Chapter 6

Breathing oxygenates the blood to allow food to be respired

This chapter covers:

- the structure of the human gas exchange system
- the mechanism of breathing
- gas exchange in the alveoli
  - the concept of partial pressure
  - the difference in composition of atmospheric and exhaled air

Breathing is necessary for gas exchange and energy release. On inhalation, atmospheric air (a mixture of gases) flows into the alveoli in the lungs. Here, gas exchange takes place and a different mixture of gases is exhaled. The main differences in composition between inhaled and exhaled air are due to the exchange of oxygen and carbon dioxide in the alveoli. The oxygen absorbed into the red blood cells is transported to all living cells to allow the release of energy from organic molecules obtained from food in aerobic respiration. The carbon dioxide produced by this process is carried in the blood plasma to the lungs, to be exhaled. The structure of the human gas exchange system is shown in Figure 6.1.

◀ Do not confuse breathing, gas exchange and respiration. Breathing is the movement of air into and out of the lungs. Gas exchange is the diffusion of oxygen and carbon dioxide across the alveolus and capillary walls in the lungs. Respiration is the biochemical process that occurs in all living cells to release energy from organic molecules (usually glucose).

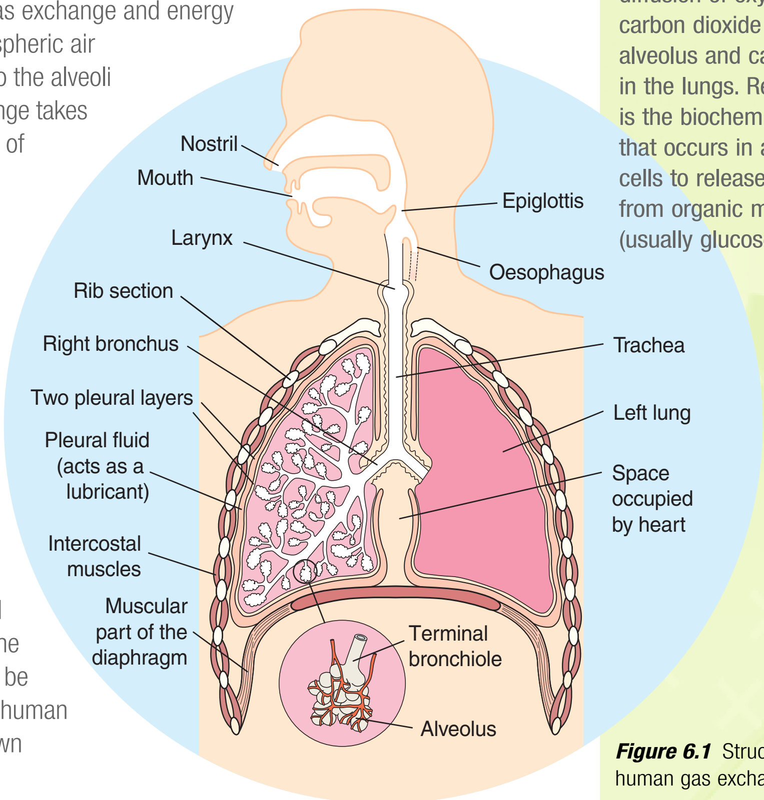


Figure 6.1 Structure of the human gas exchange system

How do we breathe?

The breathing system moves inhaled air through the various passages into the alveoli, where gas exchange takes place. The air in the alveoli is then exhaled. Air is a mixture of gases and, like any gas, it moves because of pressure differences. Gases move from a region of high pressure to a region of low pressure. To move air in both directions, the relationship between the pressure in the lungs and the pressure in the atmosphere must change.

When you turn on a gas tap to light a Bunsen burner, gas flows from the region of high pressure in the gas pipe to the lower pressure area in the Bunsen tubing.

To bring air into the lungs (**inhalation**), the pressure must be lower in the lungs than in the atmosphere. To move air out again (**exhalation**), the pressure must be higher in the lungs than in the atmosphere. Breathing movements create these pressure differences.

Breathing movements alter the pressure between the lungs and the pleural layers that surround the lungs.

