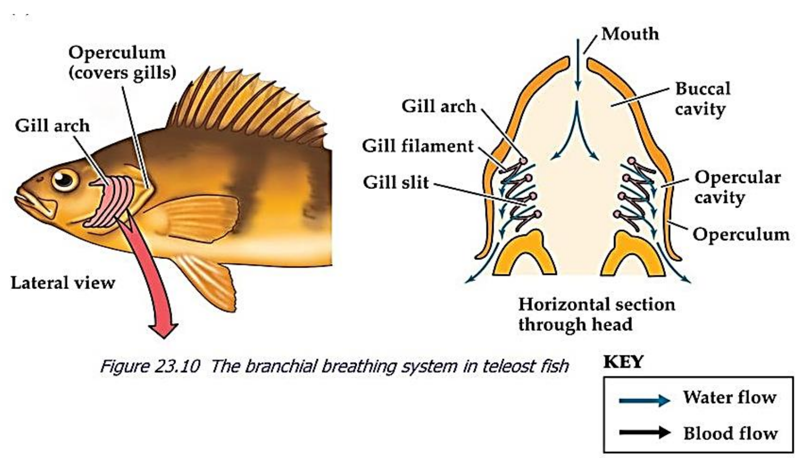


Figure 23.10 The branchial breathing system in teleost fish

opercular flap which results in water being expelled. This serves to maintain an almost continuous flow of water over the gills. Many active, fast swimming fish, such as tuna and some sharks, swim with their mouth open and consequently force water over their gills. This is called ram ventilation. However, such a system does increase the energy requirement for swimming since it increases the drag of the fish in the water (i.e. it increases its resistance to flow through the water). Since ram ventilation is seen in many fish, particularly when swimming fast, it suggests that the increased energy requirements of swimming are less than the energy requirements of mouth and opercular pumping in order to ensure the delivery of water and oxygen to the gills. In teleost fish, gill size is related to activity, so that a fast swimming fish, such as mackerel, has a gill area ten-times that of the bottom-dwelling and much slower flounder.

4) **Lungs:**

Lungs are ingrowths of the body surface, as opposed to gills which are outgrowths, and are the gas exchange organs of air-breathing animals. In a similar manner to gills, they are highly folded to increase the surface area available for gas exchange. They are intimately linked with the circulatory system in order to distribute gases around the animal. **As** will be seen later, lungs have evolved which work in various ways; for example, some lungs are actively ventilated, whilst others simply rely on diffusion to renew their gas content. In lungs that are actively ventilated, air may either be pumped or sucked into them. **A** major problem associated with breathing air is water loss and various solutions to this problem have evolved. However, it should be remembered that as water evaporates it cools, so water loss from the gas exchange organ may be important in terms of thermoregulation. This is particularly well developed in animals which do not possess sweat glands, e.g. dogs and birds.

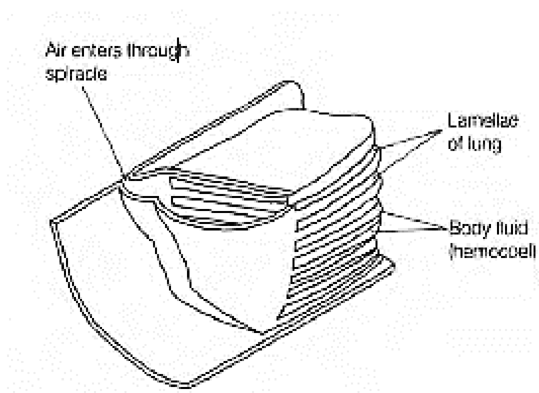
Check progress:

i. **Account for the major problem associated with breathing in air.**
ii. **Explain the significance of breathing air in thermoregulation of air breathers.**

a) **Invertebrate lungs.**

Several invertebrate phyla have made the transition to a terrestrial way **of** life, some more successfully than others. Lungs have evolved in some classes of molluscs, e.g. the pulmonate snails. The lung is found at the back of such animals where the mantle cavity fuses with the rear of the animal and it can be closed off to the atmosphere by closure of the pneurnostome. It is capable of being ventilated, but exchange of gases between the environment and the lung generally occurs by simple diffusion. Crustaceans show varying degrees of success in their adaptation to terrestrial life and air breathing. Some amphipods which have invaded land retain gills, and their ability to live on land is due to behavioral adaptations (living in moist habitats, for example). Even those crustaceans which have evolved lungs or lung-like structures (e.g. woodlice), are still restricted to moist habitats. Other invertebrates, such as spiders and scorpions (i.e. chelicerates), also have lungs. In this case they are called **book lungs**, and they are located on the abdominal surface and consist of layers of lamellae, rather like those of fish gills.

NB: Air enters the spaces between the lamellae and gases pass into the body fluids.



Structure of the book lung.

b) **Vertebrate lungs.**

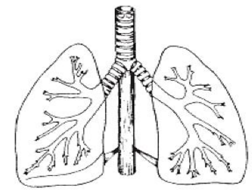
Lungs are found in **amphibians**, **reptiles**, **birds** and **mammals**.

Amphibians show tremendous diversity in the structure of their lungs, ranging from a simple non-compartmentalized cavity to well vascularized, highly compartmentalized lungs. However, when it comes to ventilating the lung they are all ventilated by positive pressure pumping. Air enters and leaves the mouth almost continually, as can be seen by the constant motion of the mouth in these animals.

During this stage, air is prevented from entering the lungs by closure of the glottis. When lung ventilation occurs, the already open nostrils close, the glottis opens and air is forced from the mouth into the lungs under positive pressure. In many cases, this process occurs several times in order to fill the lungs with air. Removal of air from the lungs is achieved by opening the glottis, coupled with the natural elasticity of the lungs which return to their original volume, expelling air from the lungs.

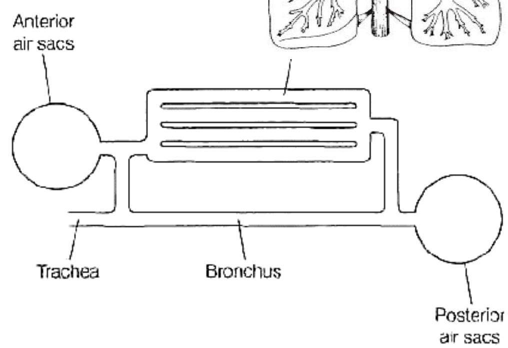
The **lungs of reptiles** are morphologically more complicated than those of amphibians in that they are much more compartmentalized. A second major difference in reptilian lungs is that they are ventilated by a suction pump. Movement of the ribs outwards results in the development of a sub atmospheric pressure in the thoracic cavity where the lungs are located. Air in the environment is at greater pressure than that in the lungs, so air moves inwards down its pressure gradient. Turtles and tortoises have enhanced this process even further by the development of a true diaphragm, which separates the thoracic and abdominal cavities.

Mammalian lungs are, in turn, more compartmentalized and morphologically more complex than reptilian lungs. Air is drawn into the lungs, again, by a suction pump mechanism. Air enters via the trachea, which, via a series of bifunctional divisions, terminates at the **alveoli,** the sites of gas exchange.



The anatomical organization of a **bird's respiratory system** is relatively complex. The **lungs** are connected to an extensive series of air sacs, which are known to extend into bone. These can be conveniently divided into two main groups: the posterior air sacs and the anterior air sacs.

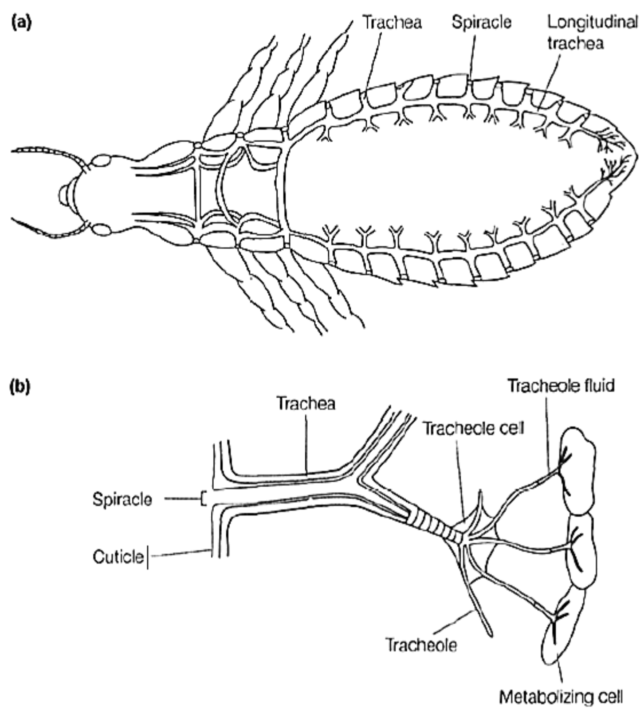
Gas exchange in the bird lung takes place in the parabronchi, which are, essentially, a series parallel tubes open at both ends and through which there is a unidirectional flow of air. The flow of air through the respiratory system of a bird is shown in ***Figure*** 5.8. It can be seen that two complete breathing cycles are required in order to move a single volume of gas through the system. The air sacs act as bellows, forcing air to move around the system.



GAS EXXCHNAGE IN BIRDS NOT ON SYLLABUS: The generalized arrangement of the lungs and air sacs.

5) **Tracheal system in insects.**

Gas exchange in insects occurs through a series of tubes called **trachea**, which branch dichotomously to give increasingly finer tubes called **tracheoles**. The trachea connect to the environment through openings in the insect cuticle called spiracles .In principle, air **is** piped directly to the cells of the insect. In some cases, tracheoles are known to penetrate individual cells and terminate near mitochondria. This arrangement makes the respiratory system independent of the circulatory system. The basic pattern is that twelve pairs of spiracles exist, three pairs of which are located on the thorax, with the remainder located on the abdomen. Generally, all the trachea interconnect with each other.



This means it is possible to have a unidirectional flow **of** air throughout the animal. However, this basic pattern has been modified in many ways. For example, some insects, particularly large active insect (se .g. locusts), have developed **air sacs**. Air sacs are simply thin walled extensions **of** trachea. Since they are thin-walled, they are compressible, which means that their volume can be increased or decreased, so air can be pumped into and out of the system. In many aquatic insect larvae, the majority of the spiracles have become such cases, the larvae are suspended in water with the tip of the abdomen penetrating the surface, thus allowing gas exchange to occur. In the case of small, inactive insects, the air in the tracheal-system enters and leaves by simple diffusion. In large, active insects, this is insufficient to meet the demands of the animal, hence the development of air sacs.

Question: How is the insect tracheal system adapted to its function?

Tracheae are kept open by circular bands of chitin to enable continual air movement to reach and leave tracheoles.
Highly branched tracheoles; provide a large surface area.

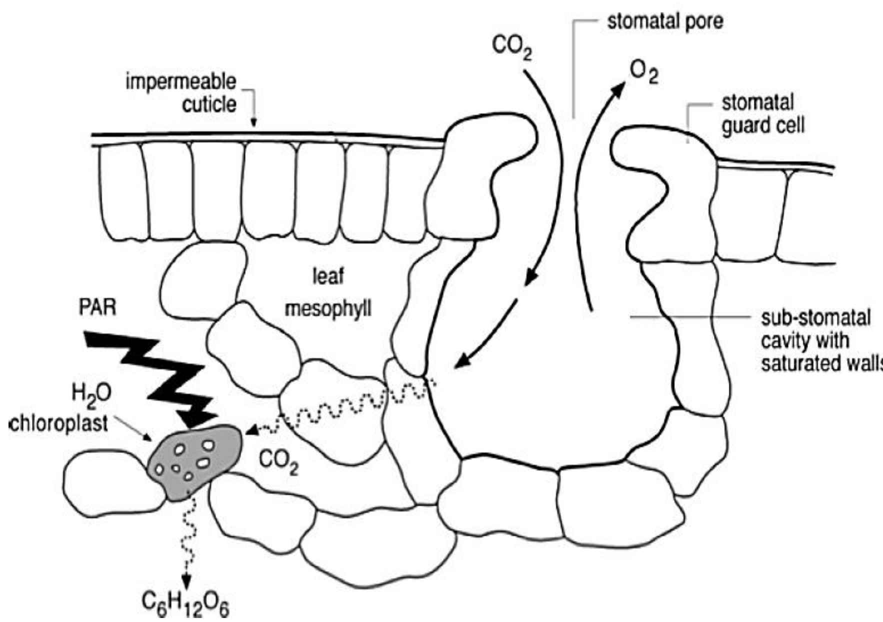
Tracheoles are **moist** to enable dissolution of respiratory gases for increasing their diffusion.
Tracheae are **impermeable to gases** to maintain a high diffusion gradient in the air that reaches the tracheoles
Spiracles **open** and **close**; to regulate diffusion;
Impermeable cuticle; reduce water loss by evaporation.

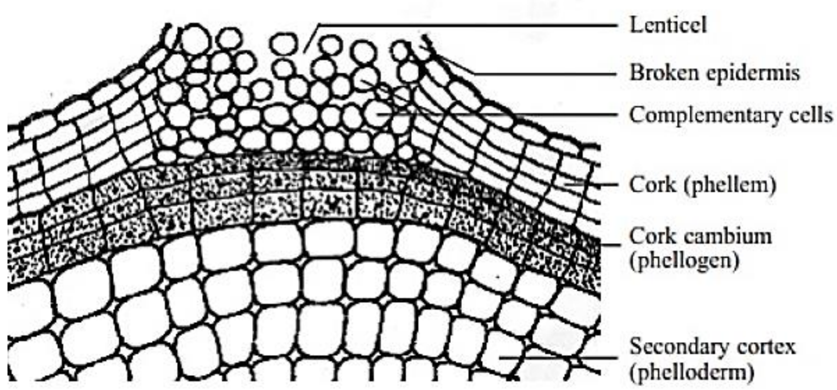
Question: As with all air-breathing animals, loss of water can be a major problem, however insects have overcome this. Explain.

Through **discontinuous** or **cyclic respiration;** With this, O2 is taken up at a more-or-less continuous rate; but CO2 is released in periodic bursts; In between bursts, CO2 remains dissolved in body fluids or is buffered; and the spiracles are seen to flutter and then close completely; During fluttering, the pressure within the tracheal system becomes sub atmospheric; thus ensuring the movement of air into the trachea and preventing air from leaving the insect; After fluttering, the spiracles close completely; and O2 from the air within the closed tracheal system is consumed; The significance of this arrangement is that it allows gas exchange and metabolism to proceed continually; whilst limiting the potentially dangerous loss of water from spiracles that would otherwise be permanently left open;

6) Plasma membrane of cells in the leaf mesophyll and cortex and stem:

- ✓ When the stomata open, production and consumption of oxygen and carbon dioxide in the leaf is sufficient to maintain a concentration gradient steep enough to facilitate gas exchange with the atmosphere.
- ✓ Large intercellular air filled spaces in the spongy mesophyll act as a reservoir for gaseous exchange.
- ✓ The cortical air spaces of roots and stems are continuous up and down and also in a sideways direction, thus allowing gas transport throughout the stem and root tissues.
- ✓ Root hairs lack a waxy cuticle and have moist surfaces to facilitate rapid diffusion of gases through the cell wall.
- ✓ Mangrove species that grow in water logged soils with less air content develop breathing roots above the ground level to increase gas exchange.
- ✓ Root hairs are numerous to increase the surface area for gas exchange.
- ✓ In the stem, lenticels consist of loosely packed cells at the opening to enable diffusion of respiratory gases.





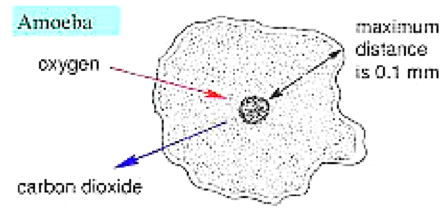
Structure of a lenticel

CHECK PROGRESS:

1. **Why do most plants lack specialized organs for gas exchange?**
2. **Why do most animals have a specialized respiratory system?**

MECHANISMS OF GAS EXCHANGE:

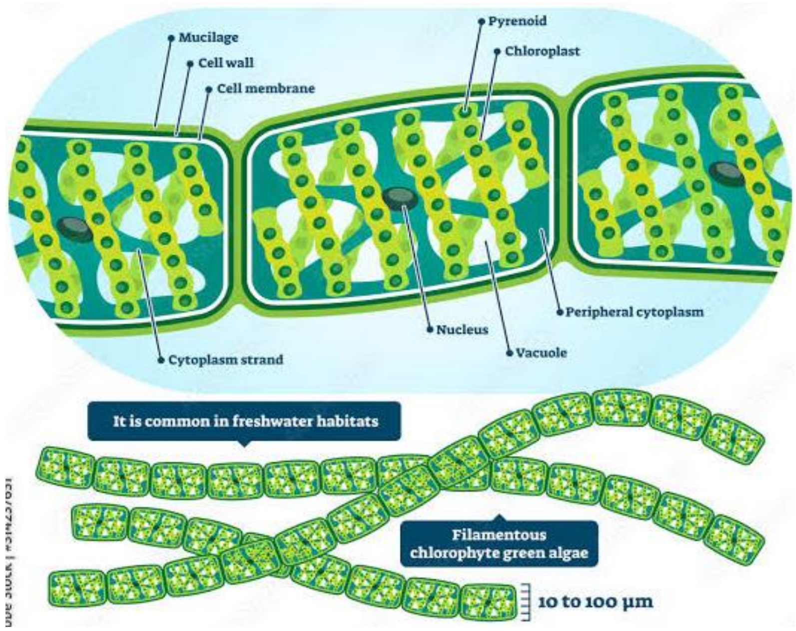
❖ <u>GAS EXCHANGE IN UNICELLULAR ORGANISMS.</u>



In unicellular (single-celled) organisms such as protozoa e.g. amoeba, paramecium, euglena, Chlamydomonas, yeast; & bacteria; the medium of gas exchange is fresh water and the gas exchange surface is the thin plasma membrane, which contributes to presentation of a large surface area: volume ratio. 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.

❖ <u>GAS EXCHNAGE IN SPIROGYRA/ FILAMETEOUS ALGAE.</u>

In filamentous algae, the medium of gas exchange is fresh water and gas exchange occurs across the plasma membrane by diffusion.



(i) In the dark, no photosynthesis occurs in the chloroplast, no oxygen is made. Dissolved oxygen diffuses from the water across the cell membrane into the mitochondria while dissolved carbon dioxide diffuses into water, along their concentration gradients.

(ii) In the light, photosynthesis in chloroplasts releases oxygen, some of which diffuses into the mitochondria, the excess diffuses out.

<u>Check progress:</u>

a. Spirogyra achieves efficient gas exchange through simple diffusion yet many cells. Explain.

Spirogyra is <u>unicellular</u> with single cells in rows; of greatly reduced thickness in a range 10 to 100 µm; this presents a larger surface area to volume ratio; increase diffusion rate of oxygen and carbon dioxide between the surrounding water and cells of spirogyra;

<u>MULTICELLULAR ORGANISMS</u>

❖ <u>GAS EXCHANGE IN PLANTS</u>.

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.

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.**

What is compensation point? The light intensity at which the photosynthetic intake of carbon dioxide is equal to the respiratory output of carbon dioxide.

***NB:* THE major cells involved in gas exchange in plants are stomata and lenticels.**

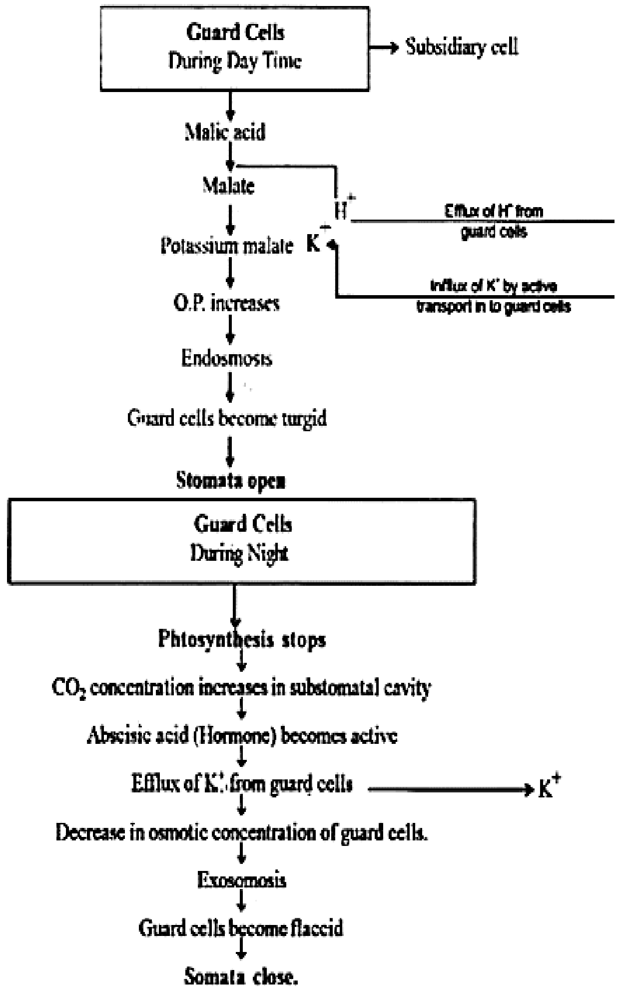
1. **Stomata**; these open and close by the guard cells, regulated by CO_2, light and moisture. Found in epidermis of leaves and stems of herbaceous plants.
2. **Lenticel**; loosely arranged cells acting as a pore to allow gas exchange. Found in stems of woody plants only.
3. **Spongy mesophyll cells**; increases surface air by increasing air spaces (around 50% of the cell); Necessary for circulation of oxygen, carbon dioxide and water vapor.

