GASEOUS EXCHANGE

This is the diffusion of gases from an area of higher concentration to an area of lower concentration, especially the exchange of oxygen and carbon dioxide between an organism and its environment.

VENTILATION is an active mechanism which draws over and expels respiratory gases away from the gaseous exchange surfaces.

Pulmonary ventilation

It is simply taking in of air from the atmosphere and giving out of air from the lungs. It is carried out by breathing which constantly renews the air present in the lungs. It involves two processes - inspiration and expiration

Difference between inspiration and expiration

Inspiration	Expiration
(i) Taking in of atmospheric gasses	(i) Giving out of air from the lungs.
(ii) Contraction of external intercostal mus-muscles or inspiratory muscles and relaxation of internal intercostal	(ii) Relaxation of external intercostal muscles and contraction of internal intercostal muscles,
(iii) Rib cage moves forward and outward.	(iii Rib cage moves downwards and inwards.
(iv) Diaphragm contracts and becomes flat-tened.	(iv Diaphragm relaxes and becomes dome shaped (original
(v) Increase in the volume of thoracic	(v) Decrease in the volume of thoracic cavity.
(vi) Decrease in pressure of thoracic cavity (below the atmospheric pressure) arid hence in the lungs,	(vi Increase in pressure of- thoracic cavity hence in the lungs.
(vii) Rushing in of air through nostrils into alveolar sacs causing inflation of lungs.	(vi Expulsion of air from lungs into the atmo-sphere causing deflation of lungs.
(viii) Composition of inspired air Oxygen - 20.95% Carbondioxide - 0.04% Nitrogen - 79.01%	(viii) Composition of expired Oxygen - 16.4% Carbondioxide - 4.0% Nitrogen - 79.6%

Note: One breathe includes one inspiration and one expiration, the respiratory rate is the number of breathes taken per minute. For a person breathing normally at rest, it is equal to 12-14 breaths per minute.

CONDITIONS NEEDED FOR GAS EXCHANGE

a) The supply of oxygen

(1) Air - About 21% of air is oxygen.

(2) Water - Amount of oxygen in water varies (about 1.03% in fresh water and 0.85% in sea water) but is always much less than in air, being even lower in warmer water than colder water.

b) Diffusion

Diffusion is faster when the

- surface area to volume ratio is large

- distance travelled is small
- concentration gradient of the diffusing substance is high.

c) A ***moist surface*** is required because oxygen and carbondioxide must be dissolved in water to diffuse across a membrane.

d) Permeable membranes

(e) large surface area to volume ratio

Therefore, an efficient gas exchange surface must

(1) Have a large surface area relative to the volume of the organism to ensure a faster diffusion rate of respiratory gases

(2) provide a short distance (be thin) for gases to diffuse across

(3) be moist to enable dissolving of respiratory gases

(4) permeable to the respiratory gases to enable their diffusion

(5) be organized or operate in a way that maintains a favourable concentration gradient for the diffusion of respiratory gases

Hence a circulatory system may operate in tandem with the gas exchange system to maintain the concentration gradient.

Advantages of air over water as gas exchange media	**Disadvantage of air as a gas exchange medium and why most land animals have internal respiratory surfaces**
(1) Air has a much higher oxygen concentration than water **(2)** Diffusion occurs more quickly so less ventilation of the surface is needed **(3)** Less energy is needed to move air through the respiratory system than water	• Water is continuously lost from the gas exchange surface by evaporation so the gas exchange surface is folded into the body to reduce water loss.

A comparison of selected properties of fresh water and air

Property	**Air**	**Fresh water**
Oxygen content (cm^3/l)	210	8
Diffusion rate (arbitrary units)	1	10^{-5}
Viscosity (arbitrary units)	1	100
Density (arbitrary units)	1	1000

Gaseous exchange surface in organisms

Gas exchange surfaces	***How the gas exchange structures are suited to their function***
Cell surface membrane in unicellular organisms e.g. amoeba	• The cell surface membrane has a sufficiently large surface area to volume ratio enables efficient diffusion of gases. • Being aquatic, the cell membrane is always moist to dissolve respiratory gases to enable their diffusion.

	• The cell surface membrane is permeable to respiratory gases
Entire body surface e.g. skin of earthworms	• Skin surface is moist to enable dissolving of respiratory gases for efficient diffusion. • Skin is thin to reduce the diffusion distance such that there is increased rate of diffusion of respiratory gases. • The epidermal tissue is highly vascular to deliver and carry respiratory gases such that a high concentration gradient for the gases is maintained
Across the surface of flattened body e.g. flatworms	• The flatness increases the surface area to volume ratio to increase the rate of diffusion of respiratory gases.
Lung-books in spiders	• The internal cavity increases the surface area for exchange of respiratory gases.
External gills in young tad poles and lugworms *NB:* *External gills are epidermal outgrowths suspended in water unprotected and therefore easily get damaged.*	• There is increased surface area for diffusion of respiratory gases.
Tracheoles in insects Note: *Size of insects is limited by the relatively slow diffusion rate of respiratory gases.*	• Tracheae are kept open by circular bands of chitin to enable continued movement of air in and out of tracheoles. • Tracheae branch to form tracheoles that reach every cell to delivered oxygen directly to respiring cells and take away Carbondioxide. • Ends of the tracheoles are moist to enable dissolution of respiratory gases for increasing their diffusion
Internal gills in fish *NB:* *Increased surface area is needed because **(1)** water holds less oxygen than air and **(2)** diffusion across the skin of the fish would be inadequate due to the large size of the animal*	• Gill filaments have folds called ***secondary lamellae*** that increase the surface area for gas exchange. • The gill lamellae contain a network of capillaries for carrying away oxygen or bringing in Carbondioxide for expulsion. • There is counter current flow i.e. water and blood in the gills flow in opposite directions to maintain a favourable concentration gradient for diffusion of respiratory gases. • Gills are moist to enable dissolution of respiratory gases for efficient diffusion. • Gills are ***thin-walled*** and in close contact with water to provide a short distance for diffusion of respiratory gases.

Inner alveolar surface of lungs in mammals	• Lungs have many tiny alveoli which provide a large surface area for gas exchange. • Diffusion of respiratory gases is made faster by the shortened distance due to **(1)** alveoli and capillary walls being only one cell thick **(2)** epithelial cells are flattened so are very thin **(3)** capillaries are pressed against alveoli. • The moistened alveolar surface enables dissolution of respiratory gases to increase the rate of diffusion. • The gas exchange system is internal to reduce water loss by evaporation. • There are high concentration gradients of the gases, maintained by ventilation and flow of blood in the capillaries.
Cell walls of cells in the leaf mesophyll and cortex of root 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 side ways 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.

