



Gas Exchange in Animals

All living organisms respire. They need to do this so that energy can be transformed into a form that cells can use. In aerobic respiration, oxygen is used by cells and carbon dioxide is a waste product. In anaerobic respiration, although oxygen is not used, carbon dioxide is still a waste product. Gas exchange is the diffusion (passive movement) of these gases into and out of cells and it is essential for respiration to take place.

For gas exchange to occur efficiently, organisms require:

- a **large surface area** over which gas exchange may take place rapidly
- a **concentration gradient** down which gases may diffuse
- a **thin surface** across which gases may diffuse rapidly
- a **moist surface** on which gases may dissolve and diffuse into and out of cells

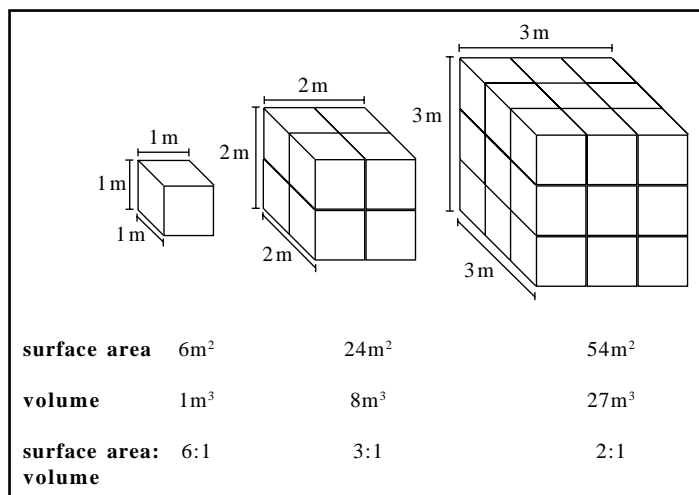
Such surfaces are called **gas exchange surfaces**.

This Factsheet will discuss how living organisms achieve gas exchange and each of the examples given will make reference to the four points above.

Unicellular organisms

The gas exchange surface of unicellular (single-celled) organisms is the cell surface membrane. Although this is not a specialised gas exchange surface (as in the case of many multicellular organisms) it achieves efficient gas exchange because it has a large surface area to volume ratio. Fig 1 demonstrates how the surface area to volume ratio of a cube decreases as its volume increases. The same is true of living organisms. The small size of unicellular organisms means that they have a large surface area over which gas exchange may take place. In other words, the smaller the organism, the greater its surface area to volume ratio and the greater the efficiency of diffusion of gases through the outer cell surface membrane.

Fig 1. Surface area to volume ratios of differently sized cubes



The build up of carbon dioxide inside a respiring unicellular organism sets up a concentration gradient so that the gas diffuses out of the cell. If the organism respire anaerobically then oxygen diffuses down a concentration gradient into the cell as the oxygen is used up.

The cell surface membrane of unicellular organisms is thin ensuring rapid gas exchange and it is moist to allow gases to dissolve.

Multicellular organisms

Most multicellular organisms respire aerobically. This is because the energy requirements of multicellular organisms tends to be great and aerobic respiration provides nineteen times more ATP (Adenosine triphosphate) per molecule of glucose respired than anaerobic respiration. Multicellular organisms therefore require an efficient supply of oxygen so that their energy needs can be met.

To achieve efficient gas exchange, multicellular organisms have large gas exchange surfaces. In small multicellular organisms the outer surface of their bodies is usually sufficient. Larger multicellular organisms require specialised surfaces such as lungs or gills.

Maintaining a concentration gradient for gases is a problem that large organisms face because diffusion becomes less efficient over larger distances. Transport systems (e.g. circulatory systems) are needed to ensure that dissolved gases can move to and from respiring tissues rapidly.

Terrestrial (land-living) organisms often have internal gas exchange surfaces to reduce evaporation losses. The following examples illustrate some of the gas exchange surfaces of animals.

Animals without specialised gas exchange surfaces

Many small terrestrial animals use their outer body surfaces efficiently for gas exchange. The earthworm, *Lumbricus terrestris*, achieves this with:

- an elongated body to increase surface area to volume ratio
- a primitive circulatory system to maintain a concentration gradient
- a moist outer body surface

The outer body surface of the earthworm is supplied with a dense capillary network, which join up to form contractile blood vessels. The earthworm does not contain a heart but the circulatory system transports oxygen to and carbon dioxide away from respiring tissues, thereby increasing the efficiency of diffusion.

