

Gaseous exchange

This is the process by which respiratory gases are exchanged between the external medium and the blood with oxygen leaving the external medium and carbon dioxide being returned to it following ventilation of respiratory gases.

Necessity for gaseous exchange

Living cells and organisms need to respire to obtain oxygen for the oxidation of food to yield energy and carbon dioxide to be gotten rid off since it is a waste product. Accumulation of carbon dioxide is toxic to the tissues that produce it. It lowers the pH by forming carbonic acid.

Factors that affect the rate of gaseous exchange

- I. The total area available for diffusion
- II. The distance over which diffusion has to occur. The rate of diffusion is inversely proportional to the diffusion distance.
- III. The concentration gradient across the gas exchange surface. The greater the concentration gradient of a gas between the external medium and the blood, the greater its rate of diffusion and faster the process of gaseous exchange.
- IV. The speed with which molecules diffuse across membrane and this is affected by size, charge and solubility of the diffusing molecules

Characteristics of gaseous exchange surface/respiratory surface

1. They have a large surface to volume ratio, for some them this is attained by them being greatly folded, being many in number to increase rate of diffusion.
2. They are thin so as to minimize the distance over which diffusion occurs. This makes diffusion faster
3. They are permeable to gases so that molecular gases diffuse through their pores easily.
4. They are moist because diffusion across membrane is enhanced when gases are in solution.
5. They are highly vascularised for carriage of gases after exchange and thereby maintaining a steep concentration gradient across the respiratory surface.

Types of respiratory surfaces

The bodies of different animals have been made so as to increase surface area to volume for efficient gaseous exchange to take place across their bodies.

1. Small organisms have exchange across entire surface of the body e.g. in protists they have a big SA:VR
2. Insects and other arthropods have a tracheal system which ramifies the entire body and ventilation is through spiracles

3. External gills are supplied with a dense network of blood vessels and gaseous exchange takes place all over the body e.g. lugworms and tadpoles
4. Internal gills are densely supplied with blood vessels and thinly divided into lamellae to increase surface area. A ventilation mechanism draws water over the gills surface through the nose and mouth
5. Highly vascularised lungs. Air is drawn into them by a ventilation mechanism. They are found in all air breathing vertebrates. A tree like system of tubes which ramify from two bronchi terminate as sacs from where arise numerous alveoli and these have a very large surface area. The relationship between the alveoli and capillaries is a very intimate one because they both have a single layer of flattened epithelial cells.

The effect of size and surface area on gaseous exchange

A large organism like a mammal which has a low surface area to volume ratio has problems with gaseous exchange compared to smaller organisms like protozoa. This is because of the large diffusion distance.

The large multicellular organisms have had to develop means of bringing the external medium with which gases are exchanged nearer the cells hence the development of the respiratory system with specialized respiratory surfaces to solve the problem of surface area and a circulatory system with blood in most cases apart from insects to solve the problem of diffusion distance.

Ventilation is a special mechanism by which the flow of the medium into and out of organism is facilitated.

A table of respiratory medium and respiratory surface

Animal/organism	Respiratory medium	Respiratory organ	Respiratory surface
Amoeba	Water	None	Cell surface
Planarium (flat worms)	Water	None	Body surface
Insects	Air	Trachea	Tracheole
Fish	Water	Gills	Gill plate
Amphibian (tadpole)	Water	Gills	Gill filaments
Amphibian adults	Water	Skin	Epithelial skin surface
	Air	Buccal cavity	Epithelium of buccal cavity
	Air	Lungs	Alveoli
Reptiles, birds and mammals	Air	Lungs	alveoli

Comparison of water and air as a respiratory medium

Table comparing a sample of fresh air and water

N.B. apart from content all other units are arbitrary

	Air	Water
Density	1	1000
viscosity	1	100
Oxygen content	21%	0.8%
Diffusion rate	10,000	1

From the table one can tell that the problem facing an aquatic organism as far as gaseous exchange is concerned are;

- I. The content of oxygen in the water is low
- II. The diffusion rate of oxygen in the water is low
- III. The water viscosity is high
- IV. The water density is high

Adaptation of aquatic organisms to solve the above

- I. A high ventilation rate to bring the supplies of the respiratory medium to the surfaces at a faster rate.
- II. Use of counter flow mechanism by aquatic animals such as fish. This allows for greater oxygenation of blood. Other organisms use cilia and flagellum like flagellum and protozoans to facilitate diffusion.
- III. Water is moved over the gills in one direction
There is also an advantage of water as a respiratory medium. This is the fact that carbon dioxide dissolves easily in water and being a major respiratory waste product of organisms is easily gotten rid off.

Air breathing organisms have several advantages over those that exchange gases in water

- I. The content of oxygen in air is high
- II. The diffusion rate of oxygen in air is greater than in water
- III. The air has a less viscosity
- IV. The air has a low density

This is why air breathing organisms can grow very large sizes and are very active. The low density and low viscosity of air allow air to be moved in and out of the respiratory surface without energy expenditure and through the same pathway and so the animals use the back and forth system of ventilation.