GAS EXCHANGE IN VARIOUS ORGANISMS

1. SIMPLE ORGANISMS

(a) In unicellular (single-celled) organisms such as protozoa e.g. amoeba, gas exchange occurs by diffusion across their membranes. Along their concentration gradients, dissolved oxygen diffuses from the water across the cell membrane into the cytoplasm while dissolved carbondioxide diffuses in the opposite direction.

(b) In organisms such as green algae, the cells may be close to the environment, and gas exchange can occur easily 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 carbondioxide diffuses in the opposite direction, along their concentration gradients.

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

2. GAS EXCHANGE IN EARTHWORMS

Earthworms exchange oxygen and carbon dioxide directly through their skin. The oxygen diffuses into tiny blood vessels in the skin surface, where it combines with the red pigment **haemoglobin.** Hemoglobin binds loosely to oxygen and carries it through the animal's bloodstream. Carbon dioxide is transported back to the skin by the hemoglobin from which it detaches and diffuses out.

3. GAS EXCHANGE IN INSECTS

Terrestrial insect e.g. grasshopper

In grasshopper, the tracheal system consists of 10 pairs of spiracles, located laterally on the body surface. Of these, 2 pairs are thoracic and 8 pairs are abdominal. The spiracles are guarded by fine hairs to keep the foreign particles out and by valves that function to open or close the spiracles as required. The spiracles open into small spaces called the **atria** that continue as air tubes called the **tracheae**. The tracheae are fine tubes that have a wall of single layered epithelial cells.

The cells secrete spiral cuticular thickenings called **taenidia** around the tube that gives support to the tubes.

The tracheal tubes branch further into finer **tracheoles** that enter all the tissues and sometimes, even the cells of the insect. The ends of the tracheoles that are in the tissue are filled with fluid and lack the cuticular thickenings.

The main tracheal tubes join together to form three main tracheal trunks- dorsal, ventral and lateral. At some places, the tracheae enlarge to form air sacs which are devoid of cuticle and serve to store air.

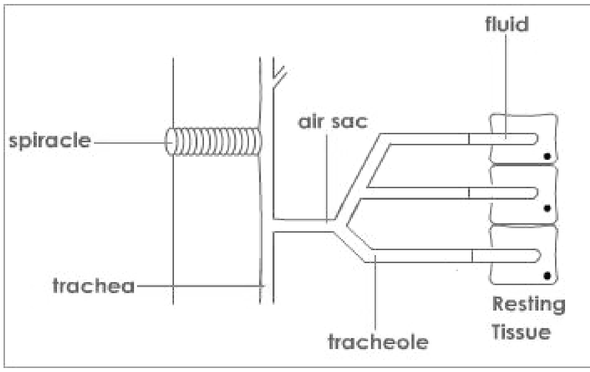
ventilation and gaseous exchange in insects

- Increased CO_2 is detected by chemoreceptors, causing relaxation of the abdominal muscles and lowering of pressure. The spiracles valves open and air rich in oxygen is drawn into the tracheal system.
- Spiracles valves then close and oxygen is forced along the tracheal system into the fluid-filled tracheoles, which are in direct contact with the tissue fluid. Gaseous exchange takes place due to difference in concentration gradients of oxygen and carbon dioxide.

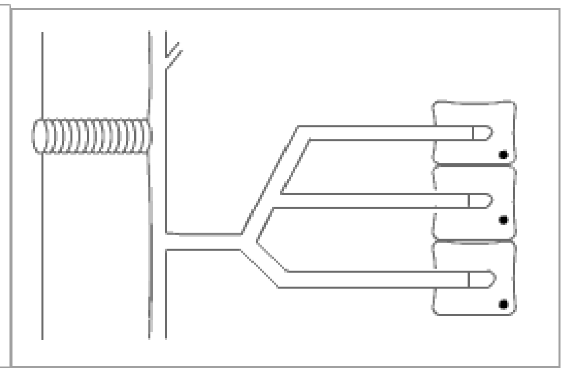
- Air is expelled out when muscles contract and flatten the insect body, decreasing the volume of the tracheal system.
- During increased metabolic activity, the water potential of tissue lowers causing osmotic efflux of water from the tracheoles; and hence air replaces the fluid of the tracheoles.

- In resting tissues, the water potential of tissue fluid increases resulting in the diffusion of much water into the tracheoles.

Appearance of tracheoles at rest



Appearance of tracheoles during activity



4. GAS EXCHANGE IN FROGS

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

(1) The skin - especially during low activity when hibernating **(2)** the mouth [buccal cavity] **(3)** the lungs.

The Skin:

Air from the atmosphere diffuses through the moist thin skin; it into the dense capillary below the skin.

Due to its low concentration in the blood than in the skin surface, oxygen is then taken to the tissues via the red blood cells. Carbon dioxide moves from the blood into the skin surface then to the atmosphere. This happens due to its high concentration in the blood tissues than in the surface of the skin.

The mouth (Buccal cavity):

The muscles of the mouth contract and then 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

There exists dense capillary network in the mouth cavity and as such, gaseous exchange takes place. Oxygen due to its high concentration diffuses into the blood 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.

The lungs:

The mouth muscles contract then lower the floor of the mouth hence increasing its volume. Pressure reduces in the mouth cavity than the atmosphere's, causing air to move into the mouth through the nostrils.

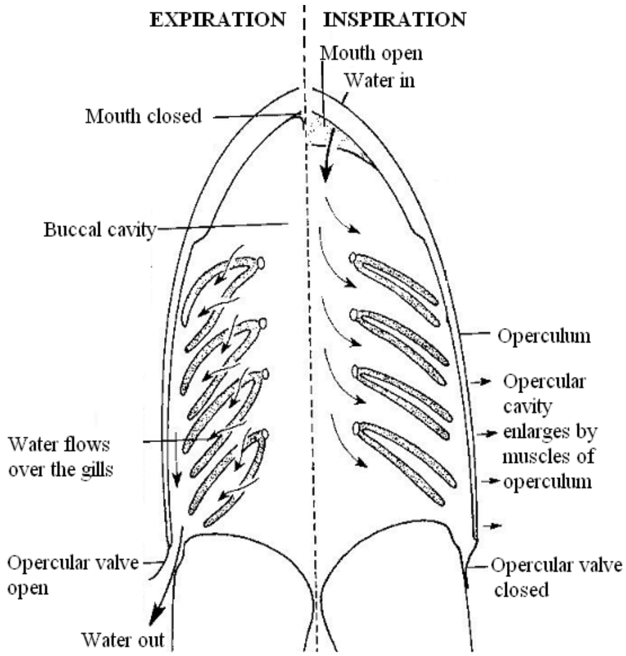
The nostril then closes and the mouth's floor is raised. This forces the air into the lungs.