Animals with specialised gas exchange surfaces

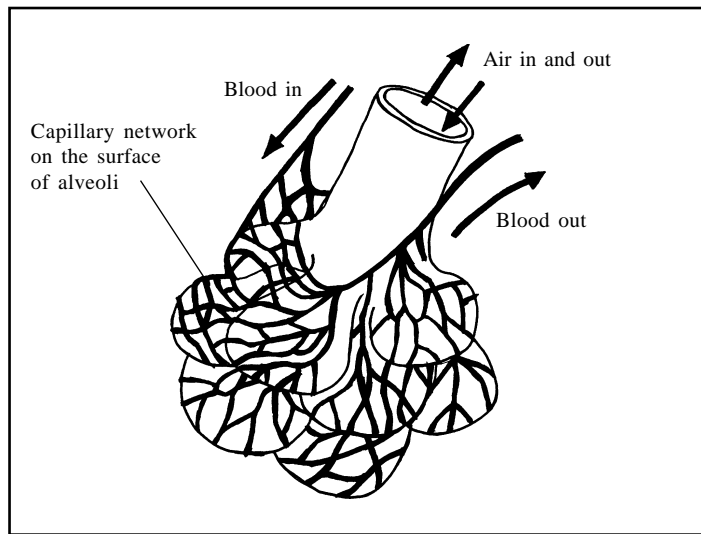
Mammals

Mammals are examples of large terrestrial animals. They do not rely on their outer body surface for gas exchange but have specialised internal gas exchange surfaces, called lungs, which have the following features:

- a large surface area due to numerous air sacs called alveoli
- a highly developed circulatory system
- a short distance between alveoli and the circulatory system ensuring rapid diffusion across the gas exchange surface
- the surface of the alveoli is covered by a thin layer of fluid

Fig 2 shows a diagram of a human alveolus. Note the numerous capillaries and their close proximity to the gas exchange surface.

Fig 2. The alveoli



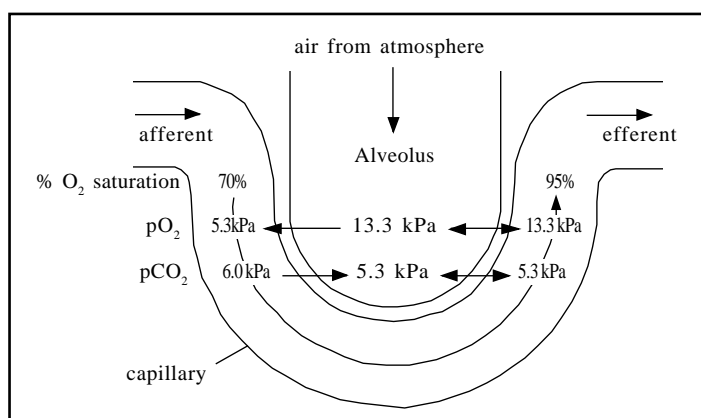
The concentration gradients of carbon dioxide and oxygen in the alveoli are maintained by the highly efficient blood transport of the capillaries surrounding each alveolus and by **ventilation** (breathing), which ensures that air moves in and out of the lungs regularly. Diffusion becomes less efficient over larger distances, so the transport system prevents the build up of carbon dioxide or oxygen, thus maintaining the necessary concentration gradient. Red blood cells contain the protein haemoglobin, which associates strongly with oxygen and carbon dioxide providing greater efficiency.

The partial pressures of oxygen (pO_2) and carbon dioxide (pCO_2) at the gas exchange surface, show how the concentration gradient is established (Fig 3).

Partial pressure is a way of expressing the concentration of a gas and is measured in kilopascals (KPa).

e.g. Oxygen represents about 21% of the atmosphere.
 The total pressure of the atmosphere is 101.3KPa.
 The partial pressure of oxygen (pO_2) is therefore 21% of 101.3KPa, which is 21.2KPa.

Fig 3. The partial pressures of oxygen and carbon dioxide in the alveoli



Oxygen inside the lungs has a partial pressure (pO_2) of 13.3KPa. This is less than the pO_2 in the atmosphere because the inhaled air has mixed with the air already in the lung (residual air) which has a lower pO_2 . Blood in capillaries travelling towards the alveoli (afferent capillaries) has a pO_2 of about 5.3kPa. There is therefore a concentration gradient between the oxygen in the alveoli and oxygen in the capillaries and oxygen diffuses into the capillary. The blood travelling away from the alveoli (efferent capillary) has a pO_2 of 13.3KPa, thus equilibrating with oxygen inside the alveolus.