There is also a disadvantage of air breathing and this is water loss accompanying the breathing

Questions for discussion

1. (a) i). Discuss the factors that affect the rate of diffusion at a respiratory surface.
ii). How are the conditions for efficient gaseous exchange fulfilled in mammalian lungs?
(b) The diameter of capillaries is smaller than the diameter of the red blood cells passing through them. How does this relationship help in gaseous exchange in the lungs?
c) What are the qualities of a respiratory surface?
2. (a) Outline the various kinds of respiratory surfaces in animals.
(b) Describe the sites of gaseous exchange in humans.
3. (a) i). Discuss the factors that affect the rate of diffusion at a respiratory surface.
ii). How are the conditions for efficient gaseous exchange fulfilled in mammalian lungs?

Table 1. Properties of air and water as gas exchange surfaces

	Air	Water
pO ₂	21.1	1.0
Stability of pO ₂	Stable with temperature changes	Decreases with increasing temperature
Diffusion rate (arbitrary units)	10 000	1
Gas exchange surface needs supporting	Yes	No
Oxygen dissolved	No	Yes
Density (arbitrary units)	1	777
Viscosity (arbitrary units)	1	100

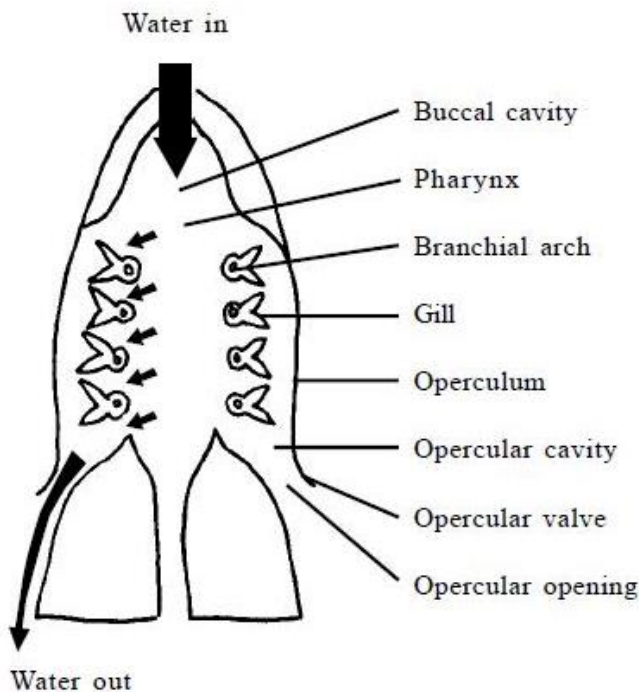
Gaseous exchange in a bony fish

Fish use water as a medium for gaseous exchange. Fish rely on specialised flaps of tissue called gills for gas exchange. Gills may be external or internal. External gills usually have a higher surface area but they are less protected.

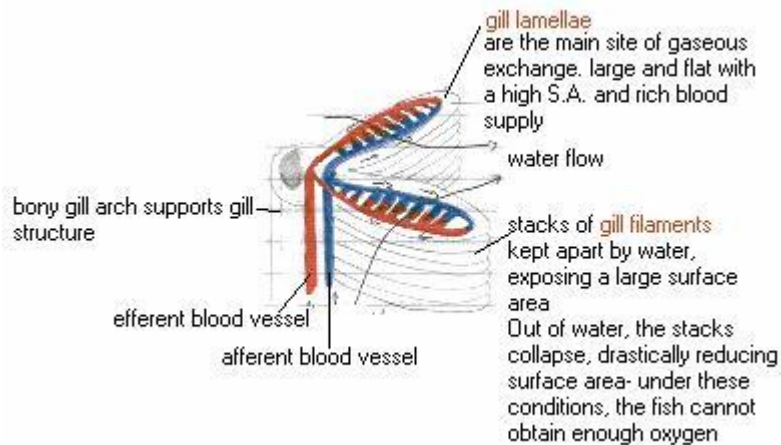
In bony fish the entire gill region is covered by a muscular flap of skin the operculum. This encloses an opercular cavity into which gills project. It protects the gills and plays a part in ventilation on the two sides of the gills are apart and point oblique outwards from the branchial arch. The bony fish has 8 branchial arches, 4 on each side of the pharynx.

The branchial bony arches separate five pairs of gill cleft and support the lamellae. Each gill on the arches is composed of two rows of fragile gill filaments arranged in the shape of V. the filament increase on the surface area by having a rich supply of capillaries.