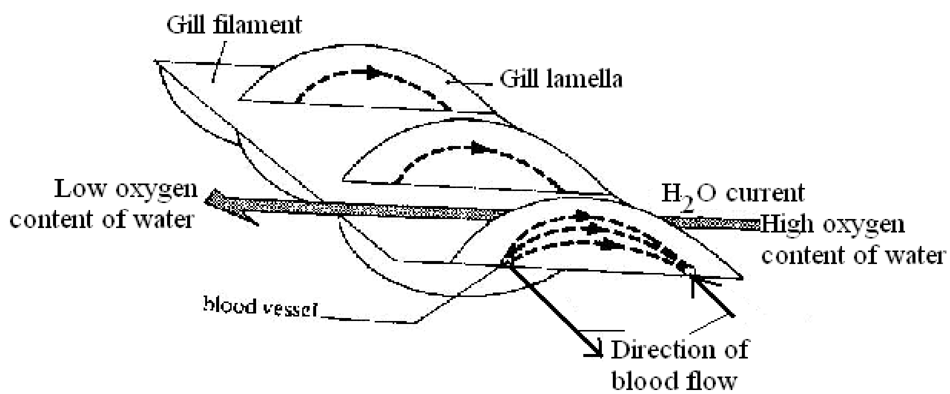
Gaseous exchange takes place between the alveoli of the lungs and the blood; oxygen due to its high concentration in the alveoli than the blood diffuse into the blood while Carbon dioxide diffuses out of the blood tissue to the alveoli where it is exhaled out through the nostrils by the muscles of the lungs which contract and relax rhythmically.

5. GAS EXCHANGE IN BONY FISH

Mechanism of ventilation in bony fish

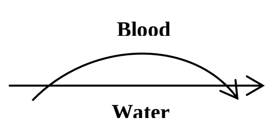
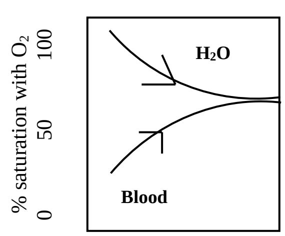
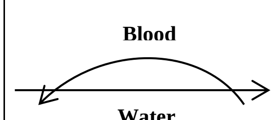
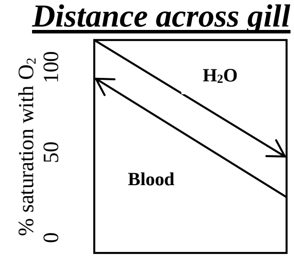
- Contraction of the mouth muscles lowers the floor of the mouth, reducing its pressure as the mouth opens. Water (with dissolved oxygen) moves into the mouth and at the same time the operculum remain closed.
- The operculum muscles relax; causing operculum to bulge open; this increases the volume but lowers the pressure in the gill region as the mouth closes.
- Water from the cavity mouth moves into the gill region due to the reduced pressure; and bathes the gill filaments in opposite direction to the flow of the blood. **This is termed countercurrent flow.** Oxygen diffuses into the blood capillaries due to its high concentration in the gill region than the blood capillaries; it combines with haemoglobin and is transported as oxyhaemoglobin to the respiring tissues.
- Carbon dioxide and toxic metabolic wastes, like ammonia which are at higher concentration in the blood than the gill filaments are excreted into the gills and exhaled through the water that moves out when the operculum opens.
- The higher internal water pressure in gill chamber forces operculum to open to exit the water