The lungs are located in the **thorax**. This region of the body is separated from the **abdomen** by the **diaphragm**. Viewed from above (or below), the diaphragm is seen to have two main regions:

- an external muscular region, the outer edge of which is attached to the body wall
- a central fibrous region, made from tough connective tissue, which cannot contract or relax, be stretched or be compressed

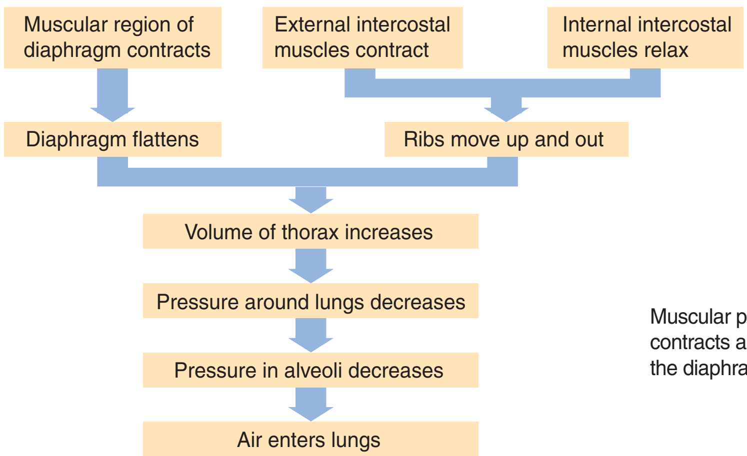
Contraction of the muscular region of the diaphragm pulls the fibrous region downwards from its normal dome-shaped position. This flattens the diaphragm and enlarges the thoracic cavity.

The lungs are protected by the ribcage. There are two sets of muscles between each pair of ribs — the **external intercostal muscles** and the **internal intercostal muscles**. These muscles are attached in different ways. Therefore, their contractions produce different effects. Contraction of the external intercostal muscles lifts the ribs upwards and outwards; contraction of the internal intercostals muscles pull the ribs downwards and inwards.

In humans, the internal intercostal muscles play little part in breathing movements at rest. We stand upright on two legs, so once the external intercostal muscles stop contracting, the ribs fall back downwards and inwards under gravity. In four-legged mammals both sets of muscles are equally important because gravity neither assists nor hinders breathing movements.

Inhalation

The mechanism of inhalation is shown in the flowchart below:



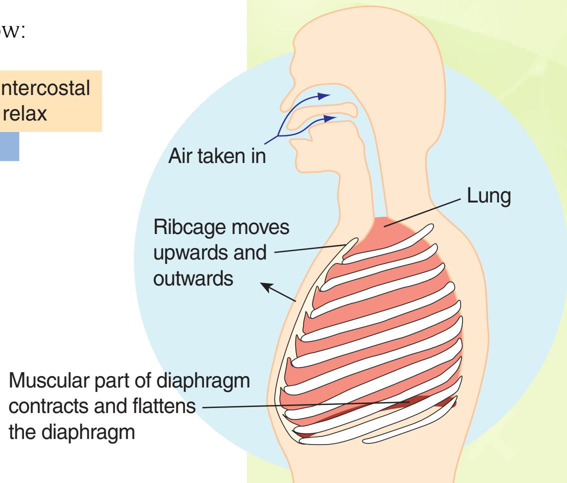
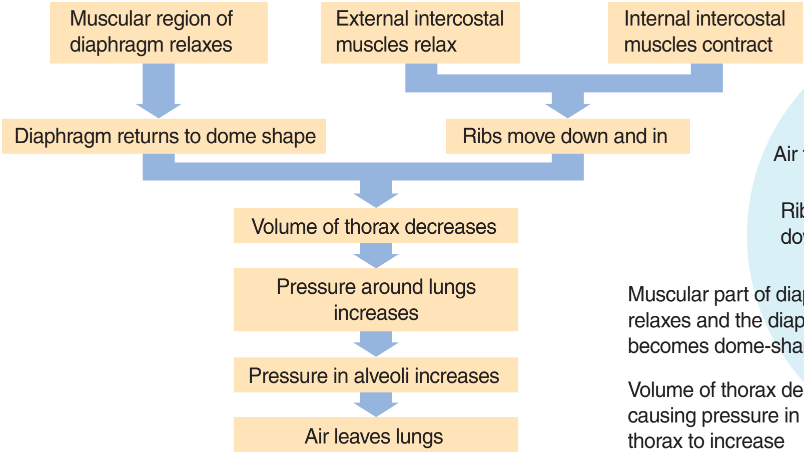