Horizontal section through pharynx and gills



Transverse section through the gill



The general structure of a mature gill is composed of several parts:

- Gill rakers are cartilagenous or bony parts on the pharyngeal margin of the gill and function in preventing food particles from entering the gill chambers
- Gill rays are found within the interbranchial septa and provide support for the gill
- Gill filaments are the feather-like projections of the gills across which diffusion of gases occurs
- Gill filaments also possess gill lamellae, which are small crevices through which water passes for diffusion
 - lamellae are oriented parallel to the stream of water through the gills to maximize efficiency of diffusion
 - the blood flow through the gills opposes the flow of water through the lamellae (countercurrent flow) and maximizes the efficiency of diffusion - this is important because water has about 1/30th the oxygen concentration of air

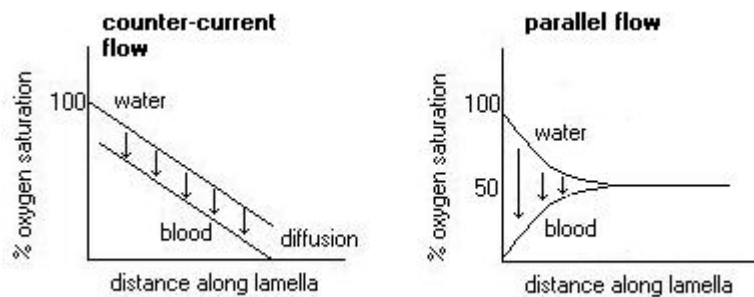
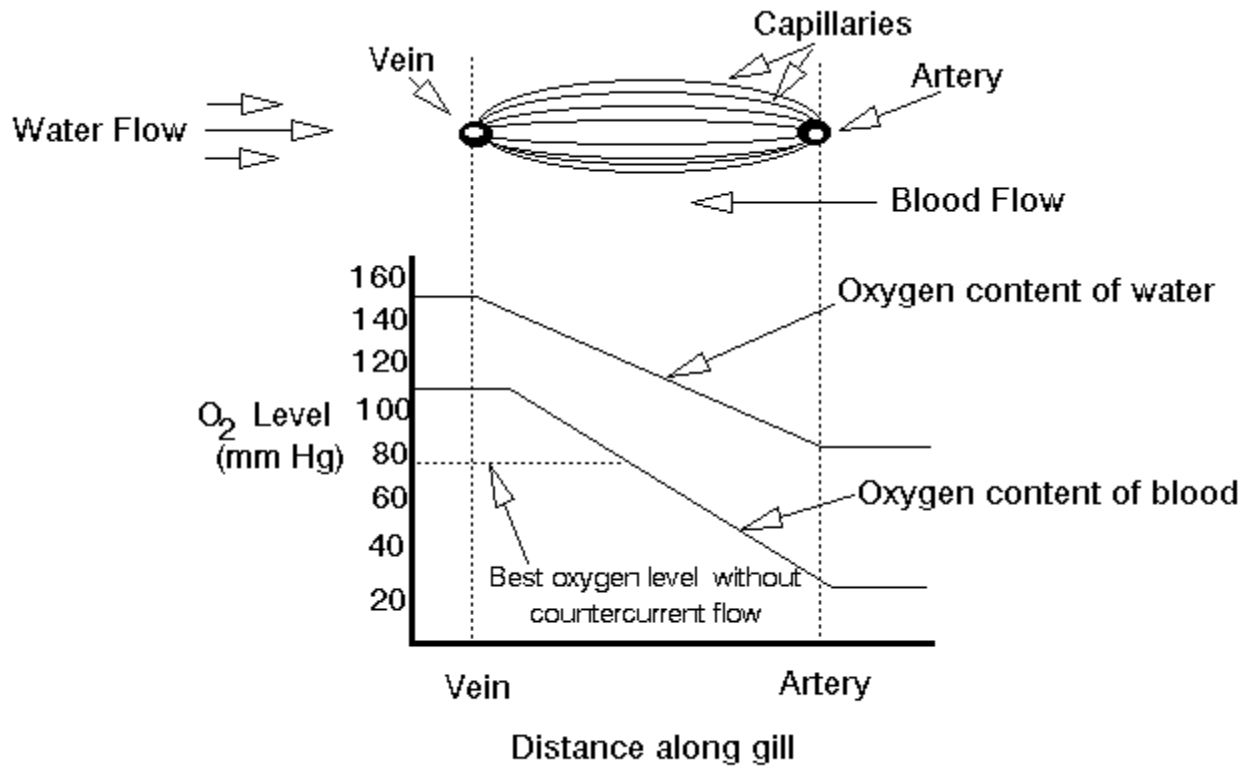
The deoxygenated blood enters the gill capillaries via the afferent branchial artery. Oxygenated blood leaves in the efferent branchial artery to join the dorsal aorta. The circulation of blood through each half gill is similar to the dog fish, but as the water pass from the pharynx into the opercular chamber, it flows between the gill plates in the direction opposite to the blood flow. The free ends of the adjacent gills touch each other to increase on the resistance to flow of water and thus the water passes between the lamellae as it flows from the pharynx to the opercular chamber and there is more time for the exchange of gases.

A single pair of opercular valves performs the function which in the dog fish (cartilaginous fish) is carried out by the five pairs of branchial valves.

The arrangement of gills with lamellae approximately at 90° to each other allows for a counter current exchange system for water and blood across the gill plates. This system is more efficient than that of cartilaginous fish.