<u>Gas exchange in leaves:</u>

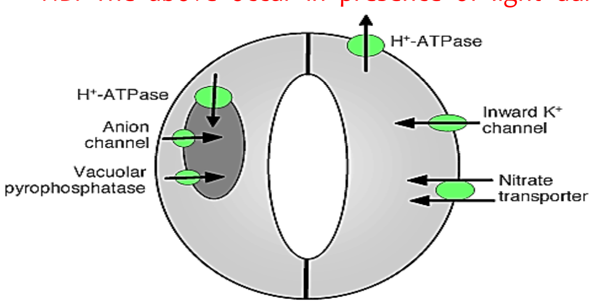
Gas exchange in leaves occurs through the stomata on the lower epidermis. (Stoma singular) opens allowing exchange of carbon dioxide and oxygen.

How are stomata opened?

They are opened by **ions** (mainly **K+**) which move into the guard cell in exchange for **H+** ions from malic acid which flow out to the subsidiary/ epidermal cells by **active transport** using ATP. Hence the **Active Potassium Ion Theory/ Potassium Pump Theory and Role of ABA/ Active Potassium Pump Theory.** Malate anions left in the guard cell from dissociation of malic acid; now neutralized by K+ ions; forming potassium malate; influx of Cl- ions increasing solute concentration; and osmotic pressure; lowering solute potential and water potential too of the guard cells; increasing osmotic uptake of water/ endosmosis by the guard cells from the neighboring epidermal cells, guard cells become turgid and bend, causing stoma to open; allowing gas exchange.

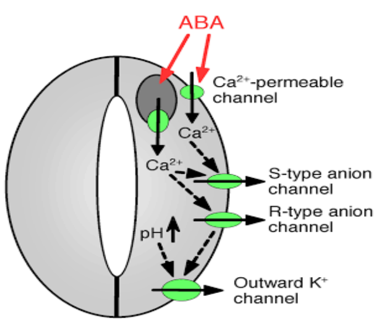


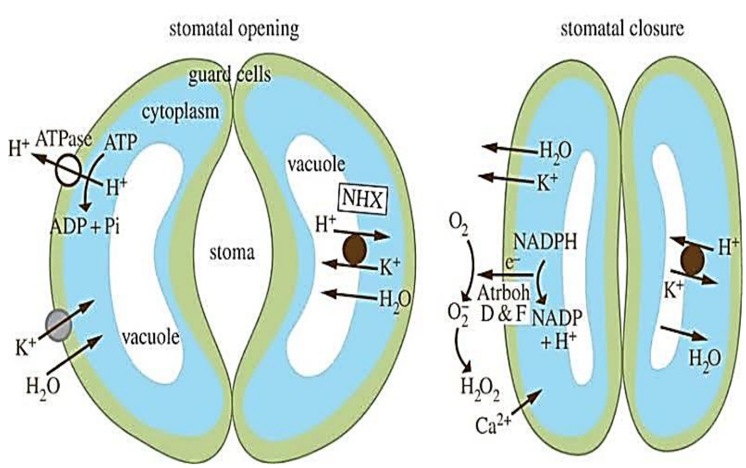
NB: The above occur in presence of light during day, when CO2 concentration is decreased, starch converted to malic acid, which dissociate to H+ and Malate ions.



How do stomata close?

During day/ dark; photosynthesis stops; carbon dioxide concentration increases in substomatal cavity; due to decreased pH of guard cells (ABA hormone activated-abscissic acid released in guard cells stops exchange of K+ ions), H+ ions accumulate in guard cells; malate ions concentration decreases as they form malic acid on combining with hydrogen ions; K+ ions efflux increases to the surrounding epidermal cells; lowering solute concentration and osmotic pressure; increasing solute potential and water potential inside guard cells, exosmosis of water; makes cells flaccid; closing the stomata.



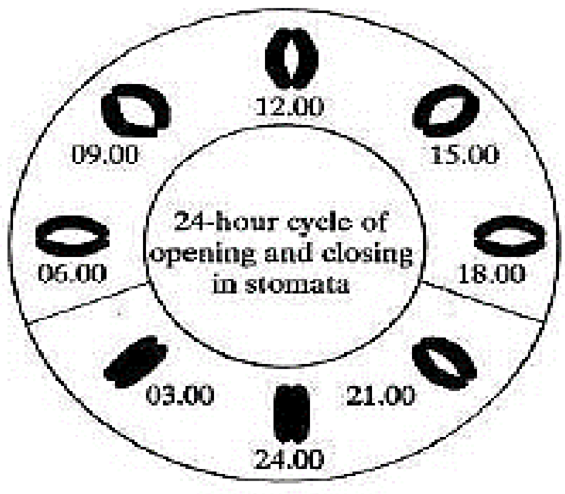


NB:

1. When soil water is insufficient to keep up with transpiration around mid-day, Abscissic acid (ABA) which is a plant growth inhibiting hormone favour 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. Ca2+ enter guard cells, which triggers release of Ca2+ from vacuole into cytosol, which reduces the solute concentration of the cell and thus turgor, causing stomatal closure.

2. ABA act as stress hormone during drought condition

CIRCADIAN STOMATAL RYTHM:



INTERPRETATIONS:

Stomatal aperture remains tightly closed from midnight (24:00) to 03:00am; because no light intensity at night, this no photosynthesis; no carbon dioxide needed; and to reduce water loss by transpiration;

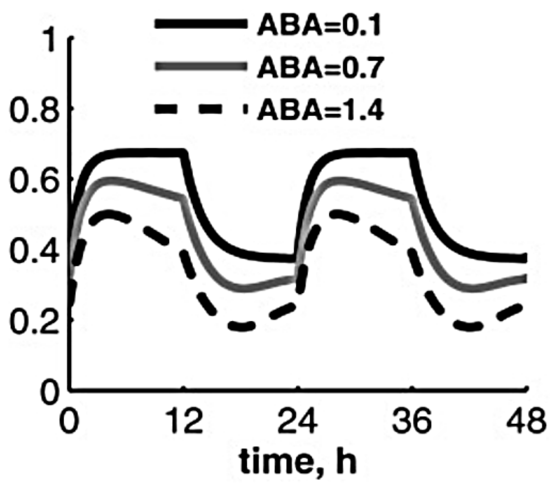
Stoma slightly opens by 06:00am; and then opening increases through morning; and maximally at 09:00am; because rate of photosynthesis increases as light intensity is increasing, so more carbon dioxide is needed for photosynthesis;

Aperture narrows/ decreases slightly by noon (12:00pm); so as to reduce transpiration around midday; which is the warmest part of the day; because increase in temperature increases rate of transpiration;

Stomata reopens up more in afternoon that is 15:00/ 3:00pm; due to reduced environmental temperatures which would cause high transpiration rates;

Later in evening, aperture progressively decreases through 18:00/6:00pm, 21:00/9:00pm; until it again becomes tightly closed by midnight; because rate of photosynthesis is decreasing; as light intensity is decreasing; and stomata close to reduce water loss by transpiration;

Graph showing relationship between ABA and diurnal profiles of three stomata of three different plants during the course of two days.



Comments:

- Stomatal aperture and activity is highest throughout the two days for stoma with ABA =0.1 (lowest concentration of ABA);
- Stomatal aperture and activity is moderate throughout the two days for stoma with ABA =0.7 (moderate/ lower concentration of ABA);
- Stomatal aperture and activity is lowest throughout the two days for stoma with ABA =1.4 (highest concentration of ABA);
- Stomatal aperture decreases from 2 to 12 hours, and 26 to 36 hours for stomata of ABA = 1.4 and 0.7, while remains constant for stoma of ABA = 0.1
- Stomatal aperture increases from 18 to 24 hours, and 42 to 36 hours for stomata of ABA = 1.4 and 0.7, while remains constant for stoma of ABA = 0.1
- Both stomata with ABA = 0.7 and 1.4 attained peaks at about 2hours and about 26hours
- Stoma with ABA = 0.1 a maximum at about 2 hours and about 26 hours.

Account for the observed pattern in stomatal aperture for stoma with ABA = 0.1 during the first day. 10 marks

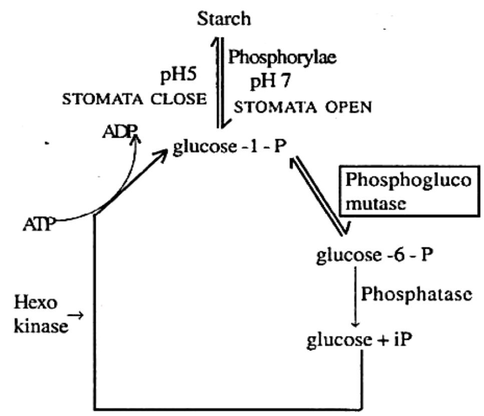
OTHER THEORIES TO EXPAIN STOMATAL OPENING AND CLOSURE

Theory of photosynthesis in guard cells.

Von Mohl (1856) observed that stomata open in light and close in the night.

- He proposed that chloroplasts present in the guard cells photosynthesize in presence of light; resulting in the production of carbohydrate/ sugar; increasing solute concentration, lowering water potential of guard cell sap. Guard cell take in water by endosmosis from subsidiary cells; turgor pressure increases in guard cells, stomata open.
- In darkness, photosynthesis in guard cells is inhibited; solute concentration of cell sap decreases causing exosmosis into subsidiary epidermal cells from the guard cell. Guard cells become flaccid; causing **stomata to close**.

Starch-Sugar Inter-conversion Theory



- **Lloyd (1998);** turgidity of guard cells depends on the Interconversion of starch and sugar.
- **Loft (1921)** supported the theory;
  - When he found that guard cells contain sugar during day time when they are open; and contain starch during night, when they are closed.
  - **Sayre (1926);** observed that,
  - Stomata open in neutral or alkaline pH, which prevails during day time due to constant removal of carbon dioxide by photosynthesis. Stomata remain closed during night when there is no photosynthesis, and due to accumulation of carbon dioxide, carbonic acid is formed, causes acidic pH; thus stomatal movement is regulated by pH due to Interconversion of starch and sugar.
- **Yin and Tung (1948)** isolated for the first time phosphorylase enzyme from the guard cells. According to them, starch is converted into glucose-1-phosphatein presence of this enzyme. During this process, inorganic phosphate is also used and light and dark phases (changing CO2 concentration) control the changes in pH.
- **Steward (1964)** proposed another modified scheme - **Stewards scheme** of Interconversion of starch and sugar for stomatal movement. He believes that conversion of starch to glucose-1-phosphate is not sufficient.
  - It should be further converted to glucose and inorganic phosphate in order to increase sufficient osmotic pressure. For this; ATP is required; from aerobic respiration. Guard cells carry enzymes such as phosphorylase, phosphoglucomutase, phosphatase and phosphorylase.

<u>**Summarized description of the starch-sugar Interconversion theory;**</u>

❖ During day, light present; photosynthesis occurs; carbon dioxide decreased in leaf cells; increase in pH of guard cells; hydrolysis of insoluble starch to soluble glucose / osmotically active sugar by enzymes; water potential decreases; endosmosis of water in to guard cells from subsidiary epidermal cells; turgor increases in guard cells; <u>stoma opens</u>.

❖ During dark, no light; no photosynthesis; carbon dioxide increases; pH decreases in guard cells; soluble sugar/ osmotically active glucose converted to insoluble/ osmotically inert starch; water potential increases; water diffuses out of guard cells by exosmosis; turgor decreases; flaccid guard cells <u>close stomata</u>.

Stomata open:

$$\text{Starch + phosphate} \xrightleftharpoons{\text{Phosphorylase}} \text{Glucose-1 phosphate}$$

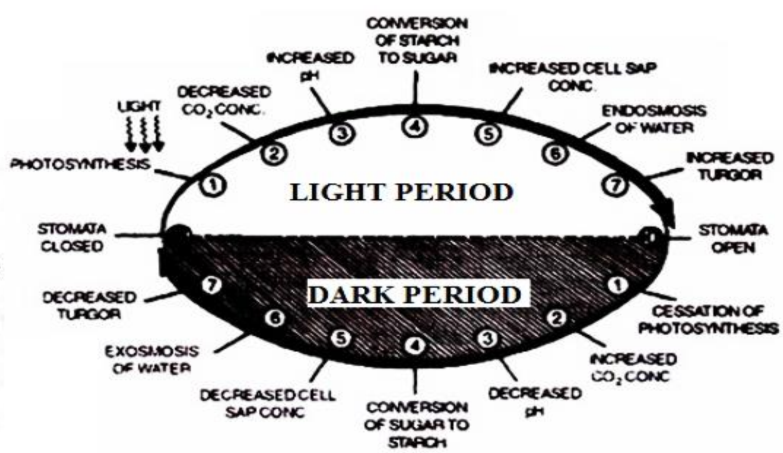
$$\text{Glucose-1 phosphate} \xrightarrow{\text{Phosphoglucomutase}} \text{Glucose-6 phosphate}$$

$$\text{Glucose-6 phosphate} \xrightarrow{\text{Phosphatase}} \text{Glucose + phosphate}$$

Stomata close:

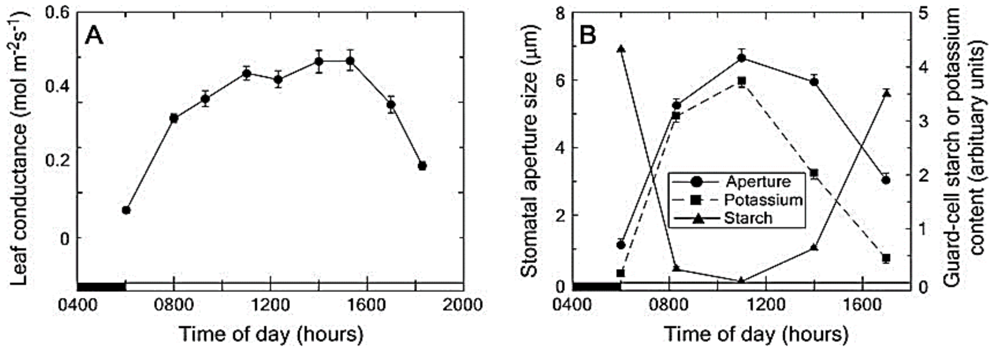
$$\text{Glucose + ATP} \xrightarrow{\text{Hexokinase}} \text{Glucose-1 phosphate}$$

$$\text{Glucose-1 phosphate} \xrightleftharpoons{\text{Phosphorylase}} \text{Starch + Phosphate}$$



<u>Check progress:</u>

1. **The basic stomatal physiological parameters were examined and results presented graphically in figure A and B. Figure A shows the pattern of leaf conductance over the course of the day. Leaf conductance was measured by counting number of open stomata during the investigation. Figure B below shows pattern of stomatal aperture size, potassium ion content in the guard cells, and starch content of a leaf guard cell over the course of the day.**



I. Describe the relationship between patterns of;
   - Guard cell starch content and potassium ion content.
   - Potassium ion content and leaf conductance.

II. Explain the effect of time of the day on the stomatal aperture size of the leaf.

III. Compare the trends in leaf conductance and guard cell starch content over the course of the day.

IV. Account for the differences in iii above.

V. What would happen leaf conductance if a respiratory poison was injected into the guard cells? Give a reason (s) for your answer.

2. The table below shows the mean width of the stomata at different times of the day for two different species of plant.

	Time of day in hours	Mean width of stomata as a percentage of their maximum width	
		Species A	Species B
DARK	0	95	5
	2	86	5
	4	52	6
LIGHT	6	6	40
	8	4	92
	10	2	98
	12	1	100
	14	0	100
	16	1	96
	18	5	54
DARK	20	86	6
	22	93	5
	24	95	5

I. Represent the above the data graphically.

II. Which species is adapted to living in the hot, dry deserts?

III. Compare the mean width of stomata for species A and species B.

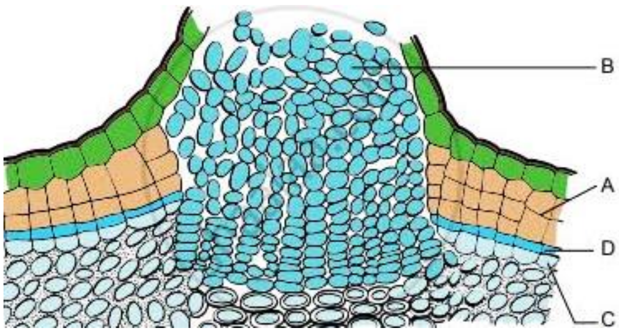
IV. Describe the physiological changes that lead to the observed pattern of stomatal mean width
   - between 6 and 18 hours;
   - between 20 and 24 hours; For species A

Gas exchange in plat roots and stems.

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

- For young roots, stomatal pores as well as lenticels are absent; exchange of gases occurs through root hairs.
- 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, O2 diffuses across the permeable cell walls and plasma membranes of living cells into the protoplasm while CO2 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.
  NB: Unlike stomata which open and close due to guard cells attached; lenticels cells have no such cells surrounding it, so remains open throughout.



Check progress:
The figure below shows section of a woody plant stem.
- **label parts A, B, C, and D**
- **Name the structure above.**
- **The structure above performs the same function as the stoma in a plant. Explain the difference in the mode of action of the above structure and the stoma.**

Adaptations of plant parts for gaseous exchange

LEAVES

(i) Spongy mesophyll cells are loosely packed to accommodate much air which increases the concentration gradient of gases to enable faster diffusion.
(ii) Spongy mesophyll cells are covered by a thin film of water to dissolve respiratory gases to enable faster diffusion.
(iii) Palisade mesophyll cells are tightly packed with thin walls to reduce diffusion distance.
(iv) High stomatal density in upper leaf surface increases rate of diffusion of gases.
(v) 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.
(vi) Floating leaves (e.g. water lilies) generally lack stomata in lower epidermis but very many stomata in the upper epidermis to maximize gas exchange with air at the upper surface.
(vii) Leaves of hydrophytes have very thin or no cuticle to reduce or prevent any barrier to the diffusion of gases into the leaves.
(viii) 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.
(ix) Leaves are thin, which increases diffusion rates of gases.
(x) Leaves have a very large surface area, which increases diffusion rate of gases.
(xi) Sunken in stomata and sub stomatal spaces enable leaves to minimize stomatal transpiration while maintaining gaseous exchange.
(xii) Some plants e.g. water lilies have elongated petioles to enable lamina maintain access to atmospheric air for gaseous exchange.

STEMS AND ROOTS.

(i) Internally, stems of hydrophytes have large intercellular / air spaces / aerenchymatous tissue to accommodate much air which increases concentration gradient for faster diffusion of gases.
(ii) 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.
(iii) 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.
(iv) Red Mangroves which live in oxygen deficient mud have air-rich pneumatophores in prop roots to supplement the oxygen uptake.
(v) Stems of submerged plants have little or no cuticle to reduce the barrier for gas diffusion.
(vi) Stems of hydrophytes have large air spaces to enable floating to expose leaves above water for access to atmospheric air.
(vii) Some aquatic plants elongate stems to enable stomata access atmospheric air for gaseous exchange.

❖ 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.

Earthworms solely use the skin for gas exchange yet their bodies are quite large (low SA/V ratio). Explain.

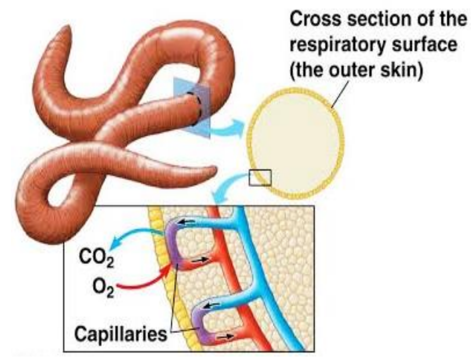
(i) Earthworms are **slow moving** and thus a **low metabolic rate**, therefore require relatively low oxygen supply for aerobic respiration.

(ii) Moist surface with dense network of blood capillaries under the skin enable efficient gas exchange between air and blood.

(iii) Earthworm **circulatory system** contains haemoglobin in blood to increases the oxygen carrying capacity of blood.

(iv) Long, thin body provides large surface area compared to body size, efficient for gas exchange.

(v) Blood capillaries are very close to the skin surface to reduce the diffusion distance for gases.



Check progress:

a) Amoeba and an earthworm carry out gas exchange across their body surfaces. Amoeba vary in size from 250 to 750µm, while earthworm varies in size from 110 to 200mm long and from 7 to 10mm in diameter. The table below shows the relationship between the diffusion rates and the approximate time required for the diffusion of oxygen.

Diffusion distance/mm	Approximate time required for the diffusion of O2/ seconds
0.001	2.38×10^{-4}
0.01	2.38×10^{-2}
0.1	2.38
1	2.38×10^{2}
10	2.39×10^{4}

(i) Describe four properties that are common to the gas exchange surface of both amoebas and earthworms. (4marks)

(ii) From the table above, explain why the earthworm requires a transport system but amoeba doesn't? (5marks)

❖ GAS EXCHANGE IN FLAT WORMS.

Describe the gas exchange mechanism in flatworms.

Flatworms are multicellular organism; with a relatively small surface are/ volume ratio compared to amoeba; however, flat structure/ shape/ morphology; provides a large surface area/ volume ratio; and thus reduce diffusion distance; simple diffusion alone is sufficient to meet the demands of respiratory process;

POSITIVE AND NEGATIVE PRESSURE BREATHING.

Insects, adult frogs, fish, birds and mammals create pressure gradients between the atmosphere and their gas exchange structures in different ways to cause gaseous exchange. Gases (like air) always move from areas of high pressure to areas of lower pressure.

Positive pressure breathing refers to actively creating a positive (increased) pressure in the breathing apparatus higher than atmospheric pressure, to establish the air pressure gradient e.g. Frogs gulp air into the mouth, then close the mouth and nostrils, and raise the floor of the mouth upwards to decrease volume of mouth cavity and increase pressure in the mouth cavity higher than atmospheric pressure.

Negative pressure breathing refers to actively creating a negative (decreased) pressure in the breathing apparatus lower than atmospheric pressure, to establish the air pressure gradient e.g. contraction of diaphragm and rib cage in mammals increases volume to create a lower pressure within the lungs than atmospheric pressure.