Figure 6.2 Inhalation

Exhalation

The mechanism of exhalation is shown in the flowchart below:



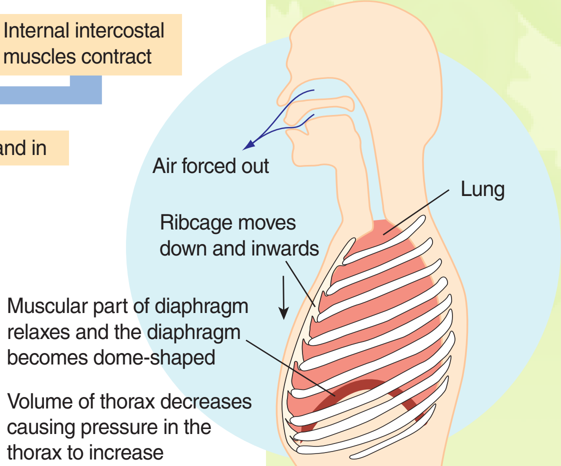


Figure 6.3 Exhalation

What happens in the alveoli?

Moving air into the alveoli

Breathing movements move air in and out of the lungs through the airways that eventually lead to the alveoli. Air is drawn into the nose and/or mouth, through the pharynx (throat), down the trachea and along a bronchus into each lung. From here it passes along ever-finer bronchi and bronchioles until it reaches a terminal bronchiole, which leads to several alveoli via alveolar ducts.

The function of the airways is to allow the passage of air into and out of the alveoli, where gas exchange takes place.

The relationship between the terminal bronchiole, alveoli and capillaries is illustrated in Figure 6.4.

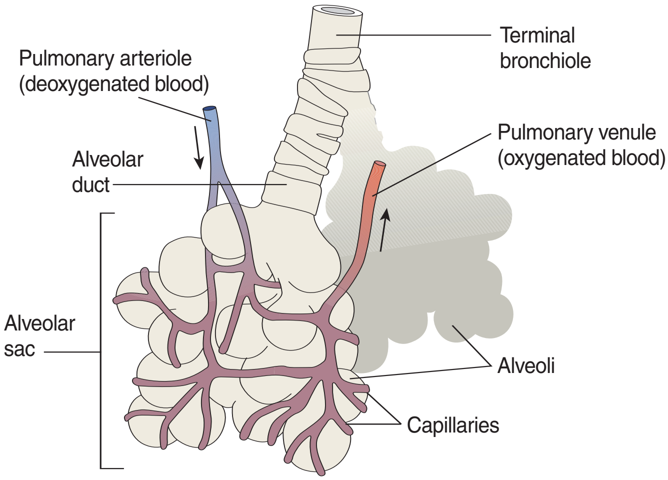
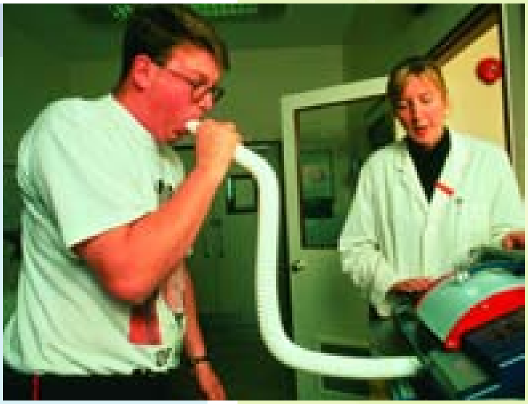


Figure 6.4 Alveoli are found at the end of terminal bronchioles

Box 6.1 Monitoring breathing movements

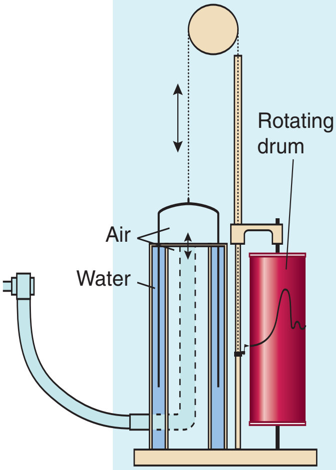
The rate and depth of breathing movements can be monitored using a spirometer. The way that a spirometer works is shown in the diagram below.