Advantages of counter current flow exchange system.

In a counter current system a concentration gradient between the water and the blood is maintained along the gill. As a result higher saturation of blood with oxygen is possible and larger amount of carbon dioxide is removed.



In parallel system like in cartilaginous fish (sharks and rays) the blood in the gills travels in the same direction as the water is flowing. Therefore a steep concentration gradient between the two is only at the beginning. Diffusion takes place until the blood and water are in equilibrium, after this no net movement of oxygen into the blood or carbon dioxide of the blood occurs. As a result

blood leaves the gill plate less saturated than it have been under counter current flow. This is worse if both blood and water are flowing at the same speed. Some animals improve on the parallel system by increasing the speed of water over that of blood.

Ventilation of the gills

A ventilation mechanism operates in most fish which involves a muscular contraction which by adjusting presents in both the bucal cavity and opercular cavity cause water to move fast into the bucal cavity then through the valves of the opercular.

These muscular movement operate by changing the volume of the bucal cavity, pharynx , gill cavity and opercular cavity in that order.

As the volume of a chamber (cavity) decreases its pressure increases resulting in the squeezing of water to where the pressure is less.

These events are summarized on the graph below..... **Check in functional approach.**

During inspiration

1. Muscular contraction exerts in the floor of the pharynx and bucal cavity resulting in bucal cavity expanding. The bucal cavity pressure decreases. Mouth valve opens leading to opening of the mouth and water with dissolved oxygen enters from the outside because of reduced pressure.
2. At the same time the operculum bulges outwards leading to the opercular cavity expanding. The opercular cavity acquires a negative pressure i.e. pressure reduces therefore opercular valve closes.
3. The expansion of the opercular cavity leads to pressure falling below that of the bucal cavity which has began to contract as a result water is sucked into the opercular cavity from buccal cavity and flows over the gills where gaseous exchange takes place.

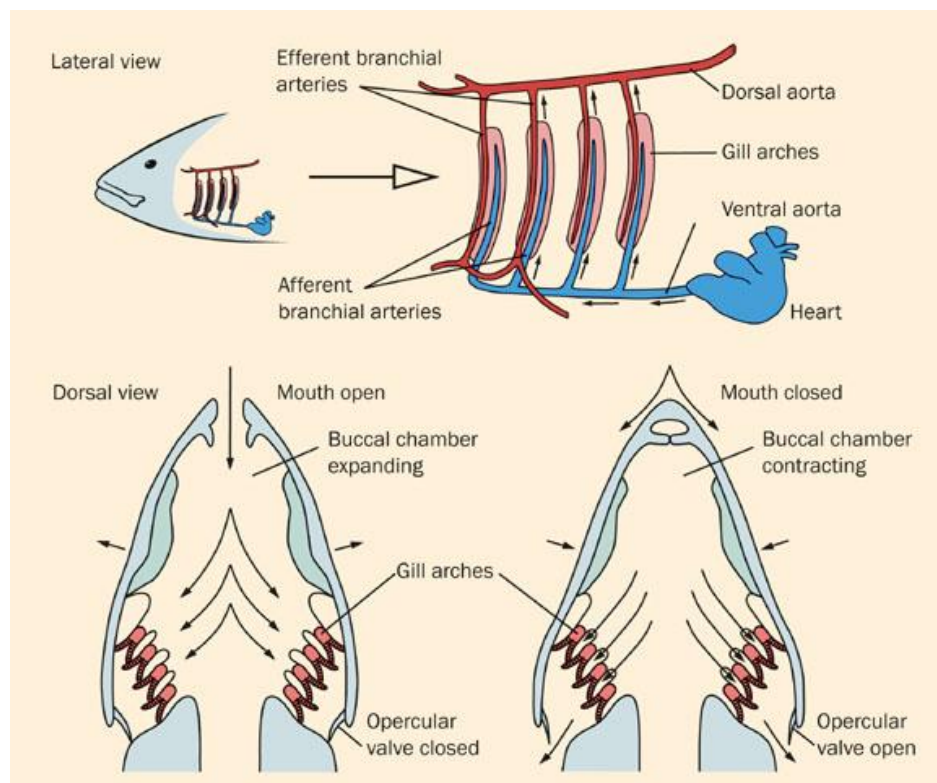
During inspiration

4. Muscular contraction leads to floor of pharynx raising and buccal cavity continuing to contract. The buccal cavity acquires positive pressure i.e. pressure increases, mouth valve closes and water is then forced from buccal cavity to opercular cavity.
5. There is inward movement of the operculum. The opercular cavity contracts and acquires a positive pressure, opercular valve opens and water containing carbon dioxide is expelled.

Note that the pressure in the buccal cavity is higher than that in the opercular cavity. Also a continuous stream of water is maintained over the gills throughout most of the breathing cycle by the combined action of the buccal cavity as a suction pump. Apart from the time when both the mouth and opercular valves are open, the pressure in the buccal cavity hence continuous flow of water from the buccal cavity to opercular cavity.