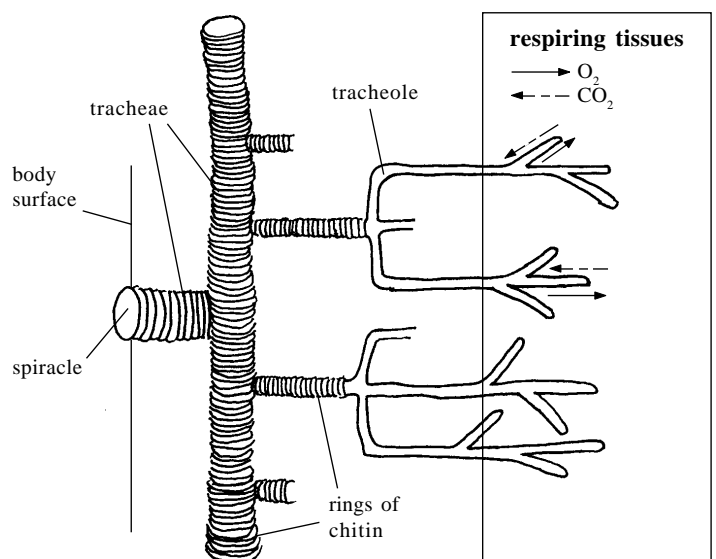
The converse is true of carbon dioxide. The pCO_2 in afferent capillaries is 6.0kPa, which is higher than the pCO_2 inside the alveoli because the blood is carrying carbon dioxide produced by respiring tissues. A concentration gradient is set up so that carbon dioxide diffuses into the alveolus. The efferent capillary has a pCO_2 of 5.3kPa (the same as the pCO_2 of the alveolus). Therefore, the carbon dioxide inside the capillary and alveolus have also reached equilibrium.

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.

Fig 4 shows a diagram of the insect's gas exchange surface. Note that the tracheoles join up to trachea. The trachea lead to the outside via pores on the insect's outer body surface (spiracles).

Fig 4. The insect tracheal system



The main features of insect gas exchange are:

- a large surface area achieved by an extensive network of tubes (tracheoles) which penetrate deep into tissues
- small bodies which enable gases to get in and out of tissues by diffusion alone, in some cases aided by rhythmical body movements
- thin, fluid filled tracheoles which allow gases to dissolve and diffuse into tissues efficiently

The extensive network of tracheoles in the gas exchange system of the insect resembles the mammalian circulation 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.

Fish

Fish use water as a gas exchange medium instead of air. The properties of both media are summarised in Table 1.

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

Fish rely on specialised flaps of tissue called gills for gas exchange. Gills may be external or internal (see Fig 5). External gills usually have a higher surface area but they are less protected.

Fig 5. Schematic diagrams of internal and external gills



The gas exchange surface of fish has the following features:

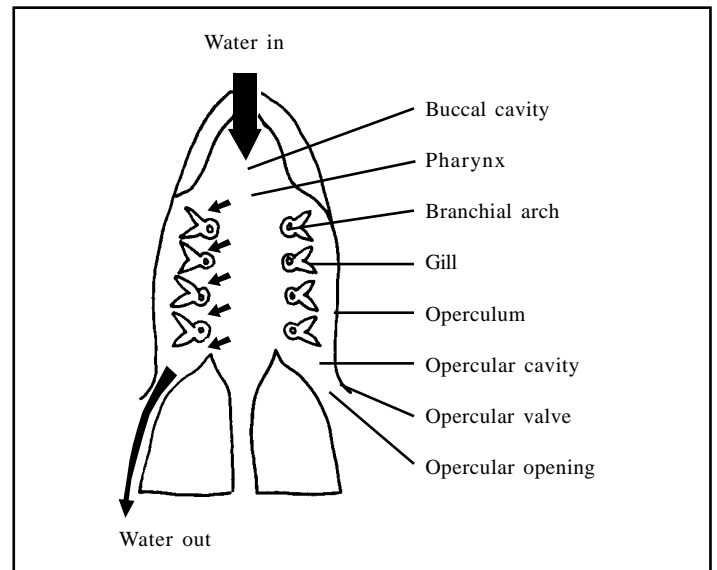
- gills have numerous folds which give rise to a large surface area
- the concentration gradient is achieved by an efficient circulatory system

Ventilation of gills

External gills receive oxygen passively from the surrounding water. Internal gills however, are protected by an operculum (Fig 6) and therefore need to be actively ventilated. The fish takes water in through its buccal cavity which then flows through the pharynx and past the gill plates, leaving via the opercular openings on each side of the fishes head.