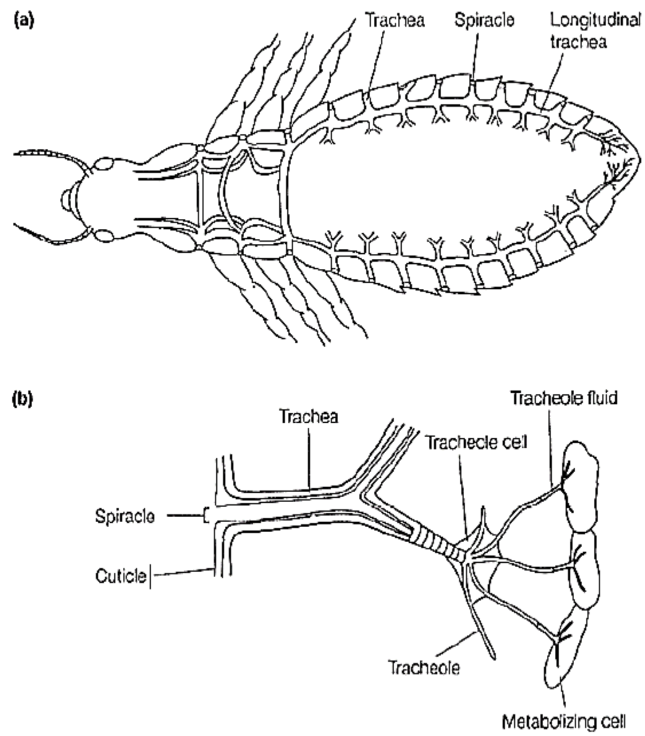
NOTE: Much as frogs use **positive pressure breathing** while mammals, fish, reptiles, insects and birds use **negative pressure breathing**, the end result is the same – gaseous exchange.

❖ GAS EXCHANGE IN TERRESTRIAL INSECTS-

Gas exchange in terrestrial insects occurs through a series of tubes called **trachea**, which branch dichotomously to give increasingly finer tubes called **tracheoles**. The trachea connect to the environment through openings in the insect cuticle called **spiracles** .In principle, air **is** piped directly to the cells of the insect. In some cases, tracheoles are known to penetrate individual cells and terminate near mitochondria. This arrangement makes the respiratory system independent of the circulatory system. The basic pattern is that twelve pairs of spiracles exist, three pairs of which are located on the thorax, with the remainder located on the abdomen. Generally, all the trachea interconnect with each other.

This means it is possible to have a **unidirectional flow** **of** air throughout the animal. However, this basic pattern has been modified in many ways. For example, some insects, particularly large active insect (se .g. locusts), have developed **air sacs**. Air sacs are simply thin walled extensions **of** trachea. Since they are thin-walled, they are compressible, which means that their volume can be increased or decreased, so air can be pumped into and out of the system. In the case of small, inactive insects, the air in the tracheal-system enters and leaves by simple diffusion. In large, active insects, this is insufficient to meet the demands of the animal, hence the development of air sacs.

Describe the main features and arragment of a terrestrial insects gas transport system. (06marks)



Mechanism of ventilation and gas exchange in terrestrial insects:

Inspiration.

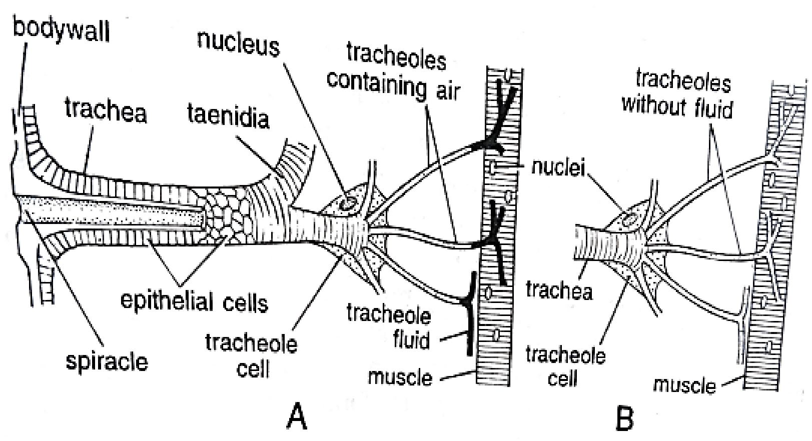
- **Expansion** of the abdomen as a result of relaxed of abdominal muscles, increased volume and lowered pressure; opens **the thorax spiracle valves** through which **air rich in oxygen enters into the tracheal system**; and closes the abdominal spiracles.
- **Thoracic spiracles valves then close and 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.

Expiration.

- **Compression/ flattening** of the abdomen as a result of contracted abdominal muscles, decreases volume, increase pressure; closes the thorax spiracles and opens the **abdominal spiracles** through which **air rich in carbon dioxide is expelled**.

PHYSIOLOGICAL CHANGES THAT OCCUR IN INSECTS TRACHEAL SYSTEM DURING EXERCISE.

- 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.



(A): Tracheoles with fluid at rest (B): Tracheoles without fluid after exercise.

NOTE;

1. 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.

2. 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.

3. When insect is resting, the tips of tracheoles remain filled with fluid so that O_2 diffuses slowly into the body and fluid. Vice versa occurs when insect performs vigorous exercise.

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.

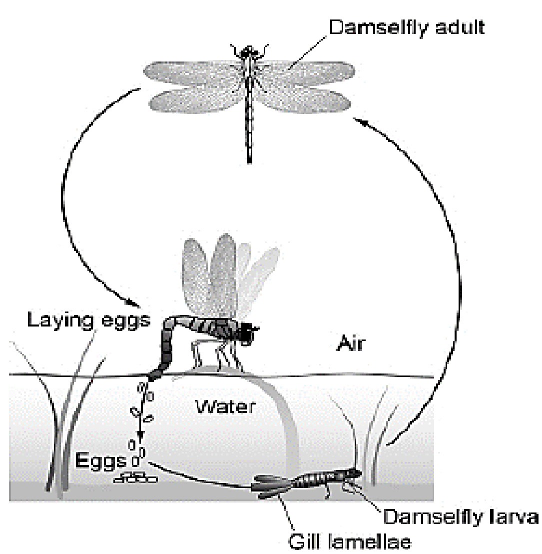
Check progress.

1) **The figure shows the stages of development of an insect called damselfly.**

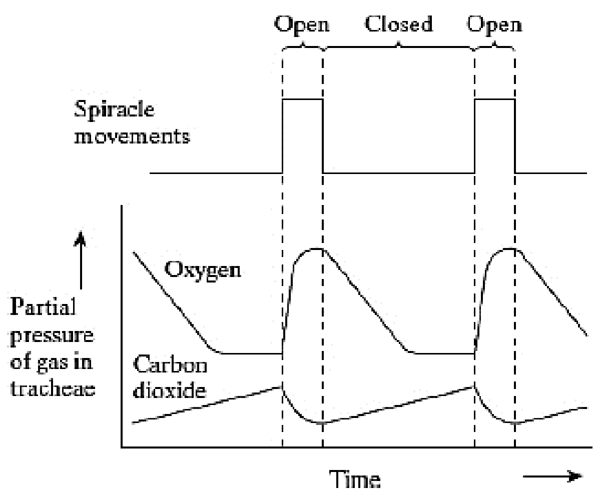
The adult damselfly uses a tracheal system for gaseous exchange.

- **Explain three ways in which an insect's tracheal system is adapted for efficient gas exchange.**
- **The damselfly larva is a carnivore that actively hunts prey. It has gills to obtain oxygen from water. Some other species of insect have larvae that are similar in size and shape to damselfly larvae and also live in water. These larvae do not actively hunt prey and do not have gills.**

Explain how the presence of gills adapts the damselfly to its way of life.



2) **Many insects release carbon dioxide in short bursts even though they produce it at a constant rate. The diagram below shows how this is achieved in one particular insect.**



- **Describe the pattern of partial pressure of gas in trachea in relation to spiracle movement.**
- **Account for the above pattern.**
- **Using information on the graph, suggest what causes the spiracles to open.**
- **Explain what causes the oxygen concentration in the trachea to fall when the spiracles are closed.**
- **The insect lives in dry conditions. Suggest an advantage of the pattern of spiracle shown in the figure above.**

3) **A biology student used grasshoppers to investigate the effect of composition of air on breathing rate in insects. He changed the composition of air they breathed in by varying the concentration of oxygen and carbon dioxide.**

The student collected 20 mature grass hoppers from a meadow. He placed the grasshoppers in a small chamber where he could adjust and control the composition of air surrounding them. The small chamber restricted the movement of the grasshoppers. His results for the three of the grasshoppers are shown in the table below.

		Percentage of oxygen and carbon dioxide in different types of air breathed in by grasshoppers			
		A Air from atmosphere	B Pure oxygen	C Gas mixture 1	D Gas mixture 2
Gas	Oxygen	20.9	100.0	91.0	84.0
	Carbon dioxide	0.1	0.0	9.0	16.0
Breathing rate of grasshopper in different types of air / breaths per minute	Grasshopper 1	53	11	99	107
	Grasshopper 2	48	25	88	99
	Grasshopper 3	61	13	96	93

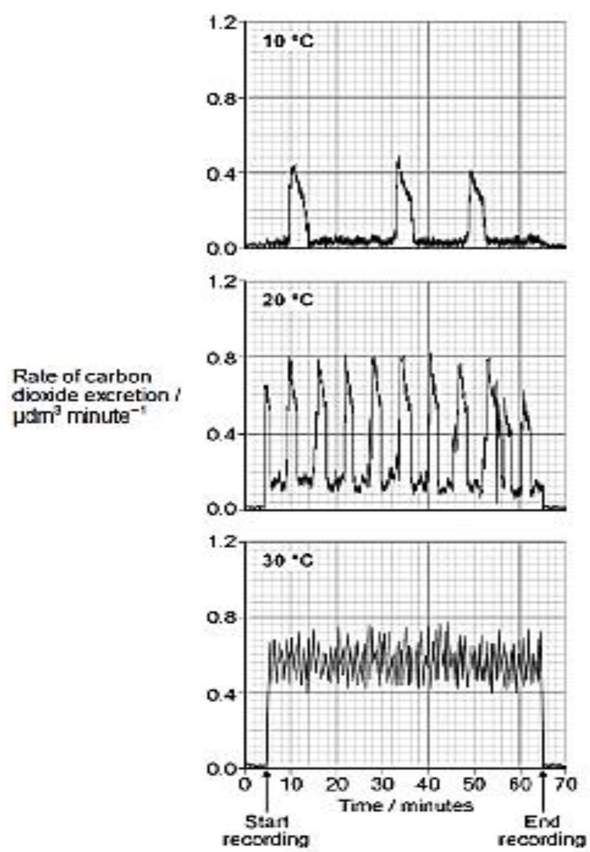
- The percentage of oxygen and carbon dioxide in column A do not add up to 100% but in column C and D they do. Suggest two reasons for this difference.
- Use all the data to explain the effect of concentration of carbon dioxide on the breathing rate of grasshoppers.
- One of the different types of air was similar to the air in the meadow where the grasshoppers were collected. It provides data that might be used to calculate mean grasshoppers collected. It provides data that might be used to calculate a mean breathing rate for grasshoppers in the meadow.
  i. Use the data to estimate the mean breathing rate of the three grasshoppers in the meadow. Show your working.
  ii. The estimate does not provide a reliable value for the mean breathing rate of all insect species in the meadow. Other than being an estimate, suggest and explain three reasons why this value would not be reliable.

4) The table below shows the rate of carbon dioxide release by three groups of insects of the same species at 10, 20 and 30°C and mean mass of each group of insects.

Temperature / °C	Mean mass / g	Rate of carbon dioxide release / μdm³ minute⁻¹	Rate of carbon dioxide release per gram / μdm³ g⁻¹ minute⁻¹
10	0.047	0.12	
20	0.046	0.33	
30	0.048	0.56	

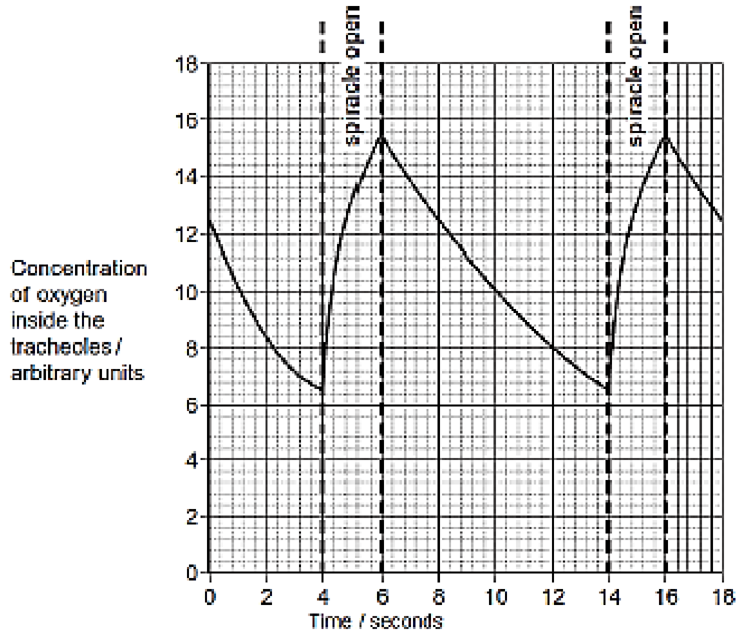
- Complete the above table and plot a graph of your calculated values against temperature.

The body temperature of the insects was largely determined by the temperature they were kept at. At each temperature, the rate of carbon dioxide released by individual insect over time was recorded. This rate depends upon spiracles opening or closing. The graph shows the three insects' results.



- Calculate the change in the rate per hour of opening the spiracles between 10 and 20°C
- Explain the effect of temperature on the rate of carbon dioxide release.

5) The graph shows the concentration of oxygen inside the tracheoles of an insect when at rest. It also shows when the spiracles are fully open.
   - Use the graph to calculate the frequency of spiracle opening. Show your working.
   - The insect opens its spiracles at lower frequency in very dry conditions. Suggest one advantage of this.
   - The ends of tracheoles connect directly with the insect's muscle tissue. Removal of water from the tracheoles increases the rate of diffusion of oxygen between the tracheoles and the muscle tissue. Suggest one reason why?



❖ GAS EXCHANGE IN AMPHIBIANS - 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

Mechanisms of ventilation and gas exchange in Frog:

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. Ventilation is tidal using a buccal force pump (positive pressure)

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.
- O2 diffuses into lung capillaries along concentration gradient while CO2 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.

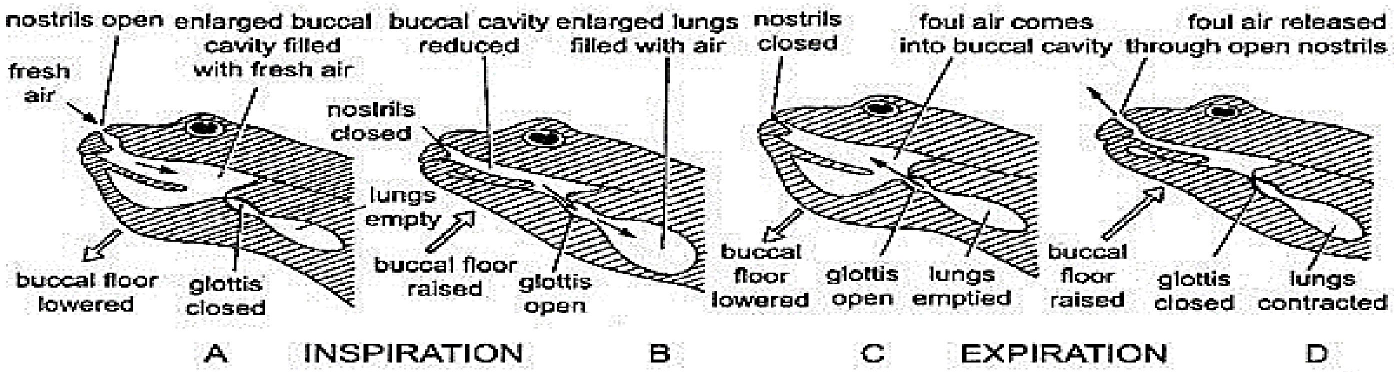


Fig. 18.39. Frog. Breathing movements during ventilation of lungs. Black arrows indicate pathway of air in and out of lungs. White arrows show up and down movements of buccal floor.

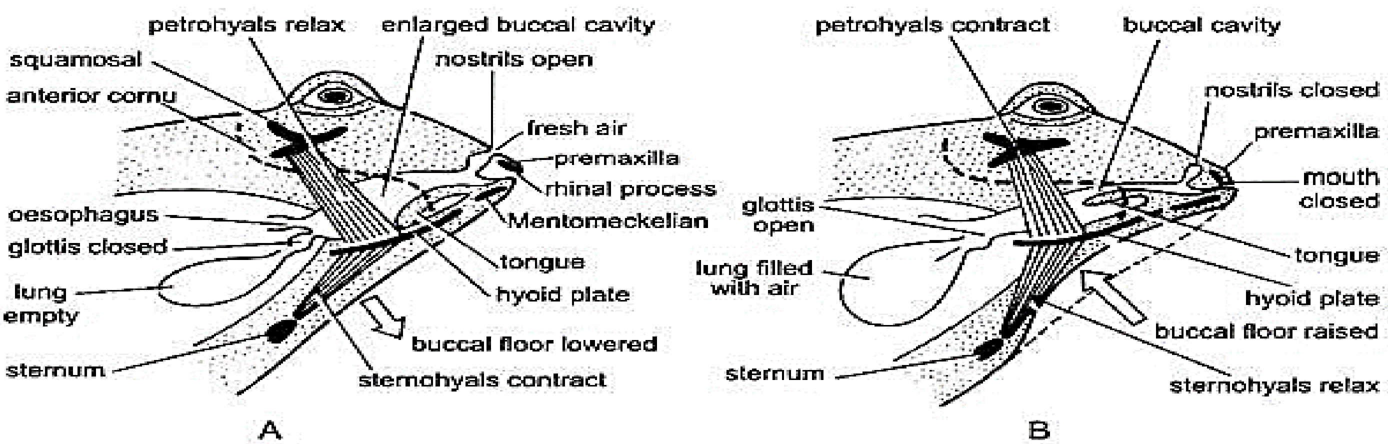
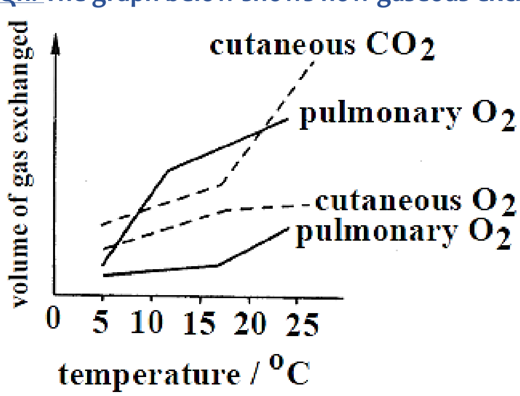


Fig. 18.38. Frog. Diagrammatic representation of respiratory mechanism involving two sets of muscles. The two stages bring respiration. Reverse sequence will result in expiration.

Check progress:

Qn: The graph below shows how gaseous exchange in adult amphibians varies with temperature.



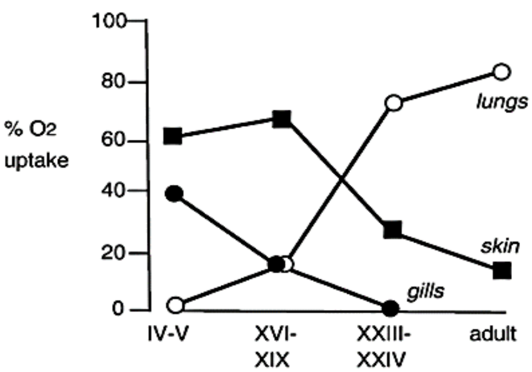
Comments:

- **At all temperatures, cutaneous CO_2 is higher than pulmonary CO_2/ skin eliminates most carbon dioxide;**
- **Below 6°C, cutaneous O_2 is higher than pulmonary oxygen;**
- **Above 6°C, pulmonary O_2 is higher than cutaneous O_2/ lungs take up most oxygen;**
- **Above 17°C, cutaneous O_2 remained constant at a maximum while pulmonary O_2 increased gradually;**
- **Above 17°C, cutaneous CO_2 increased rapidly while pulmonary CO_2 increased gradually;**

Explanations:

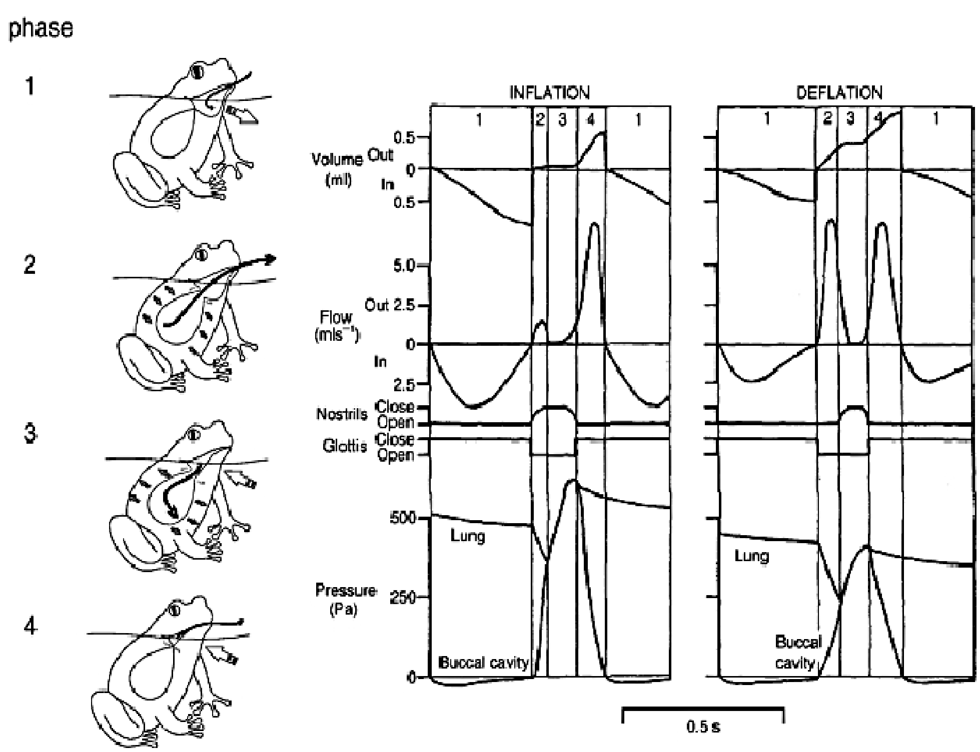
- At all temperatures most CO2 is eliminated by the skin; to increase the rate of elimination preventing CO2 accumulation in the frog's body; the skin allows faster diffusion of CO2 all over the entire body surface. CO2 elimination increased rapidly than at high temperatures to prevent excessive water loss which would occur when lung CO2 elimination had increased more than cutaneous;
- Cutaneous gas exchange and ventilation is more necessary than pulmonary gas exchange during winters (at lower temperatures); owing to low metabolism; low O2 needed for low aerobism and expulsion of reduced CO2 from low tissue respiration; is sufficiently achieved through the skin surface.
- Pulmonary intake of O2 is more necessary than cutaneous O2 uptake at high temperatures; which increase the rate of metabolism. Therefore, the high O2 demand for anaerobic respiration; is met by increased lung function; as cutaneous oxygen remains low and insufficient to sustain high rate of aerobism;

Qn: Figure below shows change in percentage of total oxygen taken up across the skin, gills and lungs during the different stages metamorphosis of a frog at 20°C.