Gaseous exchange in cartilaginous fish.

Horizontal section through the pharynx and gill



Cartilaginous fish lack the opercular cavities but have parabronchial cavities enclosed by flap like branchial valves. The gills are supported by a series of skeletal branchial arches which are separated from one another by gill pouches through which water flows on its way over the respiratory surfaces. At the base of each gill, close to gill arch, is an afferent branchial artery which brings deoxygenated blood to the gill from the ventral aorta beneath the floor of the pharynx. The base also contains a pair of efferent branchial arteries, each derived from a loop vessel encircling the pouches on either side of the gill.

An epibranchial artery conveys blood from each efferent loop to the dorsal aorta above the roof of the pharynx.

Inspiration

Water with dissolved oxygen is drawn through the open mouth and spiracles into the pharynx which is expanded as a result of contraction of hypobranchial muscles and relaxation of transverse muscles. Then it is drawn into parabronchial cavities by outward movement of branchial valves. It flows over gills in a parallel system and gaseous exchange takes place.

This takes place as blood flows through the capillaries in the gill plates. The barrier between the blood and water is only several cells thick and offers little resistance to diffusion.

During expiration water containing carbon dioxide is expelled from the gill pouches by raising the floor of the mouth cavity and pharynx. This is brought about by relaxation of hypobranchial muscles, contraction of transverse muscles and mouth plus spiracles closed.

Comparison between gaseous exchange mechanism in a bony fish and cartilaginous fish

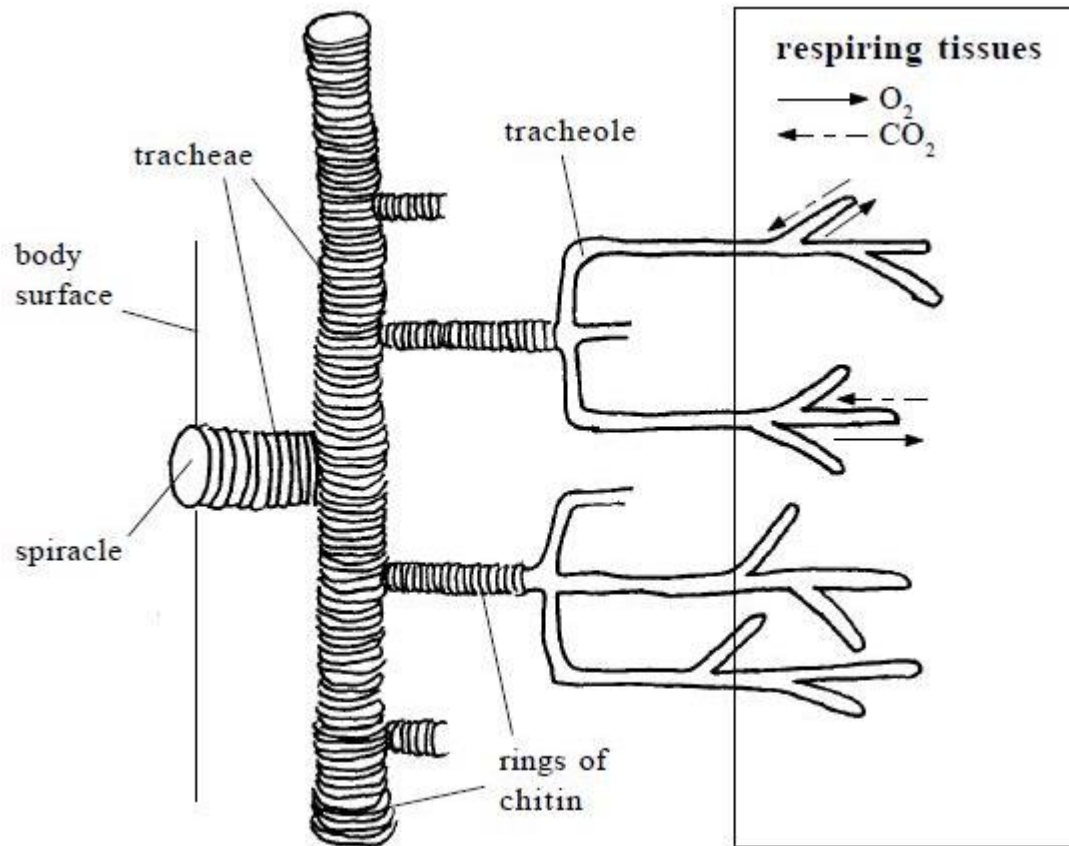
Similarities

1. The respiratory medium is water
2. Gills are the gas exchange organs and gas exchange occurs at the gill plates
3. Entry of water during inspiration is via the mouth
4. There is a ventilation mechanism ensuring continuous flow of water over the gills.

Differences

Cartilaginous fish	Bony fish
Ventilation is by adjustments in the buccal cavity and pharynx	Ventilation is by adjustment in the buccal pharyngeal and opercular cavities
During inspiration water enters through the spiracles and mouth	Water enters through the mouth only
During expiration exit of water is via gill slits enclosed by the branchial valves	During expiration exit of water is via the opercular valves
They employ a parallel flow mechanism between water and blood.	They employ a counter current flow mechanism between water and blood.