James King-Holmes/SPL

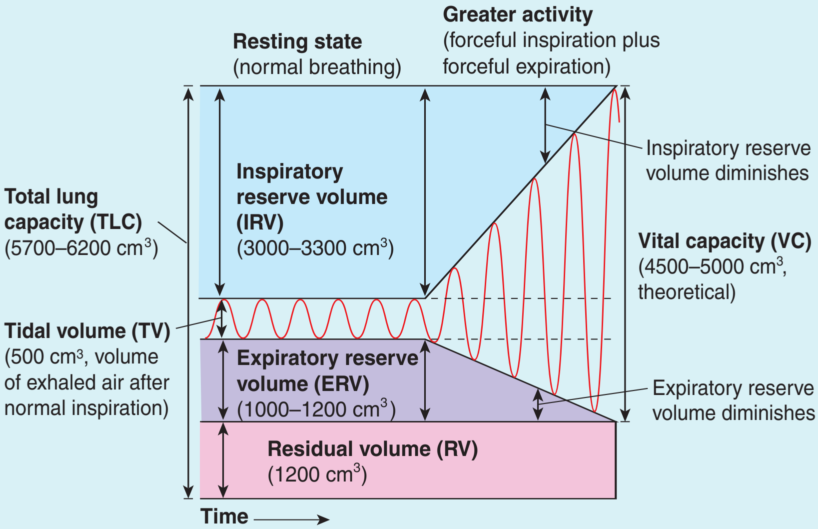
A simple spirometer linked to a computerised recording system

When the subject breathes, pressure changes in the air in the spirometer produce movements of a recording pen. This produces a trace on a drum revolving at constant speed. The trace that is produced is called a spirogram. It shows both the depth and the rate of breathing movements. The spirogram below shows the breathing movements of a person initially at rest and then becoming more active.



At rest, we inhale around 500 cm^3 of air with each breath and exhale the same amount. This is known as the tidal volume. We could inhale more — we can all *choose* to inhale deeply. This extra potential to inhale is called the inspiratory reserve volume — about 3000 cm^3 in an average adult. Similarly, without inhaling any more deeply, we can decide to exhale more forcefully. This extra exhalation is the expiratory reserve volume — about 1000 cm^3 in an average adult. So, over and above the tidal volume, there is room for another 3000 cm^3 air and an extra 1000 cm^3 can be forced out. Therefore, the total amount of air that can be brought in and out of the lungs when breathing as forcefully as possible is about 4500 cm^3. This is the vital capacity. However, we can never completely empty our lungs of air. The air left after the most forceful exhalation is the residual volume — about 1200 cm^3.

total lung capacity = vital capacity + residual volume = 5700 cm^3



As a consequence of being surrounded by blood, alveoli are lined with fluid. This fluid contains a surfactant that is produced and secreted by specialised epithelial cells in the wall of each alveolus (Figure 6.5). The surfactant reduces the surface tension of the fluid, which prevents the walls of the alveoli from collapsing and sticking shut during breathing.

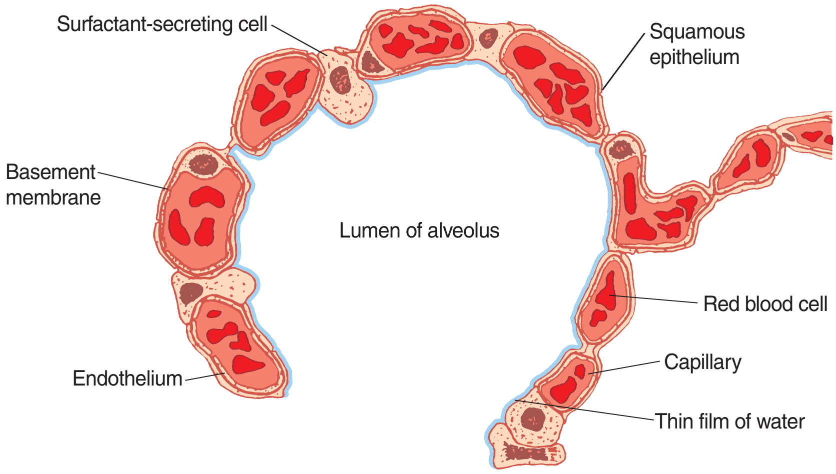


Figure 6.5 Section through an alveolus

What is the partial pressure of a gas?