- Describe the changes in percentage of total oxygen taken up across the;
  i. Gills
  ii. Skin
  iii. Lungs
- Account for the above changes.
- Air breathing occurs between stages V to XXIV metamorphosis, yet air is not utilized in initial growth and development stages. Explain.
- At stage IV, gills and skin perform 100% gas exchange. Explain.
- Stage XXIII-XXIV is the metamorphic climax. Outline the post metamorphic changes that in a frog during and after this stage.
- State the principal role of the skin in gas exchange in the adult frog. Explain.
- Briefly describe the major stages of frog metamorphosis.

Qn: In the figure below; The left hand panel is a schematic diagram illustrating the ventilatory movements in an adult anuran species which has evolved a modified ventilation mechanism and gas exchange system. The right hand panel is a summary of diagrams illustrating the changes in lung volume, air flow at the nostrils, and pressures in the lungs and buccal cavity, along with the timing of nostril and glottis movement during an inflation and deflation breath. Carefully study the graph and answer the questions that follow.



- Describe the sequence of events occurring in the different phases of
  i. Inflation
  ii. Deflation
- Compare the lung and buccal cavity pressures during;
  i. Inflation
  ii. Deflation
- Account for the significances of the observed differences in the lung and buccal cavity pressures during the two cycles.

❖ GAS EXCHNAGE FISH.

DESCRIPTION OF RESPIRATORY SYSTEM IN BONY FISH ***(Already discussed in respiratory surfaces)***

TYPE OF VENTILATION IN FISH.

Active ventilation and unidirectional.

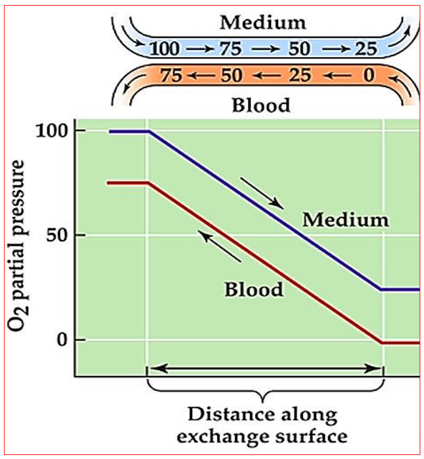
Active ventilation: Because fish uses metabolic energy to bring the environmental medium (water) to the respiratory surface/ membrane. Active ventilation is more reliable, controllable and vigorous.

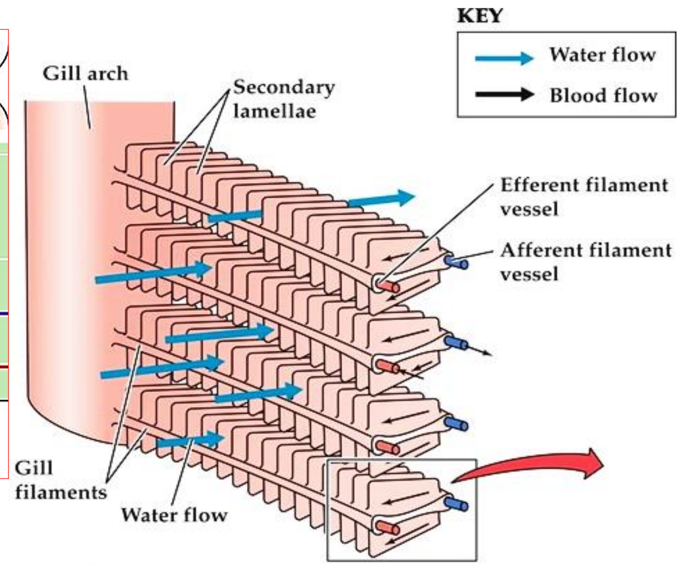
Unidirectional: because respiratory medium water is pumped over the gills in one way path.

- Water and blood may flow in **same direction** = **concurrent flow/ parallel flow**; in **Cartilaginous fish**-(**dog fish/ shark**).
- Water and blood may flow in **opposite direction** = **countercurrent flow**; in **Teleosts** (**bony fishes**).

COUNTER CURRENT VENTILATION AND CONCURRENT/COCURRENT/PARALLEG VENTILATION

CONUTERCURRENT VENTILATION/FLOW.





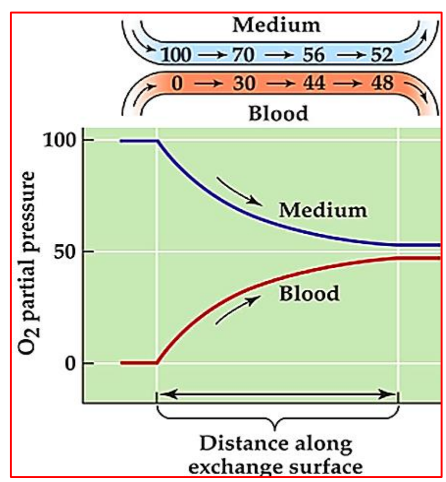
- Water flows across the gill lamellae in an opposite direction to the blood flow, enabling much of the oxygen (80-90%) from the water diffusing into the blood.
- Although dissolved oxygen levels in water drop as the water flows across the gill lamellae, the blood has lower levels; therefore a sustained 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

  (1) Enables blood of the gill lamellae to extract maximum oxygen from the water for the entire period the water flows across the gill filaments.

  (2) Under conditions permitting adequate oxygen uptake, the counter-current fish expends less energy in respiration compared to parallel flow.

CONCURRENT/ COCURRENT/PARALLEL VENTILATION/LOW.



- 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.

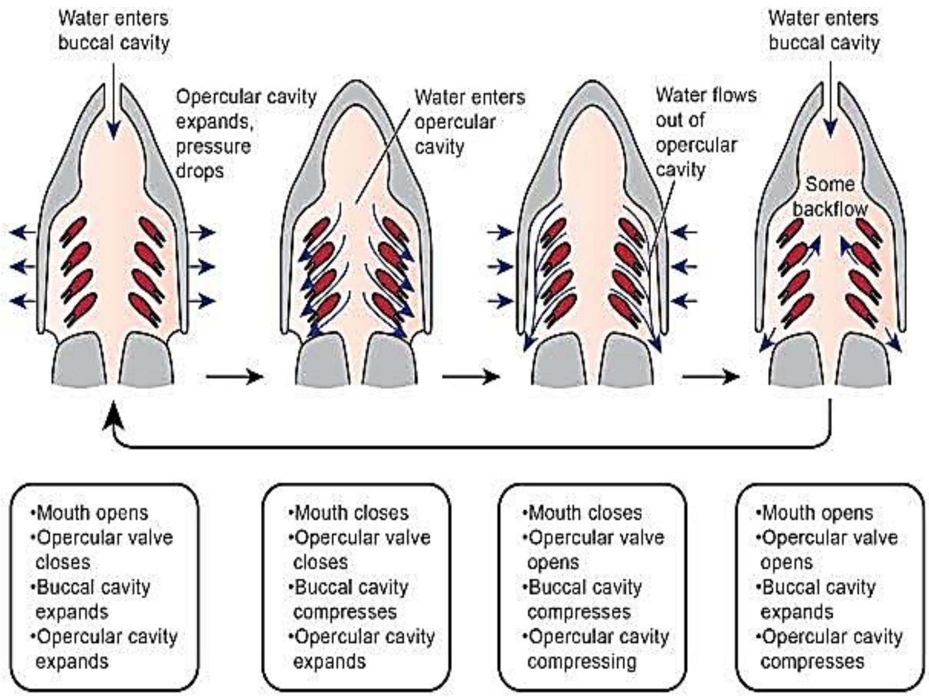
  How countercurrent is prevented in a dogfish:
- The vertical septum deflects the water so that it tends to pass over rather than between the gill plates, hence flowing parallel to the lamellae through the gill pouches.

MECHANISM OF VENTILATION/ BREATHING IN TELEOSTS –BONY FISHES, Herring (BUCCAL/OPERCULAR PUMPING).

Water flows across gills via two synchronous pumps: **(a) buccal pressure pump (b) opercular suction pump**.

INHALATION

- Fish depresses floor of the mouth, increasing buccal cavity volume as pressure decreases.
- Water rushes in, and mouth closes
- Fish raises flow of the mouth; increasing pressure; hence a pump.
- Fish expands opercular cavity, creating suction.
- Water is pulled caudally across the gills.
- As water flows over gill filaments in opposite direction to flow of blood (**countercurrent flow**) O2 diffuses into blood capillaries to combine with haemoglobin while CO2 diffuse into the flowing water along concentration gradients.



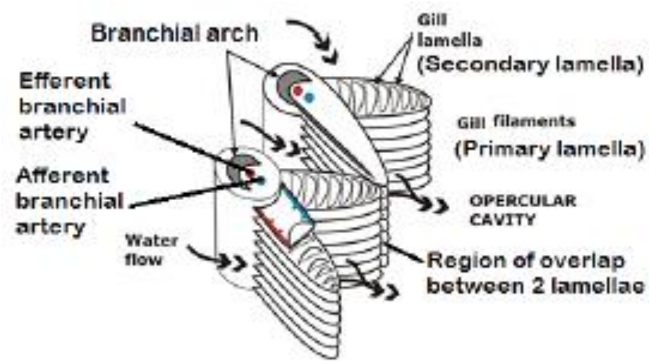
EXHALATION

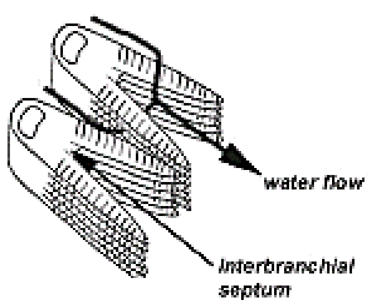
- Mouth muscles are fully contracted with mouth valve tightly closed.
- Opercular muscles relax to decrease opercular cavity volume and increase pressure.
- Pressured water in opercular cavity forces opercular valves to open as water exits.

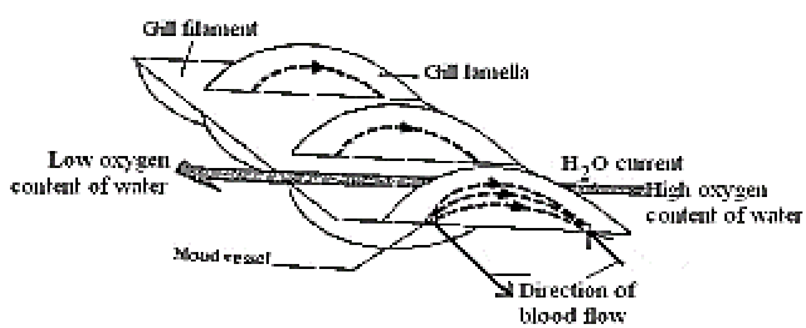
How is the structure of the gill suited for its function?

BONY FISH GILL STRUCTURE

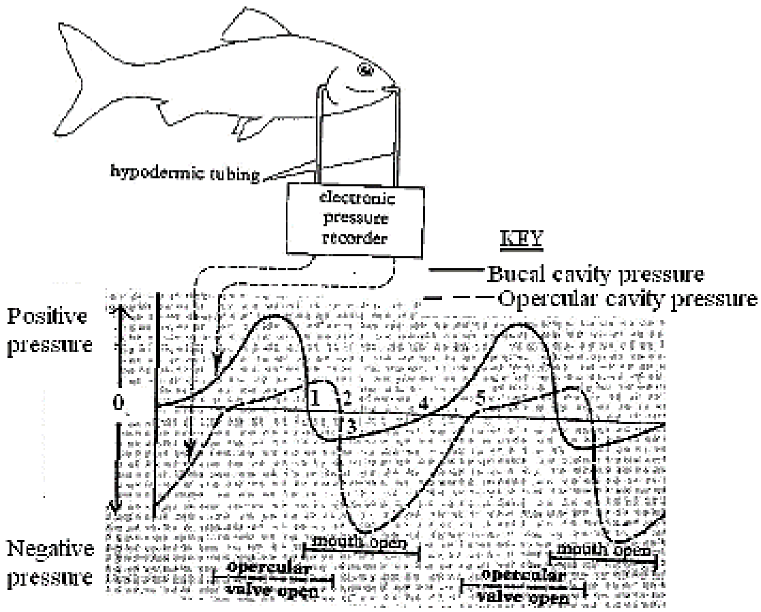
- 4 gill arches in each opercular cavity.
- 2 rows of gill filaments project from each gill arch.
- Each filament (primary lamella) is covered with rows of secondary lamellae perpendicular to filament
- Each gill arch contains an afferent & efferent artery.
- **Afferent blood vessels** carry deoxygenated blood to the capillaries in the secondary lamellae.
- **Efferent blood vessels** carry oxygenated blood from the capillaries back to the gill arch.
- Secondary lamellae (**respiratory surface**) are semicircular, thin-walled and highly vascularized with capillaries
- Blood flow through capillaries in secondary lamellae is opposite the flow of water through the gills (**countercurrent flow**).







PRESSURE CHNAGES DURING BREATHING/ RESPIRATORY MOVEMENTS OF TELEOSTS



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.

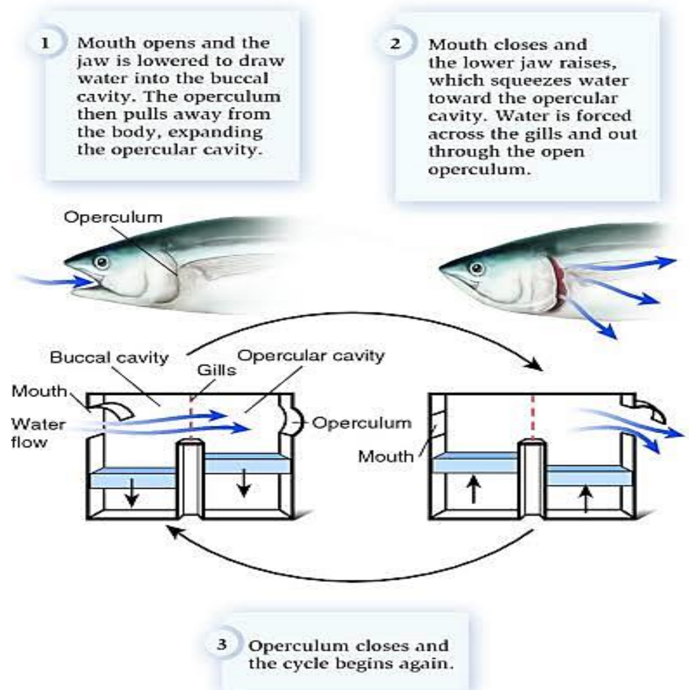
At 5, opercular cavity is contracting to decrease the volume as pressure increases above atmospheric pressure **(acquires positive pressure)**; opercular valve opens and water is expelled

NOTE:

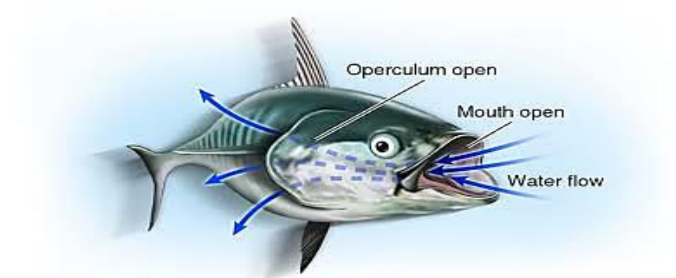
(1) Water almost flows in one direction from the buccal cavity to the opercular cavity.

EVIDENCE: *Throughout the ventilation cycle, except for one short period when the buccal cavity expands* ***(see 1above),*** *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.*

(2) *The buccal cavity acts as a force pump while the opercular cavity as a suction pump.*



(a) Buccal pumping



(b) Ram ventilation

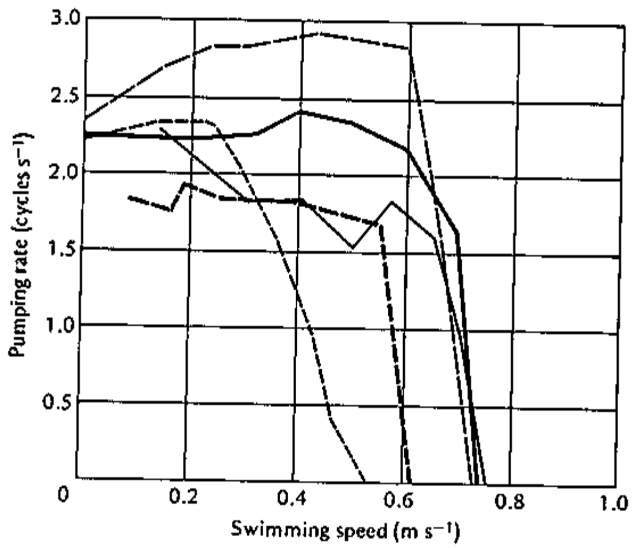
OTHER FORMS OF BREATHING IN FISH

RAM-BREATHING FISH: Ram breathing is swimming powerfully with mouth open; no visible breathing movements; forcing water continuously across the gills. Some fish such as **tuna**, **lamnid sharks,** are obligate ram ventilators: they must swim constantly forward or rather suffocate.

- Ram ventilation is not restricted to large, **fast-swimming pelagic fish**. Many fish breathe pumping at low speed and change to ram ventilation**.**
- **The change to ram ventilation does not mean that the gills are ventilated for free, but it means that the work of breathing is transferred from muscle of the**

opercular pumps to swimming muscle of the body and tail. The open mouth causes increased drag, and this has to be paid for in increased muscular work. However, the continuous flow during ram ventilation is more economical in energy that opercular pumping at high rates required for fast swimming.

- **From the graph, when swimming speed of a mackerel increases to between 0.5 and 0.8ms-1, opercular pumping ceases and the fish breathes entirely by ram ventilation of the gills. The records in this graph were obtained from mackerel individuals weighing about 70g each.**



Check progress:

Compare buccal buccal/Opercular pumping and ram ventilation.

AIR-BREATHING FISH: Air breathing fish have evolved mechanisms to tap atmospheric oxygen.
The gas exchange system may be derived from: buccal cavity, opercular cavity or gastrointestinal tract (including swim bladder)

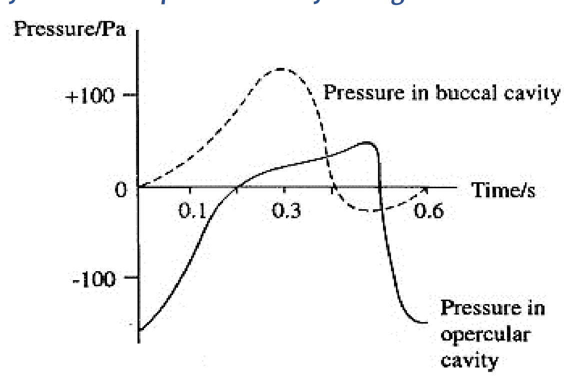
What is the biological significance of air breathing among fish?

- **Survival in oxygen poor habitats**
- **Utilization of terrestrial foods resources**
- **Abandon drying ponds to search for better habitat.**
- **Invade new territories to increase distribution.**

AMPHIBIOUS FISH: Some fish have evolved the capacity to remain out of water for an extended period of time. Such as the lung fish.

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:* the above does not account for air breathers**
b) Under what circumstances do fish suffocate in the water?
(i) When the oxygen in the water is depleted by another biotic source such as bacteria/decomposers.
(ii) When oxygen greatly diffuses out of water due to increase in water's temperature.