Gaseous exchange in insects



The hard exoskeleton of insects is unsuitable for gas exchange but their internal gas exchange surfaces differ significantly from those of mammals. The most significant difference is the lack of a transport system.

Gases diffuse passively through the spiracles, trachea and tracheoles directly to the tissues. Some species of insect produce rhythmical muscle contractions to assist the passive diffusion of gases. This is a type of ventilation.

Insects can control their rate of gas exchange. When respiration levels are high, the concentration of lactic acid in tissues increases. This sets up an osmotic pressure causing fluid to diffuse from the tracheoles into the tissues by osmosis. Gas exchange then occurs more rapidly because the gases can diffuse at a faster rate through a gaseous medium (the residual air in the tracheoles) rather than a liquid medium.

Oxygen penetrates all parts of the body of an insect by a branched network of tubes which form the tracheal system. Each trachea consists of a squamous epithelium which secretes a chitinous lining. To prevent the tubes from collapsing, they are strengthened by further spiral bands of chitin. The trachea diminish in size as they branch and they finally end in minute intracellular tracheoles which lack the chitinous lining. These tracheoles penetrate the tissues of the body and

ensure that each cell is supplied with oxygen. When the insect is not active, diffusion of oxygen through the spiracles suffices for its needs but when the insect is active e.g. during flight, special rhythmical movements of the thorax or abdomen takes place. This is due to the dorsal ventral muscle.

If the spiracles are open contraction of muscles will force air out e.g. in locust it takes place in the abdominal spiracles. If the spiracles are closed the contractions will force the air deep into the tracheoles.

The vast numbers of tiny tracheoles give a large surface area for gaseous exchange. The tracheoles containing a watery fluid towards the end of their length limits the penetration of gases for diffusion. However when oxygen demands build up e.g. when insect is flying, lactic acid accumulation in the tissues causes water to be withdrawn from the tracheoles by osmosis and expose additional surface area for gaseous exchange.

All the oxygen needed by the insects cells is supplied to them by the respiratory system, however upto 25% of the carbondioxide produced by the cells is lost directly throughout the whole cuticle.

The extent of respiration in most insects is controlled by the opening of the spiracles. There are respiratory centres in both the ganglia of the nerve cord and the brain. They are stimulated by increasing CO₂ levels and by lactic acid which builds up in the active tissues when there is lack of oxygen. A combination of lack of oxygen and carbondioxide build up work together to provide the insect with a flexible and responsive respiratory system.

Very active insects.

The type of respiratory system described so far works well for small insects and for large but slow ones. Those insects with more active lifestyles e.g. larger beetles locusts, grass hoppers, bees, wasps and flies have much higher energy demands. To supply the extra oxygen needed, alternative methods of increasing the level of gaseous exchange are used.

1. Some form of mechanical ventilation of tracheal system may be introduced i.e. air is actively pumped through the system. This is brought by the increased opening of the spiracles along with muscular pumping movement of the thorax and or abdomen.
2. Some active insects have collapsed trachea or air sacs which act as air reservoirs and are used to increase the amount of air moved through the respiratory system. They are usually inflated and deflated by the ventilation movements of the thorax and abdomen e.g. locusts.

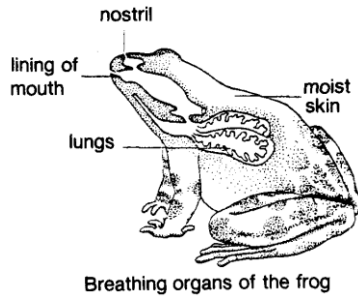
Gaseous exchange in lung fish

These belong to the order Dipnoi and an example is *Protopterus anthiopiann*. They have two lungs and these organs are used for exchange of gases directly with air when the fish is aestivating during dry season. These fish can also use gills when there is enough water.

Gaseous exchange in amphibians

Tadpoles use gills. Adults have three different respiratory surfaces i.e.

1. The skin
2. Buccal cavity
3. **Lungs**



The skin (cutaneous) gaseous exchange

The skin is adapted for gaseous exchange in the following ways

1. It is thin, thus reducing the distance across which diffusion of gases occurs, so increasing the rate of diffusion.
2. It is kept moist always by secretion of watery mucus from simple saccular glands in the dermis. This quickens the
3. dissolution of air into the skin and therefore diffusion of carbon dioxide out of blood and oxygen into.
4. It has a dense network of blood vessels supplied by blood from the cutaneous artery. This ensures more gases are absorbed and immediately carried which create and maintains a diffusion gradient between the air and blood and this favours diffusion of gases.

NB. (i) cutaneous gaseous exchange is operational in toads when in water and when they are hibernating but frogs use it mostly because the toads skin is less moist than a frogs skin.

(ii) cutaneous gas exchange system is more efficient at removing carbon dioxide than the lungs because CO_2 dissolves more easily in water.