Internal gills are ventilated as shown in Fig 6:

Fig 6. Ventilation of internal gills



Parallel and counterflow mechanisms of gas exchange

Water which comes in contact with the gills may flow in the same direction as blood in the gill capillaries - parallel flow, or it may flow in the opposite direction - counterflow.

In the parallel flow mechanism, the pO₂ of the blood in the efferent capillaries is about 50% of that of the water entering the buccal cavity of the fish. In other words, the pO₂ of the blood and the water leaving the gills are the same and there is no longer a concentration gradient.

In the counterflow mechanism, the pO₂ of the blood in the efferent capillaries is nearly 100% of that of the water entering the buccal cavity of the fish. This mechanism therefore maintains a concentration gradient between the water and the blood in the capillaries even when the blood is highly saturated with oxygen.

The counterflow mechanism is much more efficient because it ensures that there is always a diffusion gradient between the water which is flowing through the gill lamellae and the blood in the lamellae. As blood flows through the gill lamellae, it therefore absorbs more and more oxygen until the pO₂ of the blood is almost the same as the pO₂ of the incoming water. By the time the water leaves the gills it has lost almost all of its oxygen to the blood. This mechanism therefore results in the pO₂ of the water exceeding the pO₂ of the blood across the entire gill plate and this ensures that a concentration gradient is maintained. Fig 7 shows the oxygen saturation of the blood and water across the gill plate in both the parallel flow and counterflow mechanisms.

Fig 7. Parallel and counterflow mechanisms of ventilation in fish

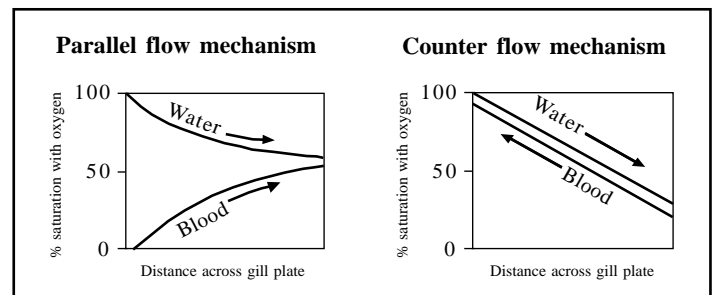


Table 2. Summary of gas exchange surfaces

Size of organism	Example	Gas exchange surface	Mechanism of gas exchange
Unicellular	Amoeba	Outer cell surface	Diffusion
Multicellular	Earthworm	Outer body surface	Diffusion
Multicellular	Mammal	Alveoli	Diffusion, ventilation and circulatory system
Multicellular	Insect	Junctions between tracheoles and respiring tissues	Diffusion (and ventilation in some species)
Multicellular	Fish	Gills	Diffusion ventilation and circulatory system

Practice Questions

- Very small organisms such as the amoeba do not have specialised gas exchange systems. Mammals are large, multicellular organisms and have a complex gas exchange system. Explain why the mammal needs such a system when the amoeba does not. (4 marks)
- Bony fish rely on gills for gas exchange.
 - Why does the highly folded structure of the gills increase the efficiency of gas exchange? (2 marks)
 - Explain how the counterflow mechanism works in bony fish. (3 marks)
 - Suggest why gill lamellae would not provide an efficient gas exchange surface on land. (2 marks)
- Name two similarities and two differences between the gas exchange of an insect and that of a mammal. (4 marks)

- Similarities:
 large surface area;
 moist gas exchange surface;
 thin gas exchange surface;
 concentration gradient achieved by ventilation (in some species of insects);

- Differences:
 Transport (circulatory) system in mammals but not in insects;
 the respiratory surface in mammals is the alveoli, in insects it is the junction between the tracheoles and the respiring tissues;

Answers

Semicolons indicate marking points.

- The amoeba has a large surface area to volume ratio/and a short diffusion pathway to all parts of the organism;
 therefore diffusion is efficient;

The mammals have a small surface area to volume ratio, a long diffusion pathway and they have skin which is waterproof and gastight;
 they need an internalised system so that the gas exchange surface can be kept moist/the folded surface of the lungs provides a large surface area;

- Increases surface area;
 over which diffusion may take place;
 - The blood flows in the opposite direction to the water across the gills;
 as a result, highly oxygenated water comes into contact with poorly oxygenated blood;
 this maintains (an oxygen) concentration gradient across the whole of the gill plate/maximises diffusion;
 - The gills may dry out;
 thus preventing oxygen dissolving on the surface of the gills;
 they are no longer supported by water/folds may stick together with surface tension/not open as easily;

Acknowledgements;

This Factsheet was researched and written by James Barratt

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