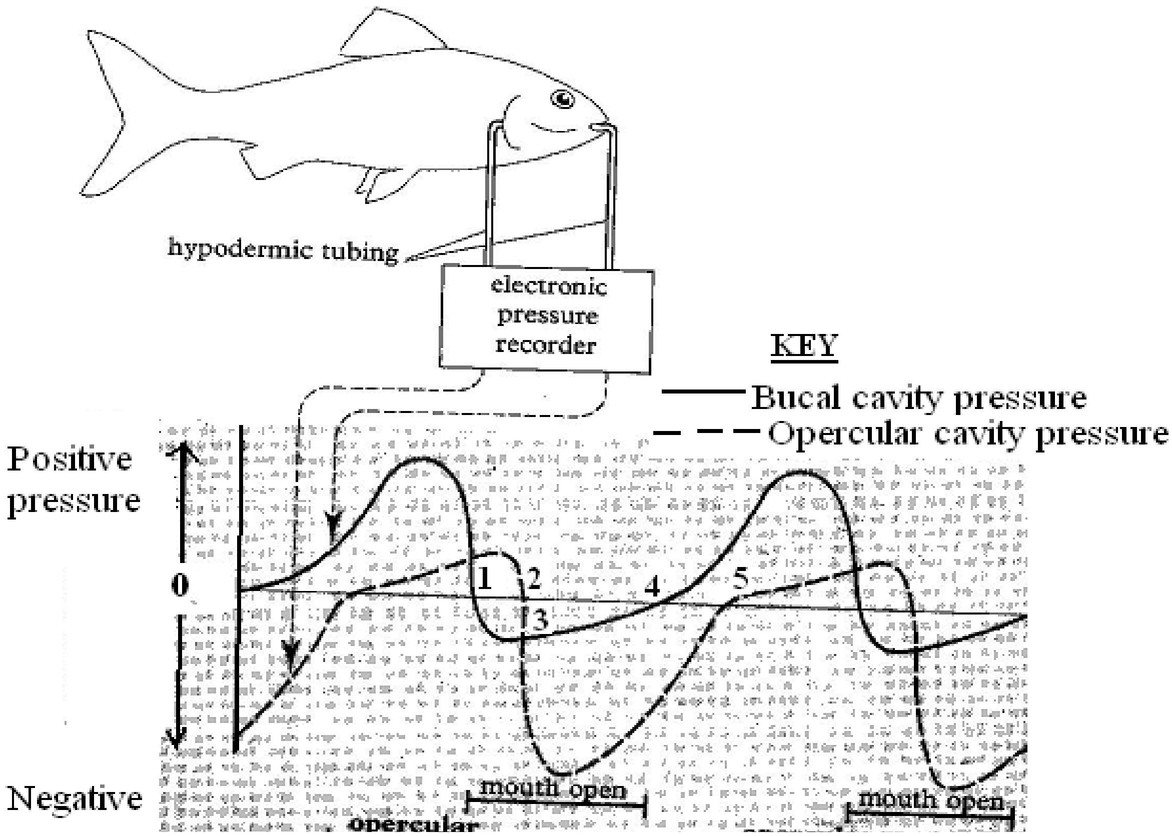


DETAIL OF PART OF ONE GILL FILAMENT SHOWING THE LAMELLAE

COUNTERFLOW AND PARALLELFLOW SYSTEMS COMPARED

Parallel flow system / Co-current flow system	Countercurrent exchange
• Blood in the gill lamellae would flow 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 would reach equilibrium in oxygen content and diffusion would no longer take place. • If the blood in the gill lamellae and water were to flow in the same direction, initially large amounts of oxygen would diffuse but the efficiency would reduce when the fluids start to reach equilibrium. • The concentration of oxygen gained from this system would not meet the physiological needs of the fish. ***How to improve parallel flow:*** The flow of water being very rapid compared with that of the blood, to ensure a higher saturation of the blood by the time it leaves the respiratory surface. ***How an efficient counterflow system is prevented in a dogfish:*** **(1)** The main flow of the water through the gill pouches is parallel to the lamellae **(2)** the vertical septum deflects the water so that it tends to pass over rather than between the gill plates. ***Gill plate*** ***Distance across gill plate***  	• Water flows across the gill lamellae in an opposite direction to the blood flow, enabling almost all 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. • By having the blood flow in the opposite direction, the gradient is always such that the water has more available oxygen than the blood, and oxygen diffusion continues to take place after the blood has acquired more than 50% of the water's oxygen content. The countercurrent exchange system gives fish an 80-90% efficiency in acquiring oxygen ***Advantages of counterflow*** **(1)** Enables blood of the gill lamellae to extract oxygen from the water maximally for the entire period the water flows across the gill filaments than if blood moved in the same direction as the passing water **(2)** Under conditions permitting adequate oxygen uptake, the counter-current fish expends less energy in respiration compared to the identical hypothetical co-current fish ***Gill plate*** ***Distance across gill plate***  

CHANGES IN THE PRESSURES OF THE BUCCAL CAVITY AND OPERCULUM DURING VENTILATION IN A BONY FISH



OBSERVATIONS AND EXPLANATIONS FROM THE GRAPH

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

At 2, opercular cavity is expanding, pressure reduces (acquires negative pressure); opercular valve closes.

At 3, pressure in opercular cavity falls below that of buccal cavity which has began to contract, resulting in water being sucked into opercular cavity from buccal cavity

At 4, buccal cavity pressure increases **(acquires positive pressure);** mouth valve closes and water is forced from buccal cavity to opercular cavity.

At 5, opercular cavity is contracting, pressure increases **(acquires positive pressure)**; opercular valve opens and water is expelled

WHAT IS THE DIFFRERENCE BETWEEN NEGATIVE AND POSITIVE PRESSURE?

Negative pressure: *It refers to a situation in which an enclosed area has lower pressure than the area around it.*

Positive pressure: *a situation in which an enclosed an area has higher pressure than the surrounding regions*

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 that of opercular cavity, causing the water to enter the buccal cavity but at the same time the opercular valves close to prevent entry of water.*

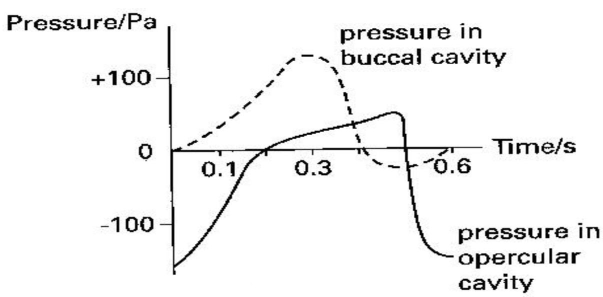
(2) *The buccal cavity acts as a force pump while the opercular cavity as a suction pump.*

Sample questions

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

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

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

b) (i) With evidence from the graph, explain why water almost flows in one direction over the gills.

ii) How does the fish increase buccal cavity pressure?

6. GAS EXCHANGE IN MAN

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.

Main features of the respiratory system

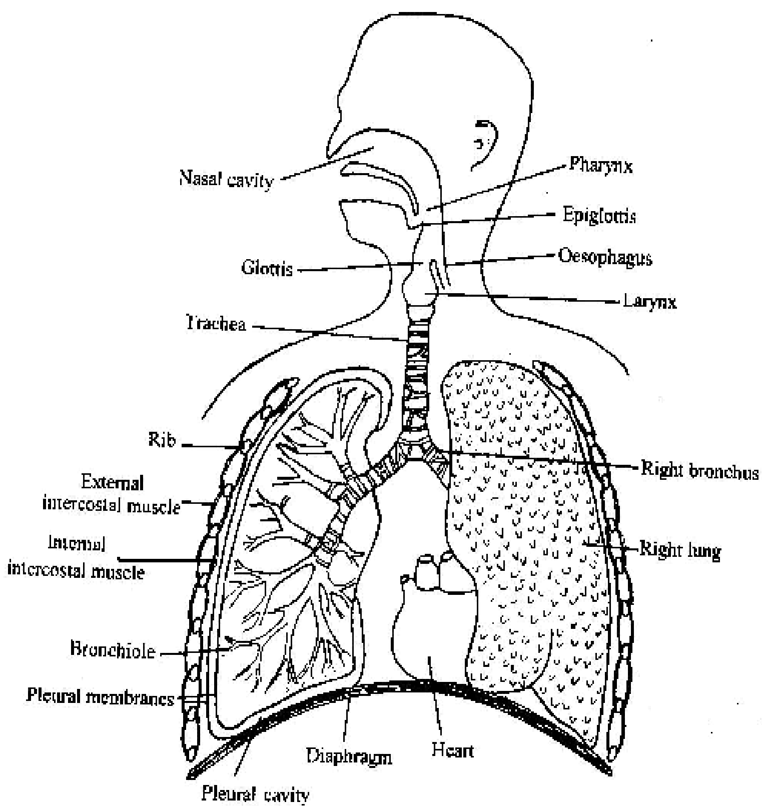
Trachea (wind pipe), the two bronchi and the bronchioles: They are held open (without collapsing) by the **C-shaped cartilaginous rings**. Epithelium is **ciliated**, have goblet cells that secret **mucus**, and have smooth muscle; there is also connective tissue with **elastic** and **collagen fibres.**