Buccal gaseous exchange

There is a thin epithelium lining the buccal cavity and is kept moist so the exchange of CO_2 and O_2 occurs here. A ventilation mechanism operates by which the air content of the buccal cavity is changed frequently.

Inspiration

There is lowering of the floor of the buccal cavity brought about by the contraction of sternohyoid muscles which stretch from the hyoid body to the pectoral girdle. This happens when the nares (nostrils) are open and mouth and glottis closed. This forces air through nasal passages from out into the buccal cavity. The inhaled air dissolves in the lining of the buccal cavity which is thin and moist allowing oxygen into and CO_2 out of the blood.

Expiration

There is raising of the floor of the buccal cavity brought about by the contraction of the petrohyoid muscles which extend from the hyoid body to the auditory capsule. This happens when the nares are open, mouth and glottis closed. This results in increase in pressure in buccal cavity and decrease in volume. Air is then forced out through the nostrils.

Buccal cavity gaseous exchange is only important on land.

Pulmonary gaseous exchange

It involves the buccal cavity and the lungs. It is used less frequently but can be used during and activity. It is only used when the amphibian is on land.

Inspiration

This involves the buccal cavity being filled with air as described under buccal respiration.

Nostrils are closed as the glottis open

Contraction of the pterohyoid muscles raises the floor of the mouth. This results in air increase in the pressure of the buccal cavity. It also forces air into the lungs because the mouth and nostrils are closed. When the lungs are full, glottis closes and air is trapped.

Gaseous exchange occurs across the epithelial lining of the lungs when O_2 diffuses in and CO_2 diffuses out of the blood. The lungs are highly vascularised and this ensures

that oxygen is carried away and CO₂ is brought in maintaining a steep concentration gradient for both gases.

Expiration

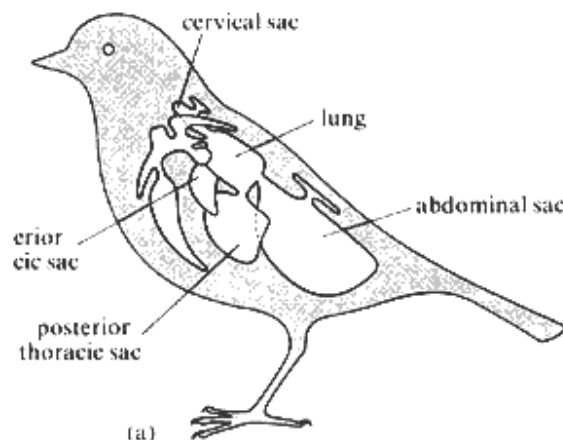
The nostrils are closed, the glottis opened and the floor of the mouth lowered by the contraction of the sternohyoid muscles. When the pressure is lowered in the buccal cavity the air is sucked in from the lungs. The lungs tend to recoil and partially aid expiration.

The nostrils then open, the glottis closes and the floor of buccal cavity is raised. This forces the air out.

Birds

Birds lungs do not have alveoli and are extensible. They have air sacs some of which extend into the bones. There is no gaseous exchange in the air sacs but their presence improves greatly the rate of ventilation, they also offer lightness to the bird.

Respiratory system of a bird



Inspiration

There is lowering of the sternum, expansion of the chest and lungs. The lungs diminish in volume and air is expelled from the lungs into the air sacs.

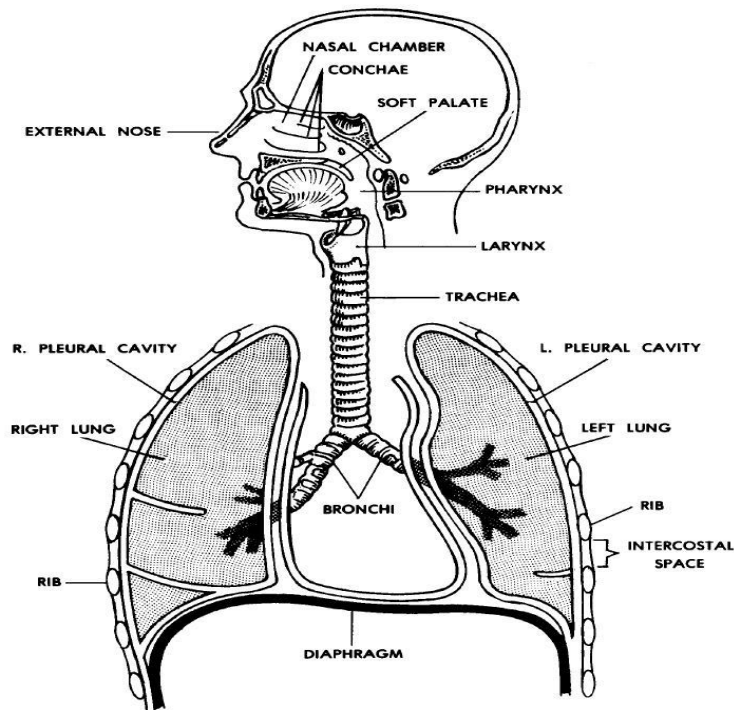
Expiration

There is raising of the sternum, contraction of abdominal air sacs and then the air is sent into the bronchi and then the capillary bronchioles in the lungs and then outside the body.