The pressure exerted by the air is caused by molecules of the gases that make up the air colliding with, and exerting a force on, the surface of an object. The molecules of the various gases produce an almost identical force when they collide with the surface. So the total atmospheric pressure is the sum of the pressures caused by the molecules of all the different gases that make up the air. As 78% of the molecules in the air are nitrogen molecules, they account for 78% of the total pressure — this is the **partial pressure** of nitrogen. Twenty-one per cent of the air is oxygen, so oxygen accounts for 21% of the total pressure. Other gases (including carbon dioxide and water vapour) account for the remaining 1%. The partial pressure of oxygen is written as pO_2 and that of carbon dioxide as pCO_2. At sea level, atmospheric pressure (the sum of the partial pressures of all the gases in the atmosphere) is 100 kPa. Therefore, the partial pressure of oxygen is 21 kPa (21% of 100 kPa).

When you open a fizzy drink, it comes into contact with air that has a much lower partial pressure of carbon dioxide than that in the liquid. Carbon dioxide diffuses from the high partial pressure to the low partial pressure — quickly! The drink fizzes as carbon dioxide is lost.

$$\text{total atmospheric pressure} = pN_2 + pO_2 + pCO_2 + p\text{others}$$

$$100\text{ kPa} = 78\text{ kPa} + 21\text{ kPa} + 0.03\text{ kPa} + 0.97\text{ kPa}$$

$$(100\%)\quad (78\%)\quad (21\%)\quad (0.03\%)\quad (0.97\%)$$

When a gas dissolves in a liquid, its molecules continue to exert a pressure and contribute to the total pressure of the liquid. The amount of a gas that can dissolve in a liquid is dependent on the partial pressure of the gas in the air around the liquid. Molecules of the gas diffuse into (or out of) the liquid until the two partial pressures are the same.

Figure 6.6 Partial pressures of atmospheric gases

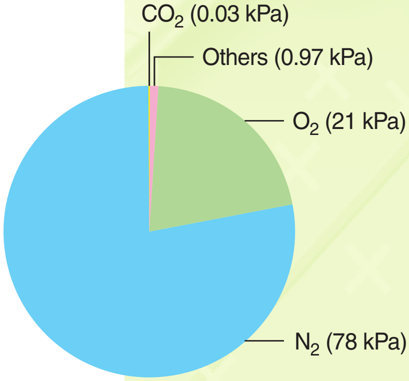


Table 6.1 shows the partial pressures of oxygen and carbon dioxide in the atmosphere, in air in the alveoli and in blood plasma (in the pulmonary artery and in the pulmonary vein). Diffusion takes place until the partial pressures of the gases are the same in the alveolar air and the blood plasma.

Table 6.1

	Atmosphere/kPa	Alveolar air/kPa	Blood plasma in pulmonary artery/kPa	Blood plasma in pulmonary vein/kPa
Oxygen	21.00	11.20	5.30	11.20
Carbon dioxide	0.03	5.30	6.10	5.30