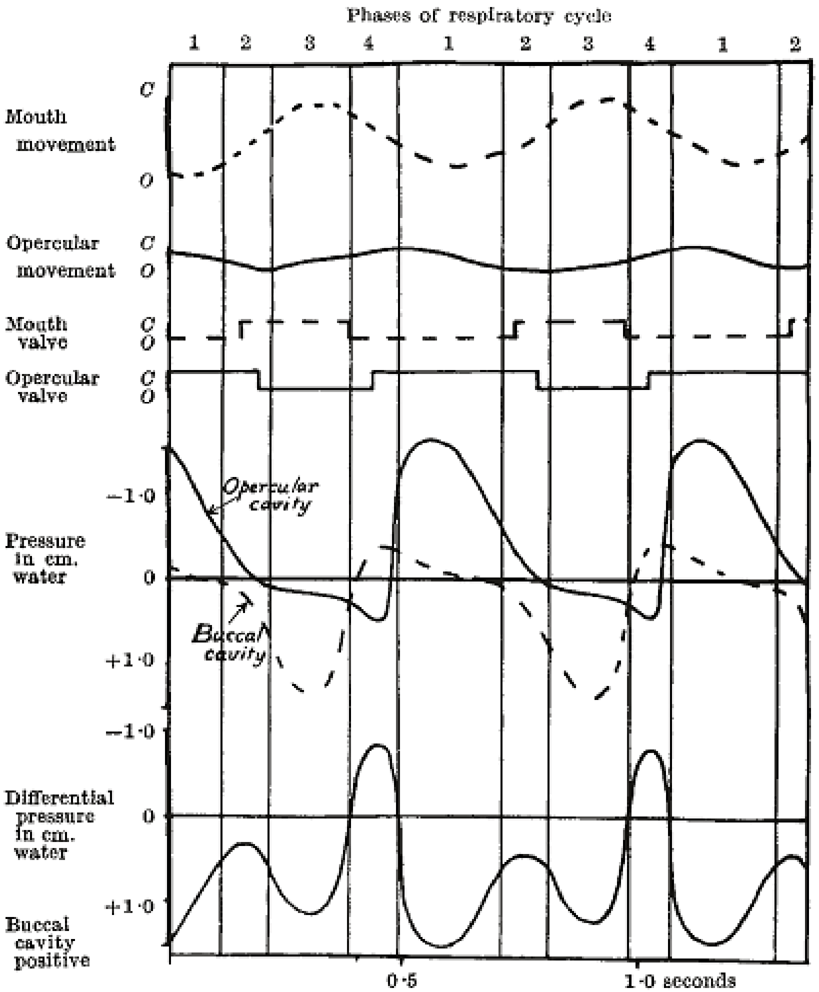
Qn. 2. The graph below shows the changes in pressure in the buccal cavity and in the opercular cavity during a ventilation cycle.



(a) Calculate the rate of ventilation in cycles per minute
Since the duration of one cycle is 0.6 seconds, therefore ventilation rate = 1.0 divided by 0.6 = 1.67 cycles per second.
(b) (i) 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.
(ii) How does the fish increase buccal cavity pressure?
The mouth closes, the floor of buccal cavity is raised and the buccal cavity pressure increases.

P530/2 POSSIBLE EXAMINATION QUESTION:

Fig. 1. Shows Movements of the mouth and operculum with associated pressure changes in the buccal and opercular cavities during breathing in a fish species, trout (*Salmo trutta sp.)* (70 gm.) at 17° C. Dashed lines relate to the mouth and buccal cavity. The differential pressure between the two cavities is shown below. *C* and *O* Indicate 'closed' and 'open' respectively. **TRICK IN QUESTION! CANDIDATES MUST TRACE FOR COMPLETE CYCLE AND ATTENTION TO SIGNS (+/-)**



(a) Account for the pressure changes in the buccal cavity in the buccal cavity during one complete respiratory cycle. (10marks)

At the start of cycle/ start of/ during phase 1, buccal cavity pressure is negative; because opened mouth valves, floor of buccal cavity lowered; opening mouth during phase 1, buccal cavity volume increases, buccal cavity pressure falls below pressure of surrounding water; making water to rush from the external surrounding into the opened mouth; by suction pump;

From start of phase 2 to mid of phase 3, buccal cavity pressure is positive and above external pressure, because the mouth valves closed; floor of buccal cavity raised; and attained a peak at mid of phase 3; to force water over the gills; by a buccal pump;

At end of phase 3, buccal cavity positive pressure decreases, falls below opercular positive pressure and external pressure of water/ below zero, because mouth valve opens, floor of buccal cavity lowered; causing mouth to open; then attains a minimum buccal cavity negative pressure towards end of phase 4/ at end of cycle; allowing sufficient water to be drawn into the mouth; repeating the cycle;

Accept: because fish has closed the opercular valves; positive pressure increases above that of mouth in phase 4;

(b) Compare the pressure changed in the buccal cavity and opercular cavity in one respiratory cycle. (10marks)

Similarities **AWARD MAX =4 MARKS**

Pressure in both cavities:

is negative in phase 1; is positive in phase 3; is negative at end of phase 4/cycle; is positive and the same/ equal at end of phase 3 / start of phase 4 and towards end of phase 4/ cycle; increase rapidly at the same rate during phase 2;

Differences **AWARD TABULATED DIFFERENCES-ANY CORRECT (06MARKS)**

In phase 1, opercular cavity has a greater/ more negative pressure than buccal cavity negative pressure;
In phase 2, buccal cavity attained a positive pressure while opercular cavity pressure is still negative;
In phase 3, positive pressure in buccal cavity is greater/ more than positive pressure in opercular cavity;
At the start of phase 4, opercular cavity attained positive pressure with respect to pressure in buccal cavity/ (while buccal cavity attained a negative pressure);
At the end of phase 4/ cycle, negative pressure in the opercular cavity is greater/more than negative pressure in the buccal cavity;
Maximum buccal cavity positive pressure is higher than the maximum opercular cavity positive pressure;
Minimum buccal cavity negative pressure is lower than the minimum opercular cavity negative pressure;

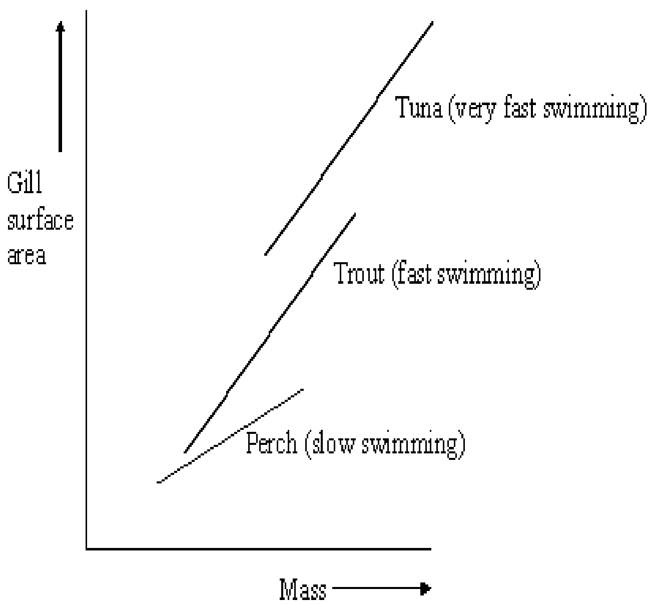
Maximum buccal cavity positive pressure attained in phase 3 while maximum opercular cavity positive pressure attained in phase 4;
Maximum buccal cavity negative pressure attained end of phase 4 while maximum opercular cavity negative pressure attained slightly after the start of phase 1;

(c) What is the physiological significance of difference between the pressure in the buccal cavity and opercular cavity? (06marks)

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) Explain the following observations.
(i) Fish breathes at a higher rate than any other terrestrial animals. (04marks)
(ii) Fish consumes less oxygen during winters. (05marks)
(iii) Fish need more oxygen as temperature of water increases. (04marks)
(iv) Identify the phases during which buccal pumping and suction pumping occurs. (01mark)

Qn: The graph below shows the relationship between gill surface area and body mass of three fish species.



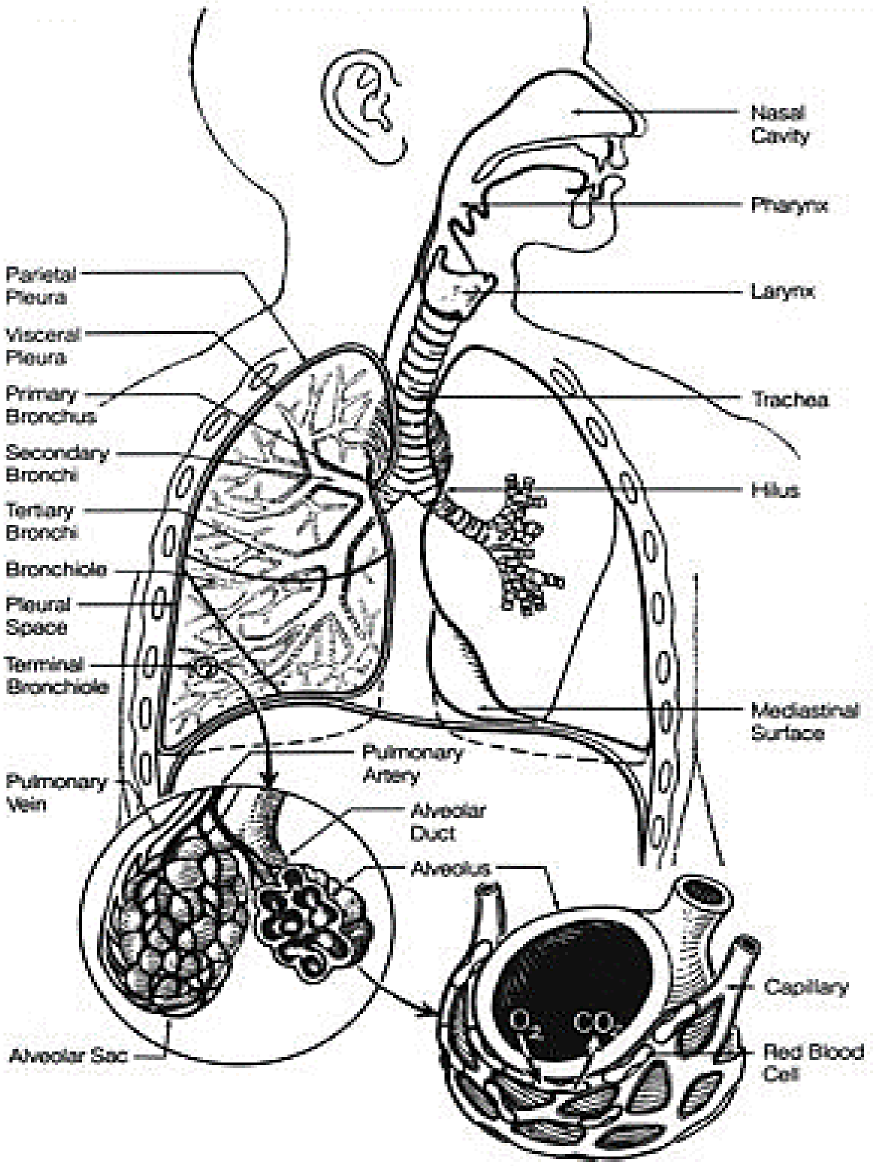
(a) Describe the relationship between gull surface area, body mass for three species of fish and swimming speed as shown in the diagram.
(b) Explain the relationship between gill surface area and swimming speed.
(c) Describe the ventilation mechanisms in Tuna and Perch.
(d) Outline the biological and physical (environmental) factors that affect breathing rate in water breathers.
(e) There is a one-way of flow of water over gills of fish whereas there is a two-way flow of air in the lungs of a mammal. Explain the significance to fish of this one-way flow of water over its gills.
(f) Explain the following observations.
(i) The concentration of oxygen is higher in the surface water than it is in water close to seabed.
(ii) Mackerel live in the surface waters of the sea. Toad fish live on the seabed in deep water.
(iii) Fast swimming saves respiratory energy in Tuna and Trout compared to slow swimming in Perch

❖ GAS EXCHNAGE IN MAMMALS.

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: **(1)** A blood transport system with red blood cells containing haemoglobin **(2)** A mechanism of ventilation to get the gases to and from the gas exchange surface.

DESCRIPTION OF RESPIRATORY SYSTEM IN MAMMALS-MAN

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 **(1)** are spongy and elastic - are capable of expanding and contracting **(2)** consist of air sacs and the alveoli **(3)** have blood vessels that are the branches of the pulmonary artery and veins **(4)**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.**

Structure of Alveolus:

Thin walled, each wall is 0.0001mm thick. Its outside surrounded with a dense network of blood capillaries, which originate from pulmonary artery, and rejoin to form the pulmonary vein.

Wall made of moist, very thin, flattened cells (squamous epithelium) of one cell thick, reducing diffusion distance over which diffusion occurs.

Walls are expanded/ bulge forming a spherical structure (sac) surrounding the alveolar space.

Collagen and elastic fibres also present, the latter allowing expansion and recoiling easily during breathing.

Alveolar walls also have special cells which secrete a **surfactant** (detergent-like chemical) on to the inside of the lining of the alveolus.

SURFACTANT/ 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.

It should be noted that: Surfactant is constantly secreted and reabsorbed in a healthy lung.

Functions of lung surfactant

(1) It greatly reduces alveolar surface tension, increasing lung compliance allowing the lung to inflate much more easily, thereby reducing the effort needed to breathe in air.

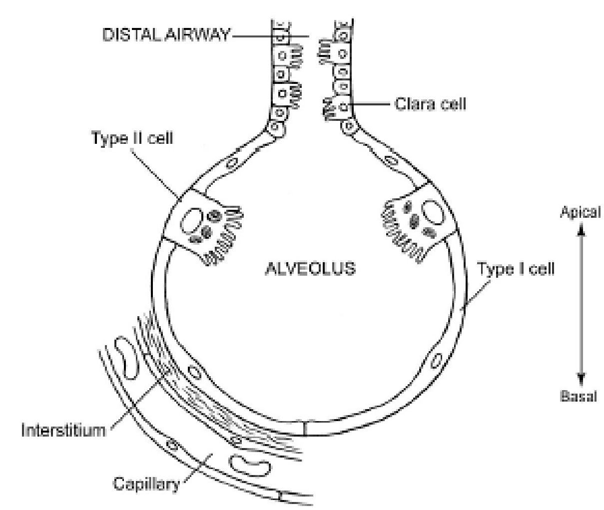
NB: ***Lung Compliance is the ability of lungs and thorax/ chest to expand.***

(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 preventing collapse by equalizing pressure as further **discussed below**.

Cross section of alveolus



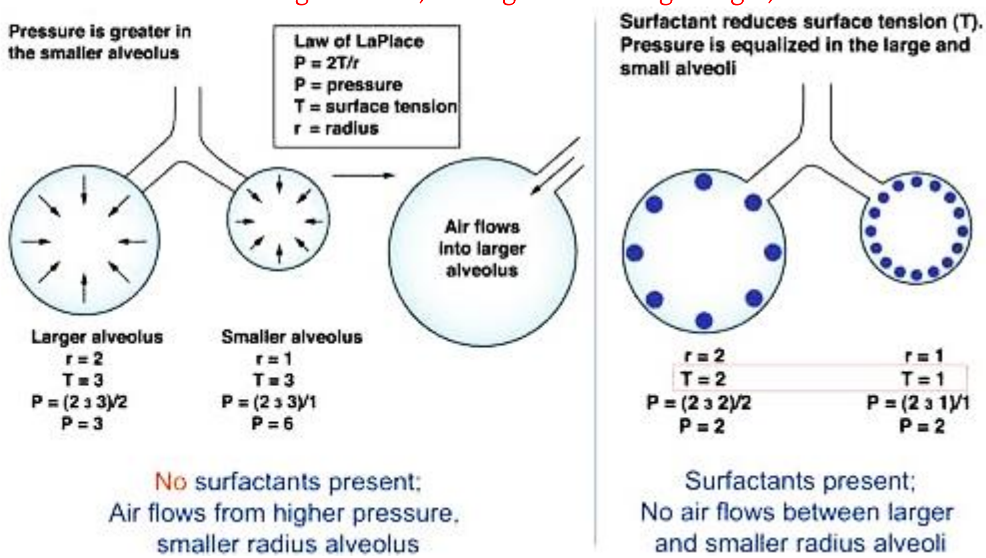
FUNCTION NUMER (4) DISCUSSED.

OBERVATION: Without surfactant the surface tension of fluid in the alveoli is about 1000times higher than normal and alveoli collapse after expiration; it also requires much greater efforts to expand them again when breathing in than when surfactant is present.

EXPLANATION: Pressure within a spherical structure with surface tension, such as the alveolus, is inversely proportional to the radius of the sphere. i.e. at a constant surface tension, small alveoli will generate bigger pressures within them than will large alveoli.

Smaller alveoli would therefore be expected to empty into larger alveoli as the pressure in the smaller alveolus is higher.

The small alveolus would get smaller, the large one would get larger, and so on until the small alveolus collapses completely.



This does not occur, however, because surfactant:-

- When alveolar radius is small, the surfactant film is compressed and surface tension reduced/ smaller/ less , at lower volumes;
- When alveolar radius is large, the surfactant film is expanded and surface tension is raised/ larger/ more, at higher volumes;

Both smaller and larger alveolus attain equal pressure, inflated and deflated equally and easily; leading to alveolar stability and reducing the likelihood of alveolar collapse.

Discussed by Law of LaPlace

Check progress:

1. Explain the following observations.

i. **Babies born prematurely are at risk of premature death due to Respiratory Distress Syndrome (a condition of being deficient in surfactant).**

ii. **Without surfactant the surface tension of fluid in the alveoli is about 1000times higher than normal and alveoli collapse after expiration.**

OBJECTIVE TYPE QUESTIONS:

2. According to LaPlace's law, the pressure required to open an alveoli in the lungs is:

A. **Directly proportional to the radius.**
B. **Inversely proportional to the length of the airway.**
C. **Directly proportional to the surface tension.**
D. **Indirectly proportional to the viscosity of the gas in the airway.**

3. Which of the following physiological consequences would develop if the liquid-gas interface were without surfactant?

A. **Large alveoli would empty into smaller ones at the end of exhalation.**
B. **Every exhalation would demand ventilatory muscle activity.**
C. **Every breath would require a considerable amount of pressure to expand the lung with each inspiration.**
D. **Some alveoli would collapse during exhalation.**

4. Which of the following physiological conditions results from the presence of normal amounts of pulmonary surfactant in the lung?

A. **Lung compliance decreases.**
B. **Uniform gas distribution during expiration occurs.**
C. **Functional residual capacity is maintained.**
D. **Pathogen invasion.**

DESCRIPTION OF VENTILATION MECHANISM IN MAN

Tidal ventilation, form of Bidirectional and active ventilation; ensures that **O2 partial pressure in alveoli is always lower and CO2 partial pressure is always higher than that of the atmosphere.**

INSPIRATION (breathing in):

Inhalation is an **active** process brought about by several muscles.

The inspiratory muscles (major muscles which cause active increase in lung volume) include: **(1)** Diaphragm **(2)** external intercostals.

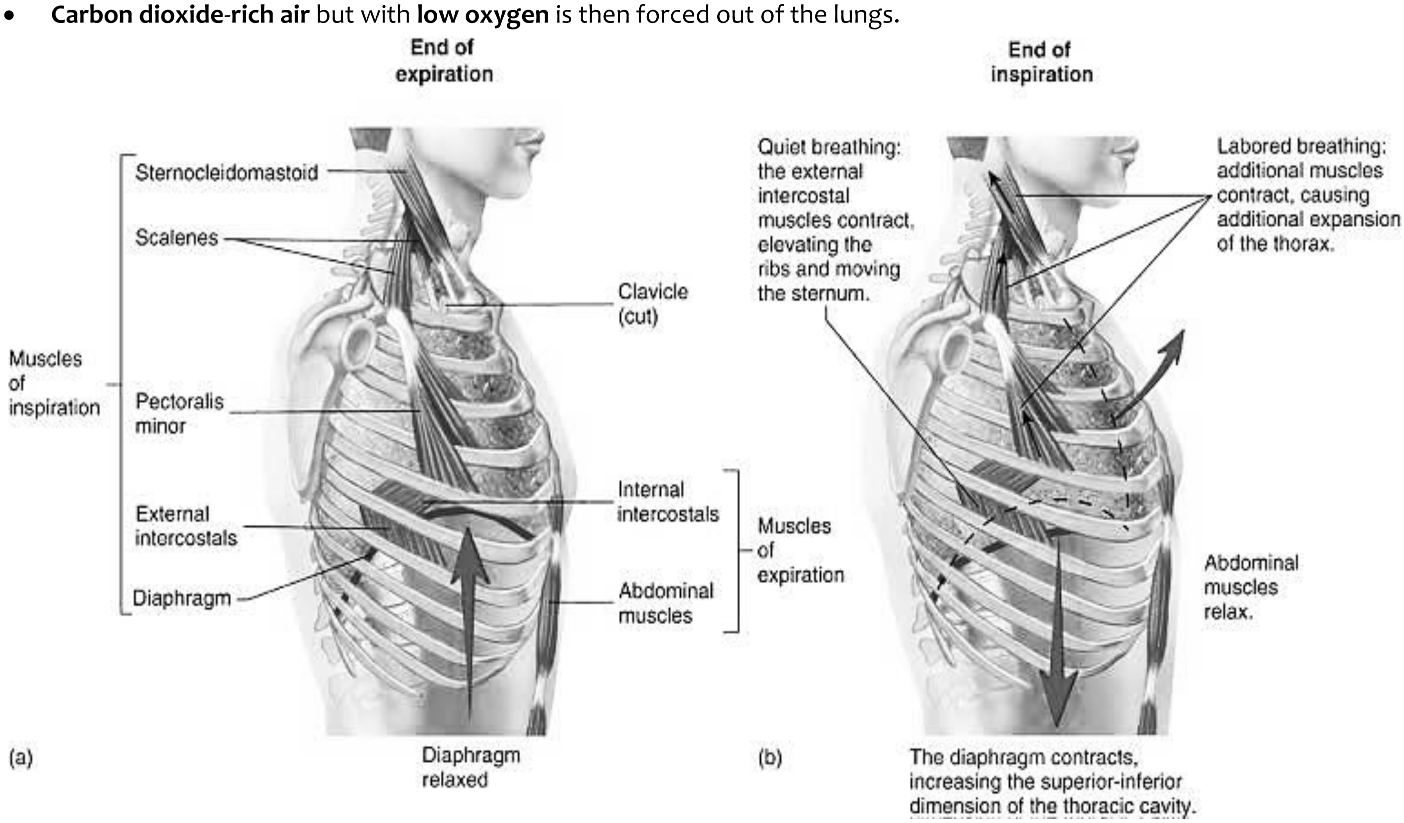
- The external intercostal muscles contract while the inner intercostals relax at the same time causing the rib cage to move upwards and outwards.
- Diaphragm muscles contract and flatten / move downwards.
- These movements increase the volume of the thoracic cavity; and lung volume.
- Alveolar lung 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 (breathing out):

Exhalation in mammals is mainly **passive**, although some muscles are involved.