Gaseous exchange in mammals such as man

Respiratory tract and associated structures (functional approach page 113)

Human Breathing System(check in the textbook as well)



In mammals the gas exchange surfaces are the **lungs**, which develop in the embryo from the gut wall - which relates us to some fossil fish! The **larynx** is formed from **cartilage** which formed the gills of our fossil ancestors. It is connected to the **trachea** - a flexible tube held open at all times by incomplete rings of cartilage. The trachea divides into the left and right **bronchi** which then enter the lungs and continue to divide forming the narrower **bronchioles**, which are surrounded by circular smooth muscle fibres. At the ends of the bronchioles are groups of **alveoli** or **air-sacs**.

It is in the alveoli that gas exchange actually occurs.

The lungs have the typical features required by an efficient gas exchange system:

- a **large surface area** provided by millions of alveoli present;
- a **short diffusion pathway** (only two layers of cells from the alveolar air to the blood to reduce on the distance of gases diffusing);
- **high concentration gradients** (maintained by ventilation and flow of blood in the capillaries);
- the moist surface of the alveoli allow gases to dissolve and then diffuse through the cells.

The actual respiratory surface is the walls of the **alveoli** inside the lungs:

1. An average adult has about 600 million alveoli, giving a total surface area of about 100m², so the area is huge.

2. The walls of the alveoli are composed of a single layer of flattened **epithelial cells**, as are the walls of the capillaries, so **gases need to diffuse through just two thin cells**.
3. The alveoli walls are kept moist by water diffusing from the surrounding cells. **Oxygen dissolves in this water** before diffusing through the cells into the plasma, where it is taken up by haemoglobin in the red blood cells. The water also contains a soapy **surfactant** which reduces its surface tension and stops the alveoli collapsing. The alveoli also contain phagocytes to kill any bacteria that have not been trapped by the mucus.
4. The steep concentration gradient across the alveoli wall is maintained in two ways: by blood flow on one side and by air flow on the other side. This means that **oxygen can diffuse down its concentration gradient** from the air to the blood, while at the same time **carbon dioxide can diffuse down its concentration gradient** from the blood to the air.

The flow of air in and out of the alveoli is called **ventilation** and has two stages:

inspiration (or inhalation) and

expiration (or exhalation).

Lungs are not muscular and cannot ventilate themselves, but instead the whole **thorax** moves and changes size, due to the action of two sets of muscles: the **intercostal muscles** and the **diaphragm**.

Inspiration

- The diaphragm contracts and flattens downwards
- The external intercostal muscles contract, pulling the ribs up and out
- this increases the volume of the thorax
- this increases the lung and alveoli volume
- this decreases the pressure of air in the alveoli below atmospheric (Boyle's law)
- air flows in to equalise the pressure

Normal expiration

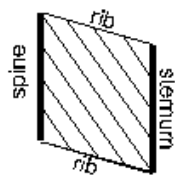
- The diaphragm relaxes and curves upwards
- The external intercostal muscles relax, allowing the ribs to fall
- this decreases the volume of the thorax
- this decreases the lung and alveoli volume
- this increases the pressure of air in the alveoli above atmospheric (Boyle's law)
- air flows out to equalise the pressure

Forced expiration

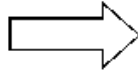
- The abdominal muscles contract, pushing the diaphragm upwards
- The internal intercostal muscles contract, pulling the ribs downward
- This gives a larger and faster expiration, used in exercise

These movements are transmitted to the lungs via the pleural sac surrounding each lung. The outer membrane is attached to the thorax and the inner membrane is attached to the lungs. Between the membranes is the pleural fluid, which is incompressible, so if the thorax moves, the lungs move too. The alveoli are elastic and collapse if not held stretched by the thorax (as happens in stab wounds).

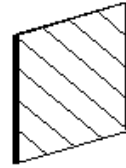
Inspiration



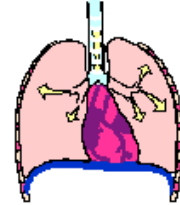
external intercostal muscles relaxed



external intercostal muscles contract

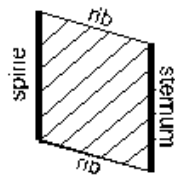


ribs raised - thorax volume increases

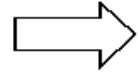


pressure decreases, so air drawn in

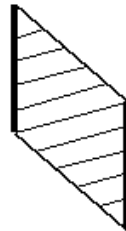
Forced Expiration



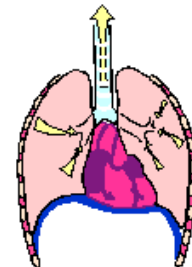
• internal intercostal muscles relaxed



internal intercostal muscles contract



ribs lowered- thorax volume decreases



pressure increases, so air forced out