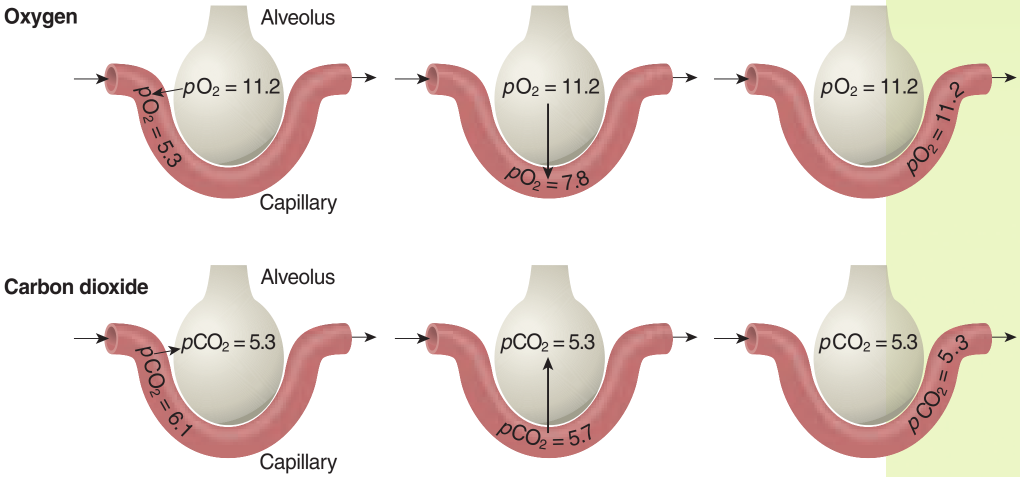


Figure 6.7 Exchange of O_2 and CO_2 between an alveolus and blood plasma

Partial pressure determines only how much oxygen and carbon dioxide are transported in simple solution in the blood plasma. However, most oxygen is transported combined with haemoglobin in the red blood cells. Only 0.3 cm^3 of oxygen is dissolved in 100 cm^3 plasma; the haemoglobin in the same volume of plasma carries 20 cm^3 oxygen. Gas exchange in the lungs saturates the plasma *and* the haemoglobin with oxygen.

Can we relate gas exchange in the lungs to Fick's law of diffusion?

Gas exchange in the alveoli occurs by passive diffusion. Therefore, the factors of Fick's law affect the overall efficiency of the process:

$$\text{rate of diffusion} \propto \frac{\text{surface area of exchange} \times \text{difference in concentration}}{\text{thickness of exchange surface}}$$

For efficient gas exchange, there must be a fast diffusion rate. This requires:

- a large surface area
- a large difference in concentration
- a short diffusion distance

The large surface area is provided, in part, by the 700 million alveoli present in the lungs of a human. Collectively, the alveoli have the area of a tennis court. However, it is the area over which exchange can actually take place that is important. This is represented by the total area of alveolar wall in contact with capillaries. So, having a vast number of capillaries is also important in providing a large exchange surface.

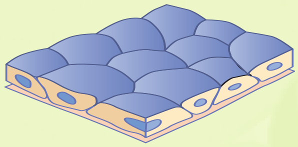
The difference in concentration is maintained by constant ventilation of the lungs and circulation of the blood. Ventilation continually replaces air in the alveoli with atmospheric air that has a high partial pressure of oxygen and a low partial pressure of carbon dioxide. Circulation removes newly oxygenated blood from the capillaries next to the alveoli and replaces it with deoxygenated blood. The partial pressure of oxygen in this blood is lower than that of the alveolar air; the partial pressure of carbon dioxide in this blood is higher than that of alveolar air.

If you look back to Table 6.1, you will see that the concentration gradient between the pulmonary artery and alveolar air is greater for oxygen than it is for carbon dioxide. Despite this, the volumes of the two gases exchanged are almost identical. How can this be? This is a consequence of the moisture lining the alveoli. Carbon dioxide is much more soluble in water than oxygen is and it dissolves quickly in the water that lines the alveoli. This allows a more rapid transfer across the alveolar walls.

The short diffusion distance is a consequence of:

- the extreme thinness of the alveolar wall and the capillary wall — both comprise only squamous epithelial tissue
- alveoli and capillaries being pressed closely together— the interstitial space (space between the two) is very small
- the shape of the red blood cell — most of the oxygen diffuses from the air and combines with haemoglobin in red blood cells, the flattened shape of which provides a large surface area and also means that the haemoglobin is close to the plasma membrane, reducing the diffusion distance

Squamous epithelial cells are the thinnest cells in our bodies. Most of the cell is thinner than its nucleus, which causes a 'bulge' in the cell. A typical squamous cell is less than 1 μm thick, whilst its nucleus is 6 μm thick. By comparison, the epithelial cells lining the gut are approximately 30 μm thick.



How does the composition of the air change while in the lungs?

As a result of the diffusion of gases in the alveoli, the composition of air that is exhaled is different from that which is inhaled and from that which is present in the alveoli (Table 6.2).

Table 6.2

	Inhaled air/ %	Alveolar air/ %	Exhaled air/ %
Oxygen	21.00	11.20	16.00
Carbon dioxide	0.03	5.30	3.00

As you might expect, alveolar air and exhaled air both contain less oxygen and more carbon dioxide than inhaled air. But why are the two different? This is because exhaled air is a mixture of air from the alveoli and air in the bronchi and bronchioles that did not reach the alveoli. This air is not involved in gas exchange and, therefore, still has the same composition as atmospheric (inhaled) air. As a result, exhaled air has concentrations of oxygen and carbon dioxide that are intermediate between those of alveolar air and inhaled air.