Lungs: they

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.**



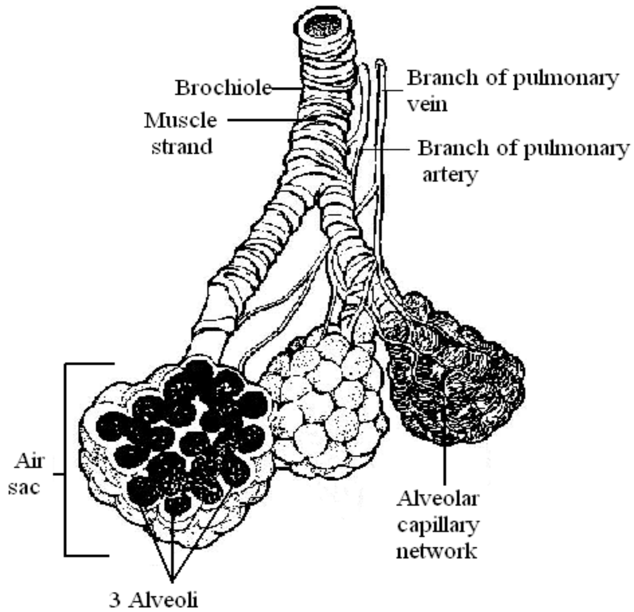
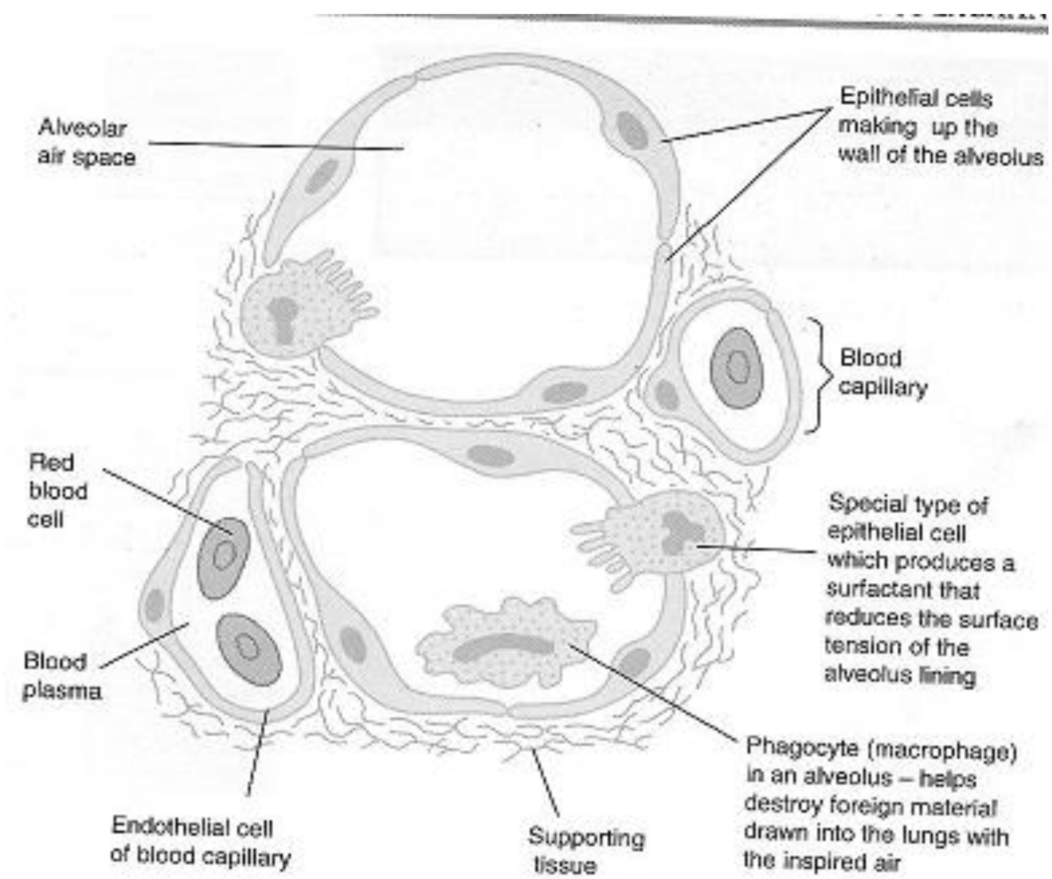


Diagram of cross section through two alveoli



WHAT IS A LUNG (PULMONARY) 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. The proteins and lipids that surfactant comprises have both a hydrophilic region and a hydrophobic region.

FUNCTIONS OF LUNG SURFACTANT

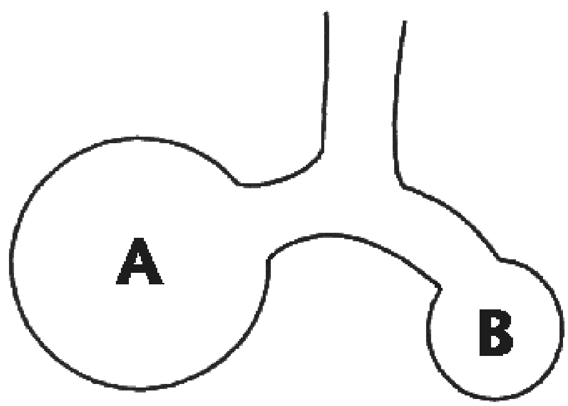
(1) It greatly reduces alveolar surface tension, increasing compliance allowing the lung to inflate much more easily, thereby reducing the effort needed to breath in air.

NB: ***Compliance is the ability of lungs and thorax to expand. Lung compliance is defined as the volume change per unit of pressure change across the lung.***

(2) It speeds up the transport of oxygen and carbondioxide 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 stabilises the alveoli.



The pressure within a spherical structure with surface tension, such as the alveolus, is inversely proportional to the radius of the sphere. That is, 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 differentially reduces surface tension, more at lower volumes and less at higher volumes, leading to alveolar stability and reducing the likelihood of alveolar collapse.

VENTILATION AND GASEOUS EXCHANGE IN MAN

INSPIRATION:

The inspiratory muscles **(the muscles which cause active increase in lung volume) include:**

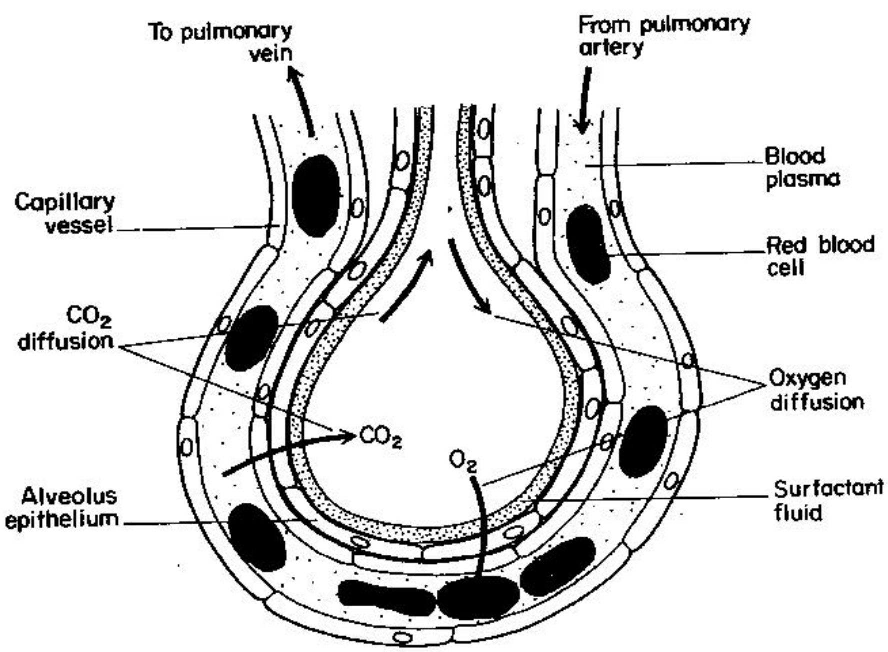
1. Diaphragm
2. external intercostals
3. sternocleidomastoid and other accessory muscles