The expiratory muscles (major muscles which cause active decrease in lung volume) include: **(1)** Abdominal rectus **(2)** 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.

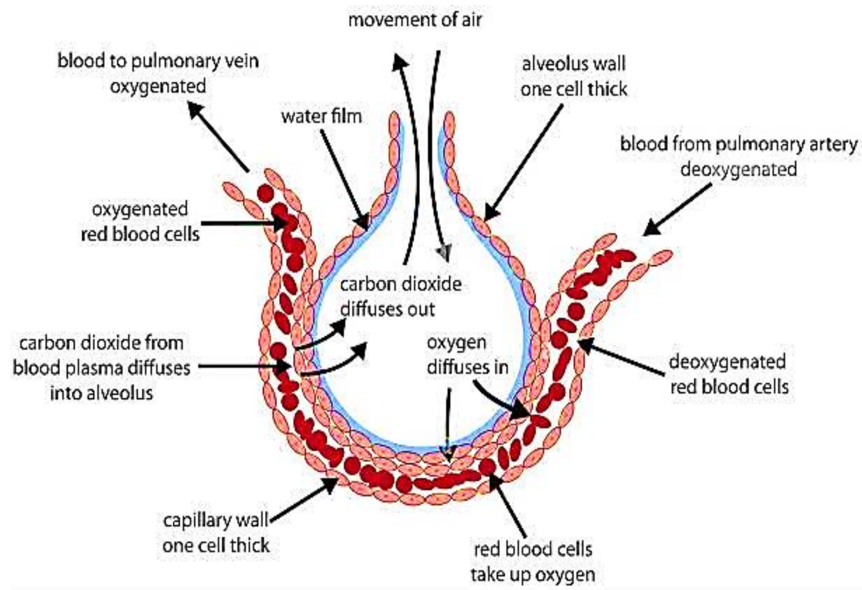


GAS EXCHANGE AT THE ALVEOLUS.

Oxygen diffuses across the thin barrier represented by the epithelium of the alveolus and the endothelium of the capillary. It passes first into the plasma and then combines with haemoglobin (discussed in topic transport in animals) in the red blood cells to form oxyhaemoglobin. Carbon dioxide diffuses in the reverse direction from the alveoli.

Diffusion is efficient because:

- Alveoli have large surface area.
- Gases have short distance to travel.
- A steep diffusion gradient is maintained by ventilation.
- A good blood supply and the presence of oxygen carrying compound haemoglobin.
- Surfactant present.



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 seen in 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
Carbon dioxide	0.03	4.90	3.60
Water vapour	0.47 (usually varies)	No available data	6.20 (saturated)

INTERPRETATIONS FROM THE TABLE ABOVE

1. Inspired air contains a higher percentage volume of oxygen than exhaled air; because 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.
2. Exhaled air contains a higher percentage volume of carbon dioxide (120 times) than inhaled air, because Tissue respiration forms carbon dioxide some of which diffuses into alveolar air and expelled during exhalation.
3. Exhaled air contains a lower percentage volume of water vapour than inhaled air; because Tissue respiration forms water some of which diffuses into alveolar air and is expelled during exhalation.
4. The percentage volume of nitrogen in expired air is higher than in inspired air; because even though 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.
5. The percentage volume of oxygen and carbon dioxide in expired air is intermediate between the inspired and alveolar values; because 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.

ADAPTATIONS OF LUNG SYSTEM FOR GAS EXCHANGE

(1) Large surface area in lungs provided by numerous alveoli;
(2) Thin alveolar epithelial lining shortens diffusion distance for gases
(3) Elastic fibres in lungs permit optimum extension during inhalation

(4) Highly vascularized alveoli maintain high diffusion gradient for gases.
(5) Moist alveolar epithelial lining dissolves gases before diffusion can occur
(6) Trachea and bronchi walls are supported by rigid cartilage rings are permanently open for uninterrupted air flow
(7) Trachea and bronchi inner walls are lined with mucus to trap to clean air to avoid damaging alveoli
(8) Stretch receptors in alveolar walls enable initiating breathing reflex.
(9) Alveolar inner lining is covered by surfactant, which lowers surface tension differentially to prevent lung collapse.

ROLE OF THE BRAIN IN CONTROLLING VENTILATION/ BREATHING IN ANIMALS – (NERVOUS CONTROL)

Breathing must be controlled in order to ensure that adequate gas concentrations exist in body fluids. The control of breathing depends on whether the organism is either a water- or air-breather. In general, aquatic organisms are more responsive to changes0 in O2, whilst terrestrial organisms are more responsive to changes CO2. This arises because O2, and CO2, are the 'rate limiting' gases in aquatic and terrestrial environments, respectively. In the aquatic environment, CO2, solubility is high, so its disposal presents no problems to animals. However, the O2 content of water is relatively low. Therefore the gas exchange system of an aquatic animal has developed to be significantly more responsive to changes in O2, as opposed to changes in CO2. In terrestrial animals, the opposite is true. The O2 content of atmospheric air is relatively high, whilst the content of CO2 is very low. Thus, the gas exchange system of a terrestrial animal is regulated by changes in CO2.

CONTROL OF BREATHING IN AQUATIC ANIMALS-WATER BREATHERS

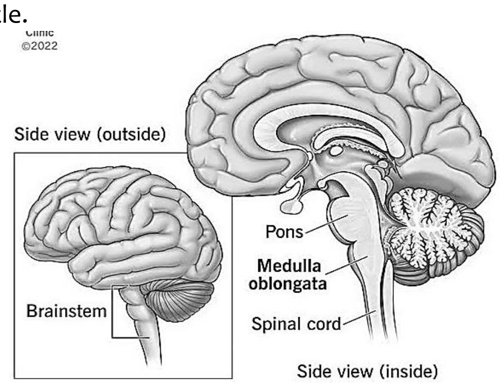
FISHES: Animals that breathe with the involvement of somatic/skeletal muscles, such as fish have a more complicated control system, as described previously. For example, fish have a respiratory produces the basic ventilatory pattern. Fish are able to monitor the level of O2, although there is some dispute over the actual location of the receptors (in this case referred to as **peripheral chemoreceptors).** They may be present in the mouth, gills, opercular cavity or in the arterial or venous circulation.
NB: There are many other stimuli which affect the ventilatory pattern, for example, temperature, and osmotic changes

CONTROL OF BREATHING IN TERRESTRIAL ANIMALS-AIR BREATHERS.

INSECTS: The regulation of ventilation in air-breathing animals follows the same principles as in aquatic animals, except that now CO2 is the primary stimulus to breathing. Control is displayed even in the invertebrates. For example, insects have a sophisticated control system whereby CO2 controls spiricular opening. There is also evidence that there may be a respiratory rhythm generated by neurons in the ventral nerve cord of some insects.

AMPHIBIANS: Amphibians have chemoreceptors that respond to both O2, and CO2; however, the main stimulus is from CO2. The precise control of breathing can vary depending upon the stage of the life cycle.

NB: In vertebrates, there is a region in the **medulla** of the brainstem where ventilatory rhythm is generated, called the **respiratory centre** comprised of **inspiratory** and **expiratory centres**. Thus carries out **INVOLUNTARY CONTROL** of breathing.



REPTILES: In a similar manner, reptile have CO2 sensors in their respiratory system, although in some reptiles, O2 rather than CO2 is the main stimulus for breathing.

BIRDS: Like amphibians, birds also have a respiratory system which is primarily driven by changes in CO2 although there are detectors which respond to changes in O2.

MAMMALS: The control of breathing **is** best understood in mammals. Once again CO2, or, more precisely, its concentration in blood, is the main stimulus to breathe.

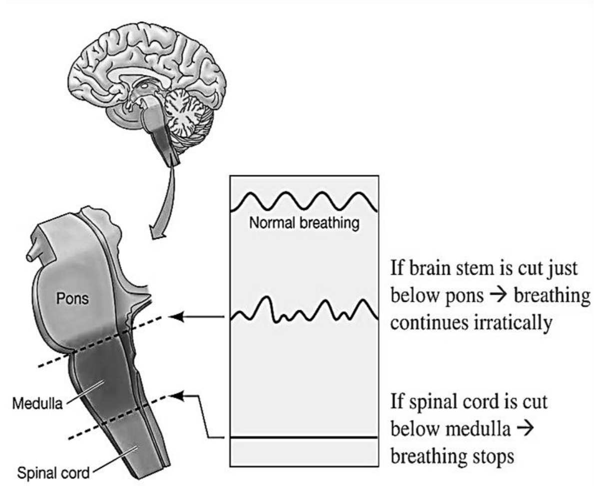
Located on the surface of the **medulla** in the brainstem of mammals are **central chemoreceptors** which are sensitive to CO2. These receptors are bathed in cerebrospinal fluid, which is produced in the ventricles of the brain and flows over the entire surface of the brain and spinal cord. The role of the cerebrospinal fluid is to act as a 'shock absorber', providing the central nervous system with some mechanical protection.

In reality, the **central chemoreceptors** in the **medulla oblongata** of the brain stimulated by **H+ rather than CO2**. This is because CO2 in the blood passes into the cerebrospinal fluid and dissolves according to the following equation;
$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ **;** This means that the central chemoreceptors are acting as pH meters. An increase in the CO2 content of blood, causes a decrease in the pH of cerebrospinal fluid (an increase in the H+ concentration **of** a solution

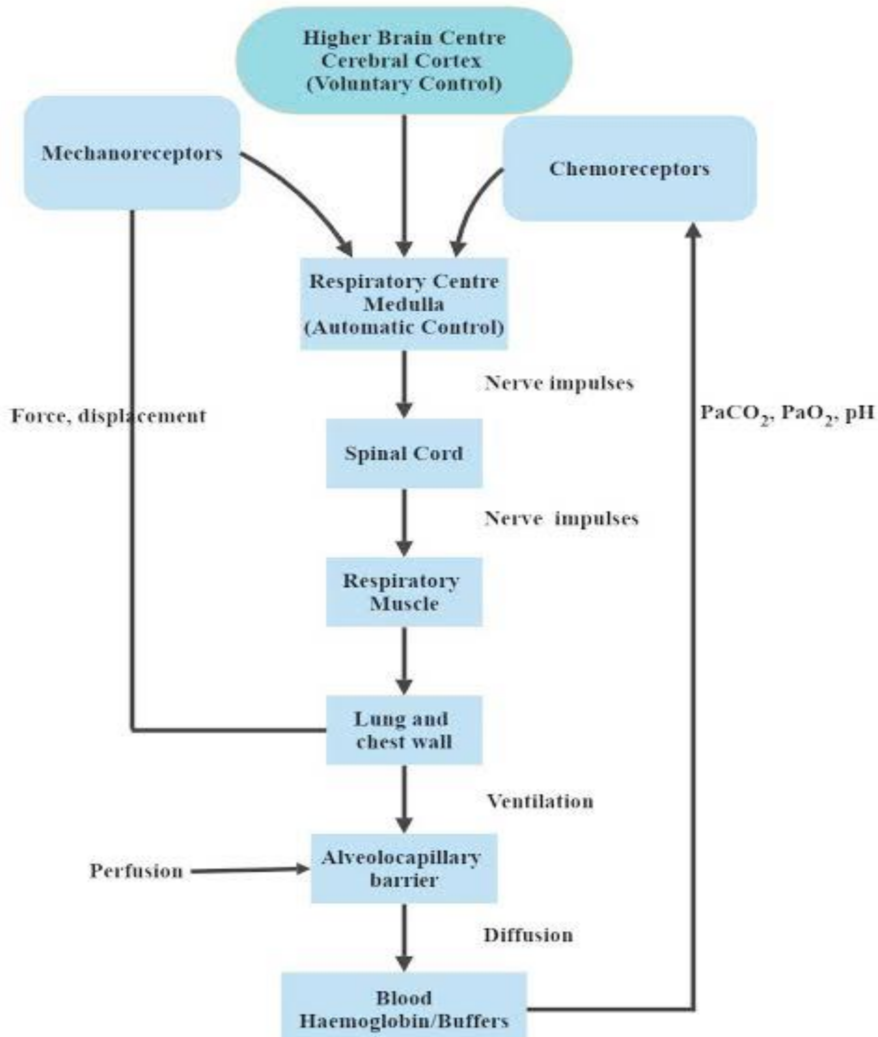
makes it more acidic). The response to this increase in blood CO2 is an increase in the rate of breathing, thus exhaling the excess CO2 and returning the blood CO2, level to its normal value.

NOTE: A BASIC RHYTHM OF BREATHING IS MAINTAINED BY THE MEDULLA EVEN IF ALL NERVOUS INPUT IS CUT, ONLY THAT UNDER NORMAL CIRCUMSTANCES OTHER STIMULI MAY MODIFY THIS RHYTHM.

There are other **peripheral chemoreceptors**, located in large arteries, such as the **aorta** and **carotid artery,** (that is **aortic bodies** and **carotid bodies** respectively), which monitor blood O2, levels. However, **given that the primary stimulus to breathe is CO2**, the sensitivity of the chemoreceptors for O2, is much less than the sensitivity of those receptors in the medulla which monitor CO2. Therefore, the O2 content of the blood must be reduced significantly before impulses are sent via the **vagus nerve** and **glossopharyngeal** nerve respectively; to the **inspiratory centres** in the medulla oblongata of the brain.



- 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, expand and stimulate **mechanoreceptors**/ **stretch receptors** in bronchi and bronchioles in expanded lungs, 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**;**

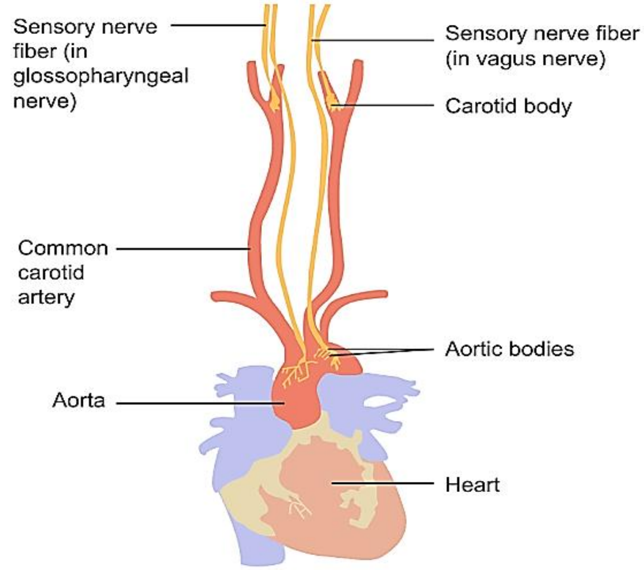


VOLUNTARY (CONSCIOUS) CONTROL OF BREATHING.

This is the ability to hold breath. Applied during forced breathing, speech, singing, sneezing and coughing.

When such control is being exerted, impulses originating in the cerebral hemispheres pass to the breathing centre; which then carries out the appropriate action. **(May be ignored when asked to describe control of breathing, unless specified)**

Control of inspiration by stretch receptors and chemoreceptors is an example of negative feedback, hence HOMEOSTASIS.



Negative feedback can be overridden by voluntary activity of the cerebral hemispheres.

HYPOVENTILATION:

1. Decrease in the rate or depth of breathing; 2. less carbon dioxide exhaled; 3. builds up in blood; resulting into acidic blood; 4. condition called acidosis.

HYPERVENTILATION:

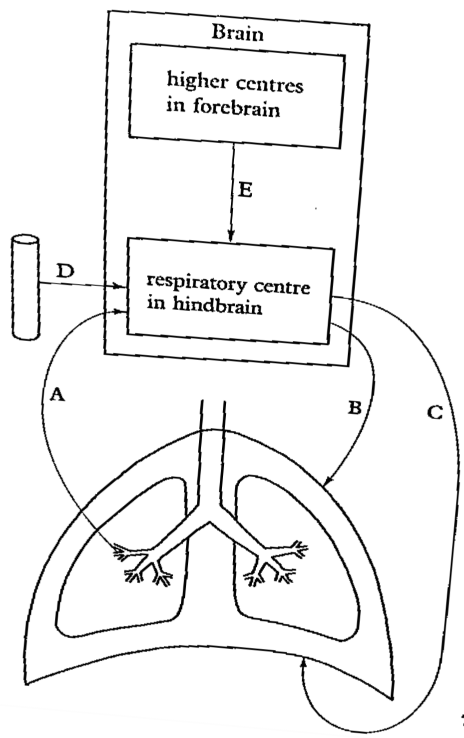
1. Increased rate of breathing; 2. Results in increase in oxygen intake; 3. Increase expiration of carbon dioxide/ decrease in carbon dioxide in blood; 4. Depletes body's supply of carbon dioxide/ decreased hydrogen ions; 5. Condition called alkalosis.

Thus: **hyperventilation decreases the urge to breathe as a result of venting carbon dioxide; leading to:-**

- **Unconsciousness as the brain is starved of oxygen. Reason for loss of consciousness in free divers.**

WORKED EXAMPLE:

The figure below shows the neuro-connections between the respiratory apparatus of a mammal and the respiratory centre in the hind brain involved in the control of breathing.



A. Represents the vagus nerve which transmit impulses from walls of the bronchial tubes in the lungs to the medulla.

B. Represents the intercoatal nerves which transmit impulses from the respiratory centre to the intercostal muscles.

C. Represents the phrenic nerve which transmits impulses from the respiratory centre to the diaphragm.

D. Represents nerves which transmit impulses from walls of a certain blood vessel to the respiratory centre.

E. Represents nerve which tracts within brain which connect the higher centres (cerebral cortex) with the respiratory centres.

- **State what is observed is observed when the following experiments are carried out. Give a reason(s) for your answer.**

1. A, B and C are cut.

Breathing ceases/ stops; because impulses from respiratory centre to stimulate inspiratory movements (contraction of both intercostal muscles and diaphragm) are disconnected from reaching diaphragm and intercostals which would be propagated through B and C; also impulses from stretch receptors in expanded lungs would no longer reach the respiratory centre as A is disconnected; thus voluntary control which the major control pathway is completely disconnected/ damaged;

2. A, D, and E cut, but B and C left intact.

Rhythmical breathing continues but slower and deeper than normal; because the inspiratory centres in medulla ably sends impulses to both intercoatal muscles and diaphragm; however slow rate of expiration due to cut B; due to disconnected impulses from distended lungs; expiration relies on passive recoil; thus delay the respiratory cycle;

3. B, C, D and E are cut. The lungs are inflated by means of a pump and impulses recorded from A with an oscilloscope.

Lung is inflated/ volume increases, displacement detected by stretch receptors; firing impulses in A; thus frequency impulses observed increases; voluntary and involuntary control damaged; lungs remain inflated due to external pump;

4. A and E are cut. The concentration of carbon dioxide in inspired air is increased to three per cent.

Ventilation rate increases; because increase in carbon dioxide rapidly fires impulses in D from peripheral receptors and in the central chemoreceptors; to inspiratory centres in the medulla; which are rapidly propagated via B and C; causing

contraction of intercostal muscles and diaphragm; increasing thoracic volume; air rich in oxygen rushes into the lungs; to get rid of increased carbon dioxide; hence hyperventilation; expiration relies on passive recoil mechanism; due to cut A;

5. Experiment 4 is repeated. But with D cut.

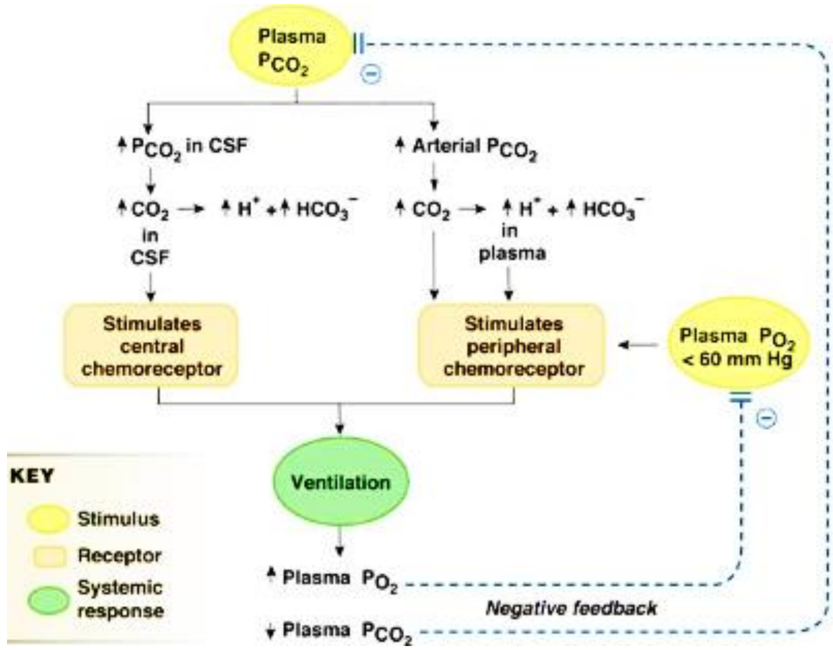
<u>Ventilation rate decreases</u>; because impulses from D to the respiratory centers concerning increases carbon dioxide concentration are disconnected; thus inspiratory centres rely on low pH detected in the CSF, sending fewer impulses; via the phrenic and intercostal nerves; slightly lowering ventilation rate compared to that in experiment 4. Also hyperventilation in experiment 4 decreases the urge to breathe/ increase breathing rate.

6. A and E are cut. The concentration of carbon dioxide increased to five per cent.

<u>Ventilation increases at a rate more than that in experiment when carbon dioxide was three percent</u>; because increase in carbon dioxide to five per cent; more impulses are rapidly fired in D from peripheral receptors and in the central chemoreceptors; to inspiratory centres in the medulla; which are rapidly propagated via B and C; causing contraction of intercostal muscles and diaphragm; increasing thoracic volume; air rich in oxygen rushes into the lungs; to get rid of increased carbon dioxide;

7. Experiment 6 is repeated. But with D cut.

<u>Ventilation rate remains constant and high/ increased</u>; to continuously get rid of high concentrations of carbon dioxide; that are detected by the central chemoreceptors; stimulating the inspiratory centres; firing impulses which are propagated via B and C to maintain a high ventilation rate; thus cutting D had almost no effect on ventilation.