- The external intercostal muscles contract and the inner ones relax.
- The rib cage moves upwards and outwards.
- The muscles of the diaphragm contract and it flattens (loses its dome shape).
- These movements increase the volume of the thoracic cavity; and that of the lungs.
- Pressure in the lungs is then decreased; lower than the atmospheric pressure. Because air always flows from a region of high pressure to a region of lower pressure, it rushes in through the nostrils, through the nasal passages, into the pharynx, through the larynx, down the trachea, into the main bronchi, then into smaller bronchioles, through even smaller alveolar ducts, and into alveoli.
- Air dissolves in the moisture lining the alveolar epithelium, oxygen then diffuses into blood capillaries while carbondioxide diffuses from blood capillaries into alveolar air along the concentration gradients.

EXPIRATION:

- The internal intercostal muscles contract while the external intercostals muscles relax.
- The rib cage moves downwards and inwards.
- The muscles of the diaphragm relax; causing it to assume its dome shape.
- The volume of the thoracic cavity decreases; resulting into decrease in the volume of the lungs.
- The pressure in the lungs increases higher than that of the atmospheric pressure; air **richer in carbondioxide** and **less in oxygen** is then forced out of the lungs.

THE RELATIONSHIP BETWEEN AN ALVEOLUS AND A CAPILLARY, AND GASEOUS EXCHANGE



PHYSICAL CHANGES THAT OCCUR TO AIR DURING GAS EXCHANGE

It is

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

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

OBSERVATIONS AND EXPLANATIONS FROM THE TABLE ABOVE

Observations	Explanations
1. Inspired air contains more oxygen and nitrogen than exhaled air, yet exhaled air contains more carbondioxide (120 times) and water vapour than those in inhaled air	Some of the oxygen in inhaled air diffuses into blood capillaries while carbondioxide and water vapour from blood diffuse into the air to be expired. The percentage of nitrogen decreases in expired air because of the increased partial pressure of carbondioxide and water vapour.
2. The volume of oxygen and carbondioxide in expired air is intermediate between the inspired and alveolar values.	Some oxygen in alveolar air diffuses into blood capillaries while carbondioxide from blood diffuses into alveolar air. The air that remains in the alveoli mixes with the incoming fresh air hence lowering the percentage of oxygen in alveolar air

TYPICAL QUESTION

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

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

(i) Calculate the average number of inspirations per minute during rest and during exercise.

During rest: 12; during exercise: 20

(ii) Calculate the average tidal volume during rest and during exercise

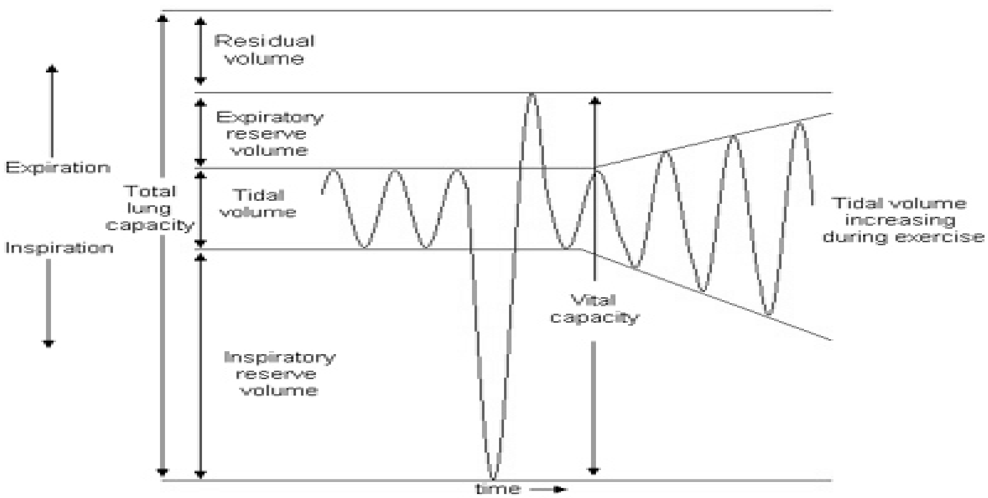
During rest: 497.8cm³; during exercise: 2292cm³

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

NORMAL LUNG VOLUMES AND LUNG CAPACITIES IN RESTING ADULTS

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

Lung volumes and capacities as shown by a spirometer



Pulmonary air volumes:

1. **Tidal volume (TV):** It is the volume of air breathed in and out during normal breathing or in in each respiratory cycles. TV= 500 ml (0.5 litre)

2. **Inspiratory reserve volume (IRV).** It is an extra volume of air over and above the tidal volume that can be taken in during deep breath. IRV = 1500-2500 ml (l.5 - 2.5 litres)

3. **Expiratory reserve volume (ERV).** After a normal expiration (tidal expiration), one can still expel a large volume of air. This is known as expiratory reserve volume. ERV = 1500 ml (l.5 litres)

4. **Vital capacity.** It is the total volume of air expired after a maximum inspiration-followed by a maximum expiration.

   Vital capacity of a normal adult = TV + IRV + ERV = 3500 – 4500 ml (3.5 – 4.5 litres)
   The higher the vital capacity, the higher the amount of air exchanged in each breath

Note:

Higher vital capacity	Lower vital capacity
Athletes	Non-athletes
Mountain dwellers	People living in plains
Men	Women
Youth	Old individuals
Non cigarette smokers	Cigarette smokers

5. **Total lung capacity**. It refers to the amount of air present in the lungs after the maximum inhalation. It is equivalent to 5000-5500 ml

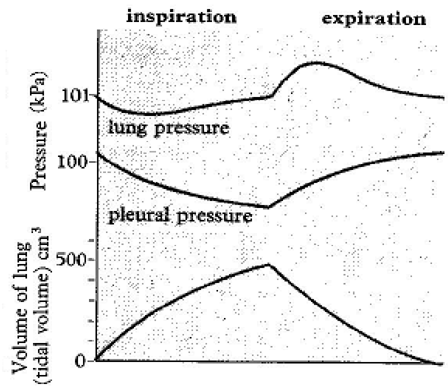
6. **Residual volume (RV).** It is the amount of air left in the lungs even after the maximum expiratory effort. It can never be forced out of lungs.
   RV = 1500 ml. (1.5litres)
   Residual volume is the air that is always present in the lungs meaning that the exchange of gases continues even during expiration, or even when you hold the breath
7. **Dead space air**. It is the amount of air that is present in the respiratory tubes where gaseous exchange does not occur. With each expiration, it is expelled out without undergoing any change in oxygen or carbon dioxide concentration.
   It is equivalent to about 150 ml (0.15 litres). Out of the tidal volume of 500 ml, 150 ml remains in respiratory tubes as dead space air and only the rest 350 ml is present in alveolar sacs in the lungs for exchange of gases.

8. **Alveolar ventilation:** Total volume of fresh air entering the alveoli per minute.

VENTILATION RATE

Ventilation = (Tidal volume - anatomic dead space) x respiratory rate. An average human breathes some 12-20 times per minute.
Minute ventilation = Tidal volume x Respiratory rate. **Units:** (ml/min) = (ml/breath) x (breaths/minute)
Since a fixed volume of each tidal volume goes to dead space, increased depth of breathing is more effective in elevating alveolar ventilation than increased breathing rate.

PRESSURE-VOLUME CHANGES DURING ONE RESPIRATORY CYCLE IN MAN



Factors affecting volumes

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

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

VARIATION OF ATMOSPHERIC PRESSURE WITH ALTITUDE

We all live near the bottom of an ocean of air. At sea level, the weight of the air overhead presses on us with pressure. We are not aware of this great weight because the air presses on us from all sides, even from our insides (due to the air in our lungs). At higher altitudes, there is less air and less weight overhead, and the pressure is less. Also, because air is readily compressible, the lower layers of air are compressed by the weight of the air above. Thus, the pressure and density of air decrease at higher altitudes. That's why a helium balloon rises: the pressure on the underside of the balloon is greater than the pressure on the top.

EXPLAIN THE FOLLOWING OBSERVATIONS

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

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

2. When someone living at or near sea level travels to locations at high altitudes (eg. the Rwenzori mountain), that person can develop a condition called <u>altitude (mountain) sickness</u>

This is because their lungs remove adequate amounts of carbon dioxide but they do not take in enough oxygen. (In normal individuals, carbon dioxide is the primary determinant of respiratory drive)

ALTITUDE SICKNESS (MOUNTAIN SICKNESS)

Is an illness that develops when the rate of ascent into higher altitudes outpaces the body's ability to adjust to those altitudes.
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

How to avoid altitude sickness: **(1)** allowing the body to get used to the altitude slowly, a process called **acclimatization.** The goal of acclimatization is to increase ventilation (breathing) to compensate for lower oxygen content in the air **(2)** Get used to the high altitude before doing a lot of exercise e.g. hiking, skiing, or biking **(3)** Don't drink alcohol at high altitudes. It takes much less alcohol to become drunk at high altitudes than at sea level.

ADAPTATIONS OF LUNG SYSTEM FOR GASEOUS EXCHANGE

1. Lungs have numerous alveoli; that provide large surface area for efficient gaseous exchange
2. Epithelial lining between the alveoli wall and the blood capillaries is thin to provide a shorter diffusion distance for easy gaseous exchange
3. The lung is spongy and has numerous alveoli to accommodate large volume of gases
4. It is highly supplied with blood capillaries that transport oxygen and carbon dioxide to and from the body tissues respectively
5. The epithelial lining of alveoli is covered by a thin layer of moisture to dissolve oxygen for easy diffusion into the blood solution
6. The whole lungs are covered with the pleural membrane which is gas tight thus changes in the pressure within the lungs can occur without external interference
7. The walls of the trachea and bronchi are lined by rings of cartilage which prevent them from collapsing and keeps them open for air passage
8. The inner passage of the air ways is lined with mucus membrane which contain ciliated cells whose movement to and from the pharynx cause a sweeping action that collects dust towards the pharynx for swallowing hence preventing their entry into the air ways
9. The mucus membrane contains mucus secreting cells which produces mucus that trap dust and pathogenic particles which would find their way into the air way
10. The mucus membrane has a rich blood supply which warms and moistens the incoming air for easy diffusion in the lungs
11. The epiglottis and other structures on the top of the trachea prevent food, drinks and other solid particles from going into the trachea during swallowing.

NON-RESPIRATORY FUNCTIONS OF THE LUNG RESPIRATORY SYSTEM

1. The vibration of air flowing across the larynx (vocal chords) in humans allows phonation (speech), and the syrinx, in birds results in vocalization or singing
2. Panting in dogs and some other animals provides a means of cooing body temperature

3. Irritation of nerves within the nasal passages or airways, can induce coughing and sneezing. These responses cause air to be expelled forcefully from the trachea or nose thereby enabling expulsion of irritants caught in the mucus which lines the respiratory tract.

INVOLUNTARY CONTROL OF BREATHING IN MAN

Introduction

Physiological control systems involving the nervous system usually have three components. These are

1. a central controlling area where information from other parts of the body is integrated to produce a coordinated response
2. an afferent pathway which relays impulses from the sensors to the central controlling area
3. an efferent pathway which conveys impulses from the central controlling area to the organs and muscles

NB: Many factors can modify the rate and depth of breathing but the **most important factors are the levels of carbon dioxide, hydrogen ions** (H^+) **and oxygen** in the arterial blood.

CONTROL OF BREATHING IN MAN

Breathing is usually automatic, controlled subconsciously by the respiratory center at the base of the brain. People can also control their breathing when they wish, for example during speech, singing, or voluntary breath holding.

The rate of breathing is controlled by the **respiratory centre**, which is in the lower part of the brain stem, in the medulla oblongata. The respiratory centre comprises of the **inspiratory** and **expiratory centres.**

Normally, an increased concentration of carbon dioxide is the strongest stimulus to the depth and frequency of breathing.

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

High CO_2 lowers the pH (an acid is a solution with a high H^+ concentration).

$CO_2 + H_2O \leftrightarrow H_2CO_3 \Leftrightarrow HCO_3^- + H^+$

Eliminating CO_2 is usually a bigger problem for terrestrial vertebrates than obtaining O_2. The body is therefore more sensitive to high CO_2 concentration than low O_2 concentration.

Aquatic vertebrates are more sensitive to low O_2 because O_2 is more limited in aquatic environments.