- Predict the effect of
    i. Cutting E but leaving all other nerves intact.

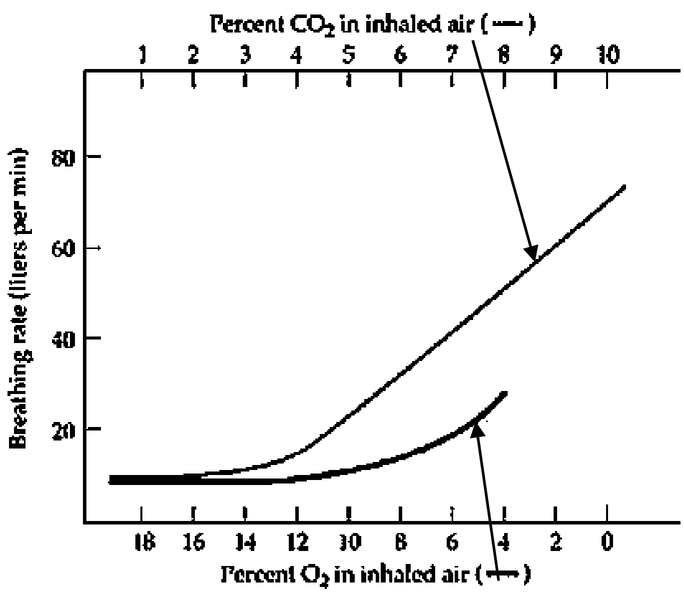
Rhythmical breathing continues without alteration;

    ii. Cutting A and D but leaving B, C and E intact.

Rhythmical breathing continues; slower and deeper than normal;

- If your predictions turned out to be correct, what conclusions would you draw concerning the role of higher centres in the control of breathing?

Higher centres (cerebral hemispheres/ forebrain) control breathing rate automatically; they send impulses to the respiratory centres in the hind brain/ brain stem (medulla oblongata and pons); which take appropriate actions; with or without the higher centres (voluntary control of breathing) breathing rhythm continues;



The figure shows the relationship between breathing rate; percentage of arterial oxygen and percentage of arterial carbon dioxide.

<u>Comments on the graph.</u>

Respiratory system is more sensitive to arterial CO2 than O2;
Decrease in O2 has no effect on the ventilation rate;
Increase in CO2, almost triples the breathing rate;

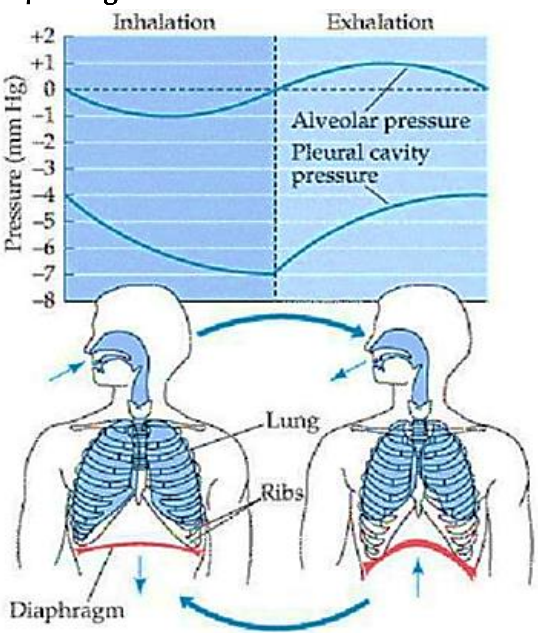
Explain the physiological significance of the relationship above. ATTEMPT THIS QUESTION.

<u>RESPIRATORY (LUNG) MECHANICS</u>

<u>LUNG (ALVEOLAR) PRESSURE, PLEURAL PRESSURE AND ALVEOLAR VOLUME - CHANGES DURING ONE RESPIRATORY CYCLE.</u>

Lungs exist within a sealed **<u>Pleural Cavity</u>**.

<u>PLEURAL CAVITY:</u> Each lung is surrounded by a pleural cavity. This is a space lined by two tough, flexible, transparent pleural membranes (pleura). The cavity is air tight and its pressure stays at 3-4mmHg lower than that in lungs. **This negative pressure is maintained during inspiration and helps the alveoli to inflate and the lungs to fill any extra available space provided by expanding thorax.**



<u>COMMENTS ON THE GRAPH</u>

<u>Inhalation</u>

- **Negative pleural cavity pressure stretches the lungs open;**
- **Both alveolus and pleural cavity have negative pressure;**
- **Both alveolar / lung pressure decreases and pleural cavity pressure decrease; due to contracted external intercostal muscles and contraction of diaphragm; to allow lungs fill with air from the environment;**
- **Alveolar pressure lower than pleural cavity pressure; creates/ maintains a negative pressure; allowing lung inflation; and stretching to fill available pace due to expanded thorax;**
- **Alveolar pressure decreases gradually to the mid of the inhalation; then gradually increases to its original pressure; at the end of inhalation; while pleural cavity pressure decreases rapidly during inhalation;**

<u>Exhalation</u>

- **Alveolar cavity pressure is positive relative while that of pleural cavity is negative;**
- **Both alveolar pressure and pleural cavity pressure increase; due to internal intercostal muscle contractions/ or passive recoil; expelling air rich in carbon dioxide;**

<u>CHECK PROGRESS:</u> (ABE CURATED SEMINAR-2022)

The graph below shows the pressure and volume changes during a single ventilation cycle of a healthy human at rest.

(a) From the graphs, describe the pressure and volume changes shown during

i) Inspiration. (08 marks)

ii) Expiration. (07 marks)

(b) From the graphs, explain the causes of the pressure and volume changes shown during (06 marks)

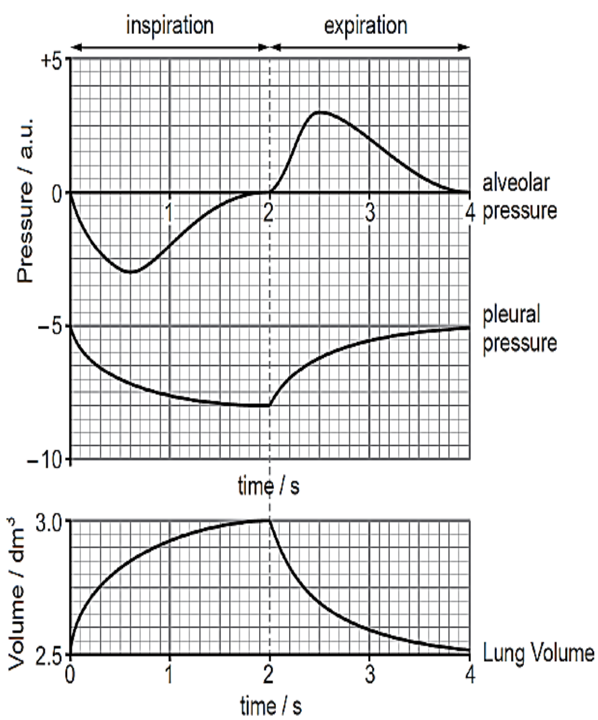
i) Inspiration.

ii) Expiration.

(c) Suggest the changes that are expected in these curves during strenuous exercise. (03 marks)

(d) Describe how the human respiratory system maintains homeostasis. (10 marks)

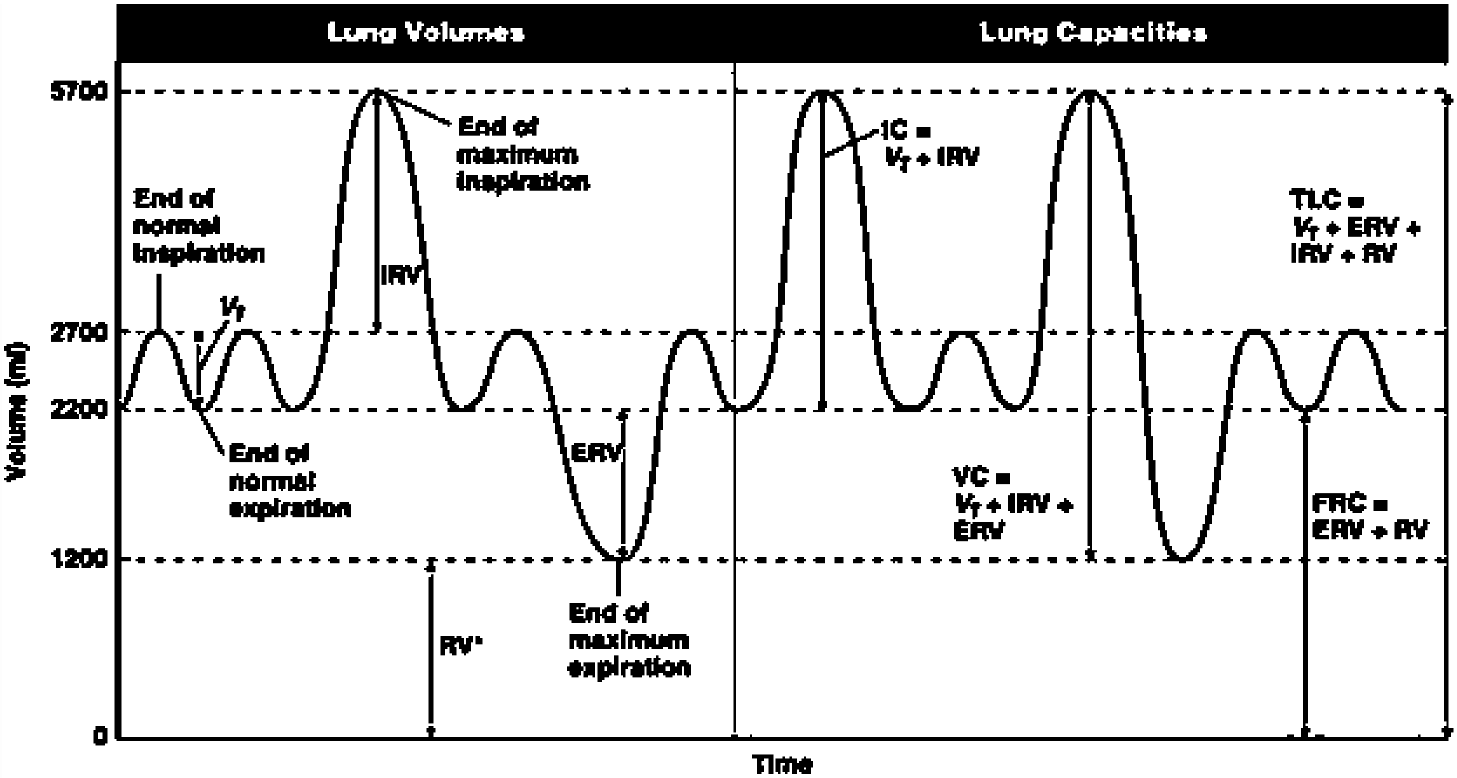
(e) Suggest why it is important to control breathing in humans. (05 marks)



<u>DYNAMIC LUNG VOLUMES AND CAPACITIES OF HEALTHY RESTING ADULTS MALES.</u>

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



Normal lung volumes and capacities for a healthy 70-kg human male

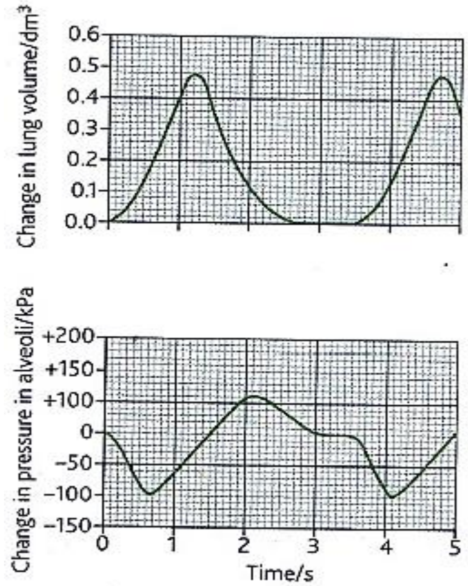
Lung Volumes	Lung Capacities
V_T = Tidal volume = 500 ml	IC = Inspiratory capacity = V_T + IRV = 3500 ml
IRV = Inspiratory reserve volume = 3000 ml	VC = Vital capacity = V_T + IRV + ERV = 4500 ml
ERV = Expiratory reserve volume = 1000 ml	FRC = Functional residual capacity = ERV + RV = 2200 ml
RV = Residual volume* = 1200 ml	TLC = Total lung capacity = V_T + ERV + IRV + RV = 5700 ml

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.

WORKED EXAMPLE:

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

= 4.7 seconds – 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 in the lungs when this person inhaled was 3000cm³, work out the volume of air in the lungs after the person had exhaled?

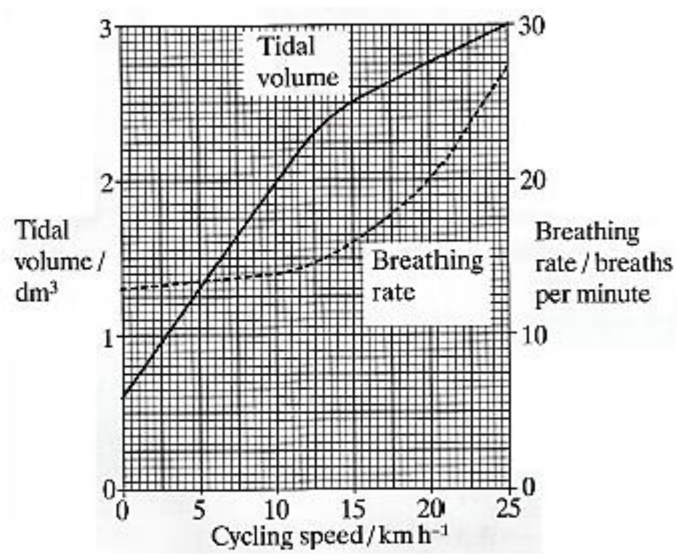
3000cm3 = 3.0dm³

From the graph, exhaled volume = 0.48dm³ less than the maximum inhaled volume.

The exhaled volume is therefore 3.0 - 0.48 = 2.52dm³ (OR 2520cm²)

(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.



CHECK PROGRESS:

1. 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:

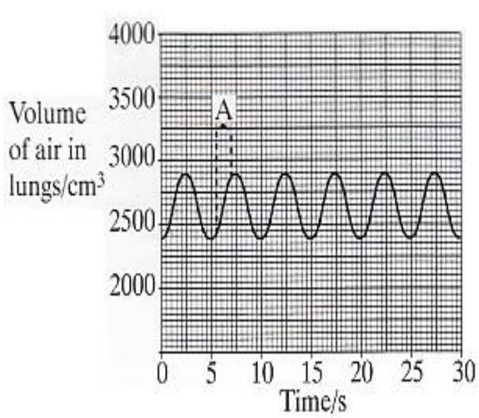
(a) Describe the changes in:

(i) Tidal volume

(ii) Breathing rate

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

2. 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 movements of air over the part of the graph labelled "A"

3. (a) without using a diagram, explain what is meant by the terms; Tidal volume. Inspiratory reserve volume. Expiratory reserve volume.

(b) the table below shows the respiratory minute volumes (RMV=TIDAL VOLUME X Breaths per minute) of three healthy men as they were subjected individually to a progressive decrease in the oxygen content of the air inspired while its carbon dioxide content was held at a constant level. The RMV was calculated each minute for 10 minutes s shown.

Time (minutes)		1	2	3	4	5	6	7	8	9	10
O2 content of inspired air (%)		21	18	16	14	12	10	8	6	5	4
RMV (dm3 per minute)	Man A	6.6	6.8	6.9	6.9	7.2	8.6	12.9	18.2	21.0	25.5
	Man B	7.4	7.4	7.3	7.3	7.3	7.4	11.5	18.0	19.7	24.4
	Man C	7.0	6.8	6.8	6.8	7.1	8.0	11.6	17.8	19.3	25.1

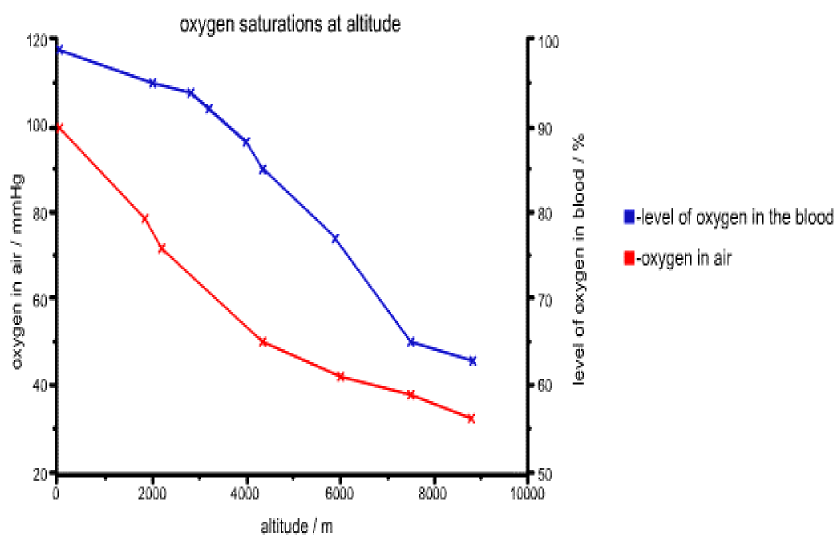
I. Calculate the mean RMV at each level.
II. Plot a graph of mean RMV against oxygen content of inspired air.
III. Describe the effect of oxygen content inspired air on mean RMV.
IV. Suggest hoe respiratory movements increase the RMV.
V. Severe oxygen deficiency (below 4%) suppresses rather than stimulates ventilation. Explain.

(c) Explain hoe breathing rate is controlled?

BREATHING AT HIGH 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 (Acute 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 minimize altitude sickness (i) Increased number of red blood cells, (ii) Increased haemoglobin content, (iii) Increased ventilation rate, (iv) increased cardiac frequency;



Qn: **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. Explain.**
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 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)** Enlarge 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 centres do not function automatically to cause breathing at a certain concentration of CO_2.

FACTORS AFFECTING RATE OF BREATHING/ VENTILATION IN ANIMALS.

There are several factors that affect breathing rate; below are examples.

1. Concentration of carbon dioxide and oxygen in blood.

Very high concentration/ too much CO2 in blood **(Hypercapnia)** increase breathing rate so as to remove accumulated carbon dioxide which would be toxic to the body, while too low concentration/ very little CO2 below normal; **(hypocapnia)** decrease breathing rate. This is because CO2 is the major stimulus for chemoreceptors that detect CO2 levels in blood.

2. Altitude (high/ low altitude hypoxia).

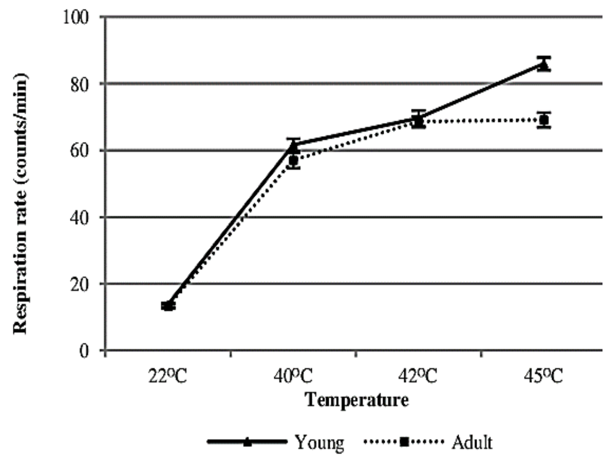
At high altitudes (e.g. mountains), there is low atmospheric pressure and therefore a low partial pressure of oxygen. Rapid ascent of high heights causes **acute mountain sickness** while **diving** into **deeper water** causes difficulties in breathing. ***Acclimatization occurs;*** *the body physiologically and physically adjusts to changes in partial pressure of oxygen;* Increased ventilation rate.

3. Age and Body size.

Breathing rate decreases with increase in age.

New born babies with small size present an increased surface area to volume ratio, losing more heat to surrounding; breathing rate increases; rapidly supplying oxygen for metabolism; to compensate for heat lost; and to growth of body tissues. Growth rate decreases in adults; also small surface area to volume due to increases body size; thus low breathing rate.

NB: In old age decrease in breathing rate is due to decline in efficiency of the respiratory system with ageing. The gradual loss of the elastic tissues in lungs; the chest wall becomes less capable of expansion.



The graph above represent change in breathing rate of a young and adult mammal with environmental temperature.

Account for the difference in the breathing rate of the young and adult at varying temperatures.

Table showing range of breaths/min in the different age groups and other specified categories.

Group	Age	Breaths/minute
New born to 6 weeks	New born to 6 weeks	30-60
Infants	6 weeks to 6 months	25-40
Toddler	1 to 3 years	20-30
Young children	3 to 6 years	20-25
Old children	10 to 14 years	15-20
Adults **(at rest)**	Adults	12-20
Adults **(during strenuous activity)**	Adults	35-40
Athletes	And old children and Adults	60-70 **(Peak)**
Elderly	≥70 years	10-20

4. Smoking.

Smoking has both short term and long term effects on breathing and gaseous exchange. Chemicals in cigarettes are (1) **Tar** -a carcinogenic substance causing cancer. (2) **Nicotine** – addictive substance that narrows blood vessels. (3) **Carbon monoxide** – reduces the oxygen carrying capacity of blood.