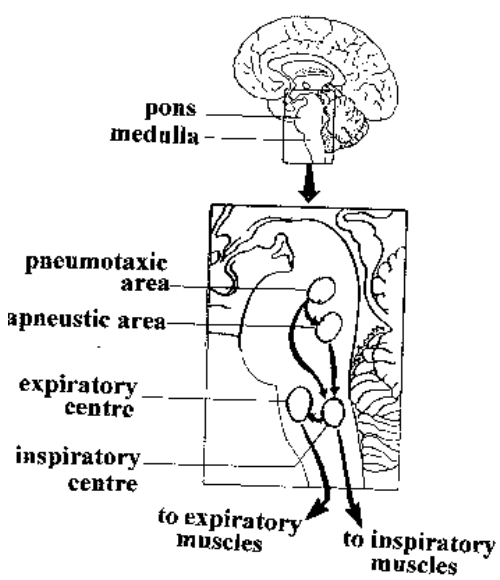
NERVOUS CONTROL OF BREATHING

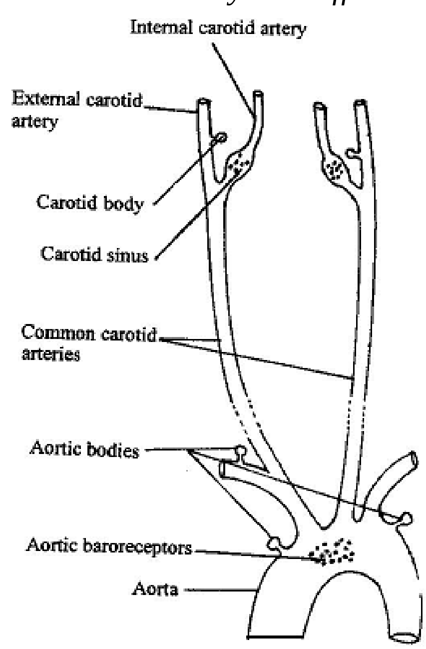
Increase in carbon dioxide concentration (a condition called **hypercapnia**) in the blood (e.g. following exercise) and reduction in oxygen concentration stimulates the **chemoreceptors** in the **carotid and aortic bodies** to send impulses via the **glossopharyngeal nerve** and **vagus nerve** respectively to the **inspiratory centre** of the medulla oblongata. Also, when carbon dioxide increases in blood, it rapidly diffuses into the cerebrospinal fluid (CSF) resulting in increased hydrogen ion (H^+) and bicarbonate ion (HCO^{3-}) concentrations in CSF.

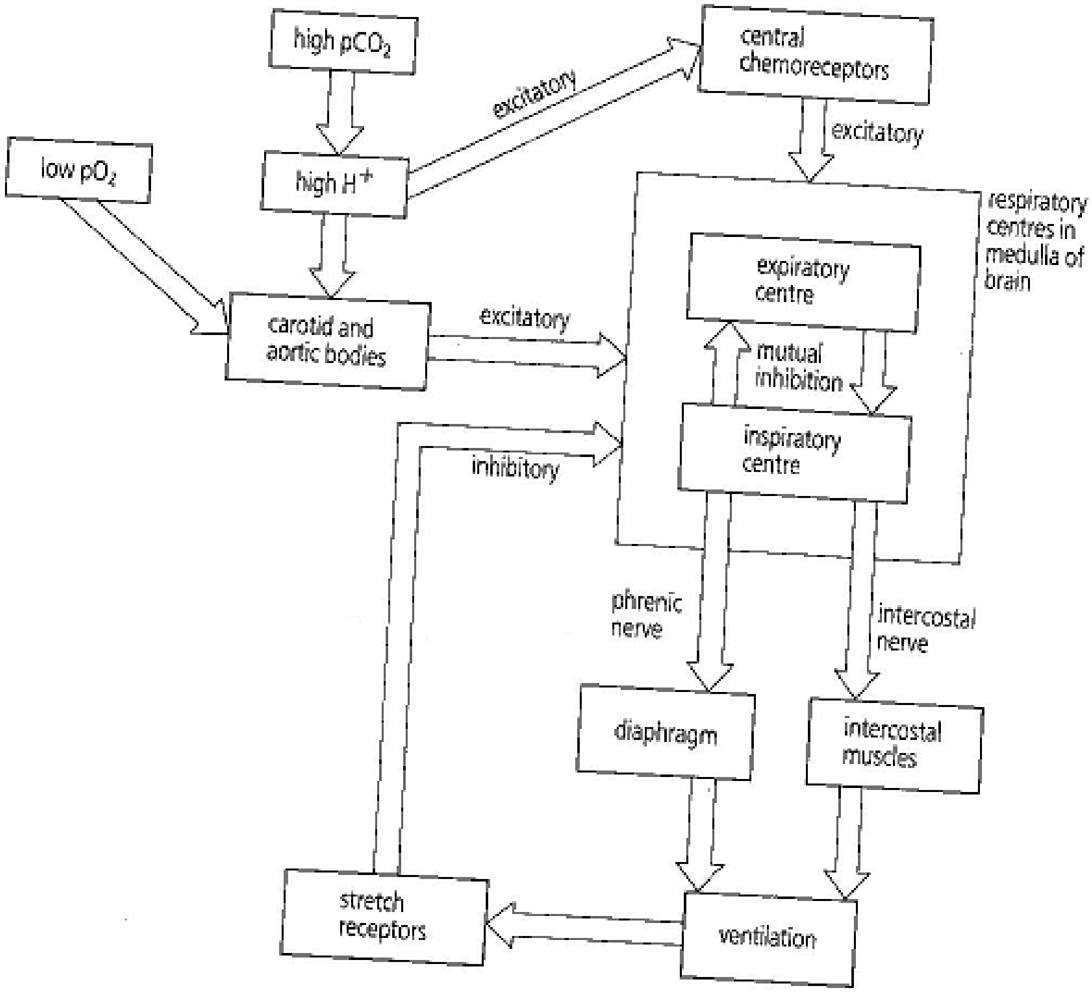
This increase in CSF acidity stimulates cells in the floor of the fourth ventricle (part of the brain stem) to generate impulses which excite the inspiratory centre in the medulla oblongata. The inspiratory centre generates and sends impulses via the **(1) phrenic nerve** to the diaphragm **(2) segmental intercostal nerves** to the intercostal muscles and **(3) cervical plexus** to the accessory muscles in the neck.

The diaphragm and intercostal muscles contract to cause the following effects: **(1)** increased rate and depth of breathing –a condition called **hyperventilation (2)** increased rate of heart beat **(3)** vasodilatation occurs. All these result in increased rate and volume of CO_2 transport and hence a reduction in CO_2 concentration to normal and increased concentration of oxygen.

As the lungs expand, **stretch receptors (proprioceptors)** in their walls are stimulated to send impulses along the vagus nerve to the expiratory centre in the medulla oblongata and this automatically switches off the inspiratory centre, causing the muscles to relax and allow expiration occur. As the stretch receptors are not/less stimulated, the expiratory centre is switched off while the inspiratory centre is switched on and inspiration occurs again. **NB:** *the main stimulus for ventilation is the change in CO_2 and hence H^+, and stimulation of stretch receptors in the lungs, while changes in O_2 concentration have relatively little effect on breathing rate.*






high pCO_2
central chemoreceptors
excitatory
excitatory
low pO_2
high H^+
respiratory centres in medulla of brain
expiratory centre
carotid and aortic bodies
excitatory
mutual inhibition
inspiratory centre
inhibitory
phrenic nerve
intercostal nerve
diaphragm
intercostal muscles
stretch receptors
ventilation