Short term effects of smoking:

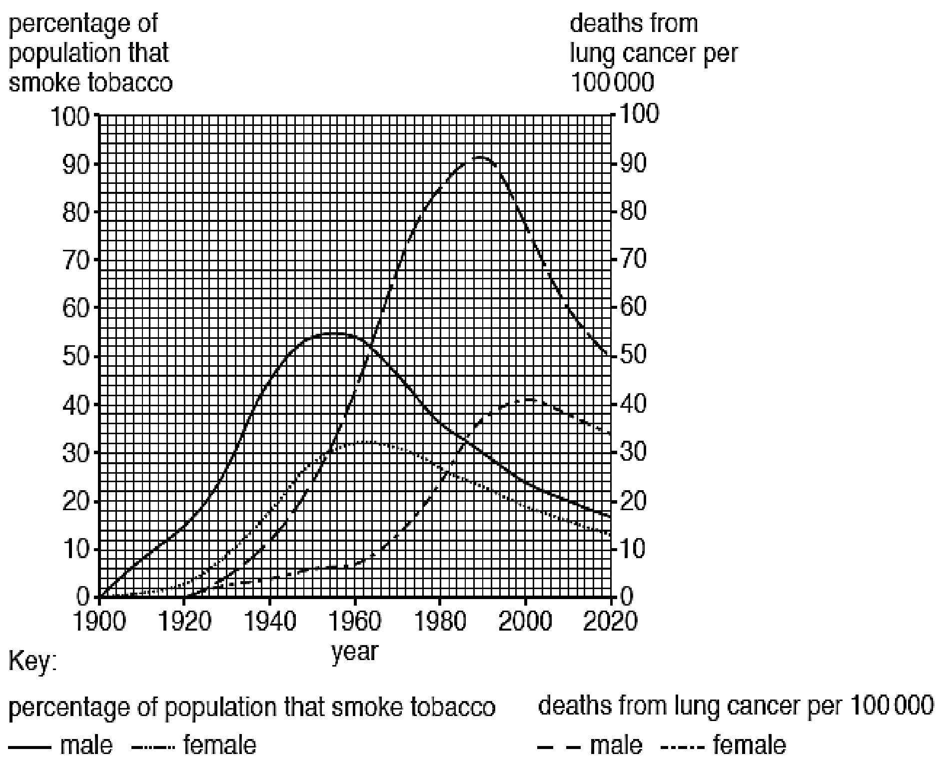
(1) Nicotine in smoke causes constriction of finer tubules; increasing resistance to the flow of air; (2) Nicotine in smoke paralyses cilia which filters dirt out of air; dirt accumulates in the respiratory pathway increasing resistance to flow of air; (3) Smoke is an irritant; stimulates secretion of excess mucus and excess fluid into the airways; increasing resistance to air flow;

Long term effects of smoking: Respiratory disease and ill health.

- **Asthma:** this is a form of difficulty breathing; (1) caused by spasms of smooth/involuntary muscles in bronchioles; muscles contract; narrowing or even closing the bronchioles; decreasing ventilation; Difficulty in breathing out among asthmatic persons is due to more compressions of the bronchioles by lungs previously during inspiration; (2) Secretion of excess mucus, which is thick; which collects in the bronchioles and difficult to cough away; making breathing difficult; thus lowering ventilation;
- **Emphysema:** caused by gradual break down of the thin walls of the alveolar lining, due to irritations of chemicals in cigarette smoke. Gradually alveolus becomes; consequently decreasing the total surface area for gas exchange.

Breathlessness/ extremely reduced ventilation; is the most obvious symptom. (1) Lungs lose elasticity, making it more difficult to exhale air. A lot more air remains in the lungs during expiration. This is measured as **"FORCED EXPIRATORY VOLUME"**- the amount of air that can forcibly exhaled in a given time (usually one second) after maximum inspiration. Note that in asthma patients, FEV also decreases.

- **Bronchitis:** mainly caused by smoking (chemical tar) but to a less extent air pollution. (1) Death rate of bronchitis is 6 times higher among smokers. (2) Breathlessness occurs/ extremely reduced gas exchange. (3) Difficulty in sweeping away mucus due to paralysis of cilia by smoke. (4) Irritations in smoke cause inflammation; leading to excessive secretion of mucus. (5) Coughing and breathlessness increase as the diseases progresses; ant the more damage that occurs, more likeliness for pneumonia to occur.



- **Lung cancer:** Female mostly affected by **breast cancer**; **lung cancer** mostly affects men. (1) Caused almost exclusively by smoking; 99.7% deaths of lung cancer are smokers. (2) Tars in smoke are responsible for the cause, they contain carcinogen – chemical that cause cancer. (3) Irritations causes thickening of the epithelium by extra cell division. (4) Usually starts in the epithelium of bronchioles.

5. Environmental hypoxia/ 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. Also oxygen depleted water bodies.

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.

6. Environmental hyperoxia/ breathing air with excess oxygen than normal.

It is **dangerous** to breathe air with **pure** O_2 because blood's ability to carry it away oxygen 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 cell membranes, (ii) Collapse of the alveoli (iii) Retinal detachment, and seizures

7. Exercise/ Level Activity-(thus Cellular activity).

At rest; breathing rate low. Breathing rate increases with increase in the level of activity; and decreases with ceasation in activity. At rest, BMR if sufficient to address the energy demands for the body vital processes. Increase in activity, increases the metabolic rate; to sustain the vigorous somatic muscle contractions; thus ventilation rate increases to rapidly supply adequate to respiring muscle tissues; and to rapidly eliminate/ expel accumulating carbon dioxide from the body. When activity ceases; ventilation rate decreases; owing to reduced metabolism;

8. Environmental Temperature.

For aquatic animals such as fish; fish is cold blooded, at low water temperatures; body temperature is also low; thus fish is dormant; due to reduced metabolism. However breathing rate is low at cold temperatures since oxygen is highly soluble in water at low temperatures, so readily available; lowering the ventilation rate. Increase in water temperature increases the ventilation rate; since metabolic rate increases; yet oxygen solubitty is low at such temperatures, as it diffuses out of water;

Table showing respiration rate of a fish species at various water temperatures.

Water temperature/°C	Average breaths per minute
28	687.5
24	568.75
19	447.5
10	318.75
	247.5

Account for the above results.

For endotherms; fall in environmental temperature; increases the rate of metabolism; so as to compensate for the heat lost to surrounding; hence homeostasis. This therefore increases the breathing rate; to rapidly supply oxygen to the metabolizing tissues to generate metabolic heat; and expel accumulating carbon dioxide from such tissues. Increase in body core temperature; body metabolism specifically to generate heat switches off; lowering the ventilation rate- negative feedback mechanism.

For terrestrial ectotherms; increase in air temperature, increases body temperature; enzymes activated; respiration increased; more oxygen needed; increasing breathing rate. Decrease in air temperature; lowers body temperature; decreasing enzyme activation; low metabolic rate; thus decreased ventilation rate;

COMPARISON BETWEEN GASEOUS EXCHANGE MECHANISMS OF VARIOUS ANIMALS

TELEOST FISHES AND MAMMALS

Similarities

- Both have highly specialized internal respiratory surfaces connected to external medium by respiratory tract.
- In both, the ventilation mechanism brings external medium into contract with the respiratory epithelium.
- Ventilation mechanism involves muscular contraction to expand cavities in which respiratory surfaces are during inspiration.
- In both, the ventilation mechanism results in pressure changes in those cavities which result in the movement of the medium from areas of high pressures to areas of low pressure.
- In both, gaseous exchange is by diffusion.
- In both gaseous exchange is between external exchange and blood.
- In both respiration surfaces are designed to have a high surface area to volume ratio, are moist, thin and highly vascularized.
- In both, ventilation mechanism is maintained by a control mechanism involving respiratory centres in the hind brain.
- Ventilation mechanism is active (need ATP to bring respiratory medium to the gas exchange surfaces) in both

Differences

	Man	Teleost fish
a)	Medium of gaseous exchange is air.	Medium is water
b)	Air enters and leaves via the same passage.	H_2O enters via mouth and leaves via opercular opening.
c)	Operate back and forth type of ventilation.	Operates one way types of ventilation
d)	Respiratory surface is alveolar epithelium	Respiration surface to gill plate epithelium
e)	Respiration organ is protected by thoracic cage	Respiratory organ is protected by pharynx wall and operculum
f)	Ventilation is done by adjustment of the thoracic cavity	Ventilation is done by adjustment opercular, pharyngeal and buccal cavities
g)	Ventilation mechanism stimulated by high CO_2 in blood	Ventilation stimulated by low O_2 in water
h)	Bidirectional ventilation	Unidirectional ventilation

AMPHIBIANS AND MAMMALS

Similarities

1. In both ventilation in lungs is of back and forth type/ tidal ventilation.

2. In both, ventilation mechanism is maintained by a control mechanism involving respiratory centres in the hind brain.

Differences

Man	Amphibian
1. Respiration medium is air only	Respiratory media are air and water
2. Has only one respiration surfaces i.e. alveoli in lungs	Have 3 respiration surfaces i.e. buccal cavity, skin and lungs
3. Lungs immediately activated to function on birth	Lungs are non-functional at early stages of growth
4. Uses lungs in early stages after birth	Uses gills in early stages after eggs hatching
5. Muscular diaphragm is present to aid inspiration	Muscular diaphragm is absent.
6. Ventilation is continuous and rhythmic	Ventilation isn't always continuous but rhythmic
7. Ventilation is only bidirectional	Ventilation is both non directional along the skin and tidal through lungs

TYPICAL EXAMINATION QUESTIONS

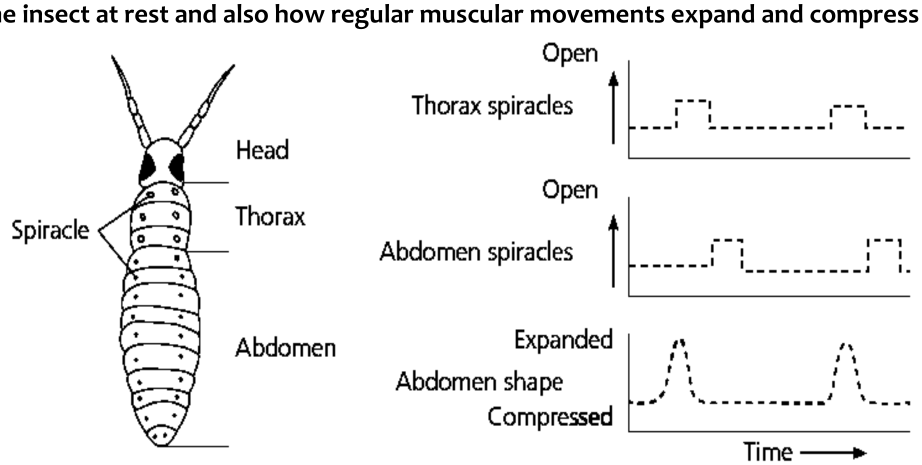
1. How is the structure of animal's respiratory surface, and its ventilation mechanism, related to its size, its activities, and its environment? Illustrate your answer with specific examples.

2. 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.
(ii) Calculate the average tidal volume during rest and during exercise
(b) Explain how the oxygen requirements of a mammal are met under different conditions of physical activity.

3. Figure 4 represents the pattern of spiracles of an insect (legs and wings removed). Each spiracle has a valve, which can be closed or opened to control the flow of air into the body. The graphs show the opening and closing of the spiracles in the insect at rest and also how regular muscular movements expand and compress the abdomen.



(i) State what is meant by the term ventilation.
(ii) Use the information provided to explain how the insect ventilates its tracheal system.
(iii) The graphs show that there are long periods when the spiracles are closed. Explain why this is important for the insect's survival.
(iv) How is the gas exchange system of the above insect suited for its function?
(v) How is gas exchange system in insects different from that of a mammal?

4. Some students investigated the effect of exercise on the rate and depth of breathing. Results are tabulates below.

Activity	Volume of each breath per minute/cm^3	Number of breaths taken per minut
Rest	500	18
20 step –ups per minute	750	25
50 step ups per minute	1200	34

(a) (i) calculate the change in the volume of each breath when the student changed from 20 to 50 step-ups per minute.

(ii) Describe the effect of exercise on the volume of each breath.

(b) (i) Describe the percentage change in the volume of each breath when the student changed from rest to 50 step-ups per minute.

(i) Describe the effect of exercise on the rate of breathing.

(c) Using results from the table;

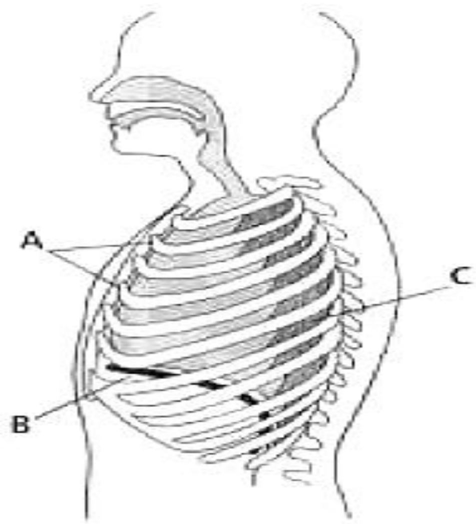
(i) Describe the effect of exercise on the students breathing.

(ii) Explain why student's breathing changed during exercise.

(d) The diagram shows the ribs and muscles of the thorax from one side.

(i) Describe how <u>structures</u> shown bring about breathing movements during inspiration and expiration?

(ii) Explain how the movements you describe cause air to move into and out of the lungs.



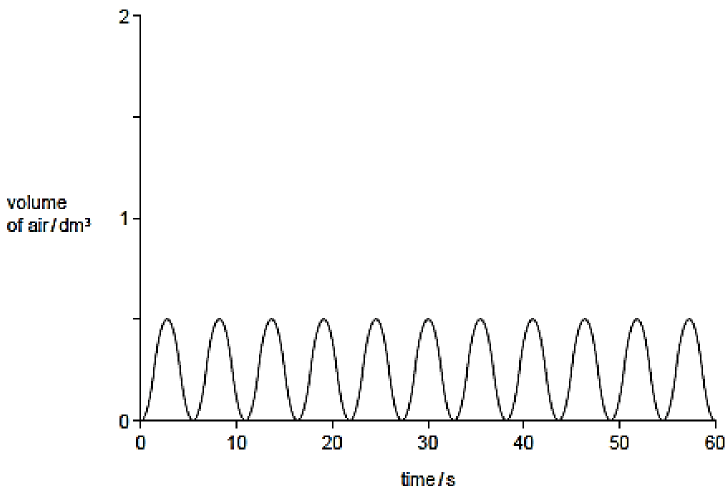


Fig. 3.1

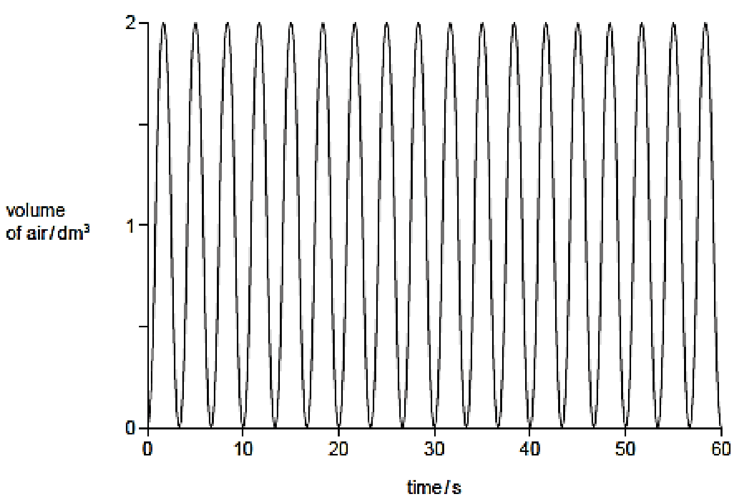


Fig. 3.2

5. Some students investigated the breathing of a 16-year old male athlete. Fig. 3.1 shows the pattern of his breathing for 60 seconds when resting. Fig. 3.2 shows the pattern of his breathing while he took some exercise for 60 seconds.

Table 3.1 shows a summary of the results obtained by the students.

Table 3.1

	breathing at rest	breathing during exercise
volume of air breathed in with each breath / dm^3	0.5	....
rate of breathing / number of breaths per minute	11	....
volume of air breathed in per minute / dm^3	5.5	....

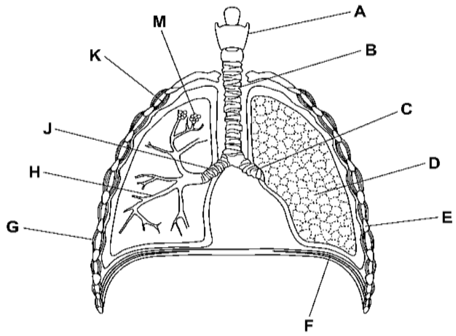
(a) Using information from Fig. 3.2, complete Table 3.1. Write your answers in Table 3.1. [3]

(b) Explain the effect of exercise on the student's breathing.

(c) During strenuous exercise, the hormone adrenaline causes changes in the pulse rate and in the concentration of glucose in the blood. Explain the importance of these changes during strenuous exercise. (i) Pulse rate

(ii) Concentration of glucose in the blood

6. The figure below shows the human gas exchange system.



(a) Name parts labelled A to M.

(b) The gas exchange system contains a cartilage. Describe the function of the cartilage in the gas exchange.

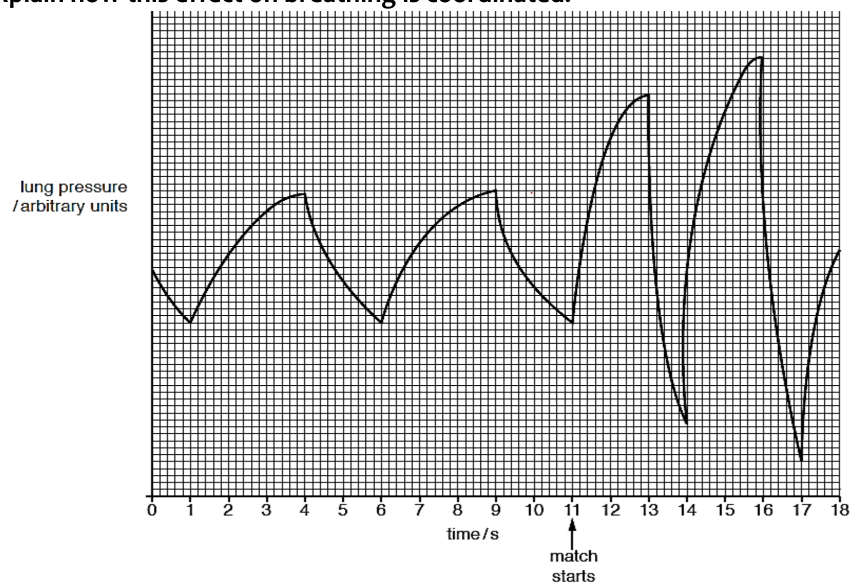
(c) Soon after starting physical activity the concentration of carbon dioxide in the blood increases.

(i) Name the process inside cells that produces carbon dioxide.

(ii) State the effect on breathing of an increase in carbon dioxide concentration in the blood.

(iii) Explain how this effect on breathing is coordinated.

7. The pressure in the lungs of a student before and during the start of a volleyball match was recorded. The results are shown in Fig. below.



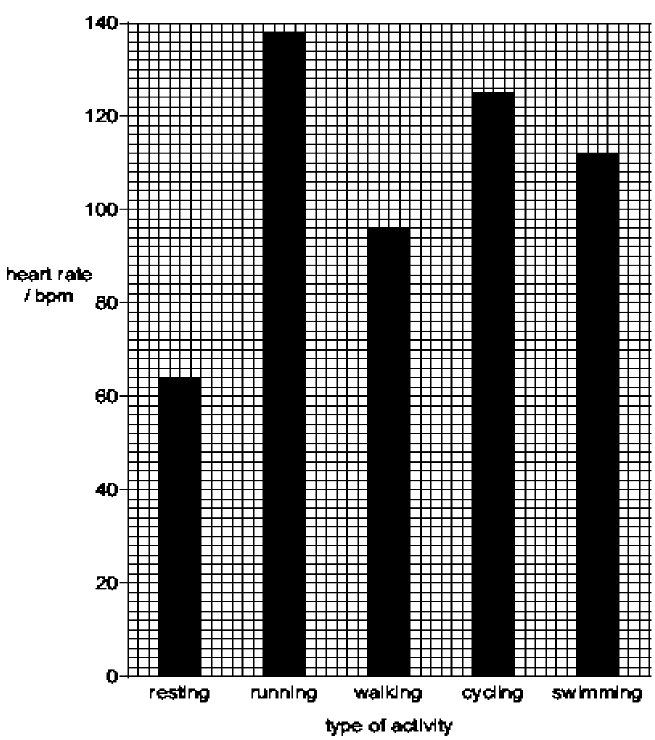
(a) (i) Use the results in Fig. 2.1 to calculate the breathing rate before the start of the match. Express your answer to the nearest whole number. Show your working.

(ii) Use the results in Fig. 2.1 to describe how the pattern of breathing during the match is different from the pattern of breathing before the match starts.

(b) Describe the process of inhalation.

(c) Carbon dioxide moves from the blood capillaries into the alveoli by diffusion. Explain why the rate of diffusion of carbon dioxide increases during exercise.

8. (a) A student performed different types of activity. She measured her heart rate during each type of activity in beats per minute (bpm).The results are shown in Fig. below.



(i) State the type of activity that results in the highest heart rate in Fig. above. (ii) State the heart rate of the student when she was cycling. (iii) Calculate the percentage increase in her heart rate between resting and walking.

(b) Measuring the pulse rate is one way of monitoring the activity of the heart. State one other way of monitoring the activity of the heart.

(c) Breathing is also affected by exercise. Describe the effects of exercise on breathing.

(d) Anaerobic respiration can occur when exercising vigorously on addition to aerobic respiration. Compare the advantages of the two processes during exercise.

DISCLAIMER.

These questions are built in a similar style to that presented within the previous exam board's sample assessment materials. There can be no guarantee of the extent to which these questions will reflect the actual examination questions students will sit. I hope that schools and students find these questions useful in the exam preparations in this Topic. However, I take no responsibility for the relevance of this document to actual examinations sat.