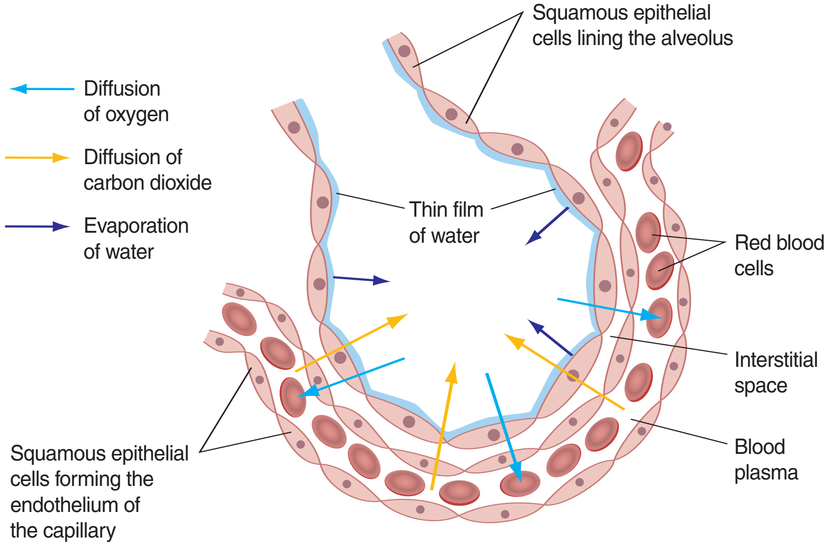


Figure 6.8 The diffusion pathway between a capillary and an alveolus

How much air do we breathe?

At rest we have a breathing rate of about 15 breathing movements (inhalations and exhalations) per minute and a tidal volume of around 500 cm^3 (0.5 dm^3). This means that a total of 7500 cm^3 (7.5 dm^3) is breathed in per minute. This is called the minute volume or the **pulmonary ventilation rate**.

pulmonary ventilation rate = tidal volume × rate of breathing

However, on exercising, an increased pulmonary ventilation rate is needed to supply the extra oxygen. Also, following exercise, the pulmonary ventilation rate is affected by high levels of lactate that accumulate in muscles as a result of anaerobic respiration. After exercise, lactate is removed by a process that needs oxygen. The pulmonary ventilation rate falls slowly as more and more lactate is oxidised.

Box 6.2 VO_2 max: a measure of athletic fitness

Athletic performance is largely dependent on how much oxygen can be supplied to the skeletal muscles.

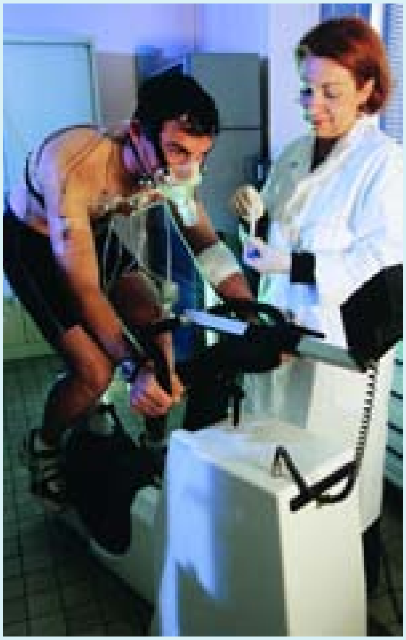
This depends on how much blood can be delivered to the muscles and how effectively the blood is oxygenated during the exercise.

The units of VO_2 max are cm^3 per minute per kilogram of body mass. One way to improve fitness is to lose weight. Does this work according to the VO_2 max formula?

VO_2 max is given by dividing the volume of oxygen used by the time it takes to perform the exercise and then dividing again by body mass. If you lose weight, you will divide by a smaller number and so increase your VO_2 max. You will also find it easier to move the new, lighter you, and complete the task in a shorter time, again improving your VO_2 max.

VO_2 max is determined experimentally by analysing the exhaled air of an athlete as he or she trains on a treadmill.

It can be determined more easily by an 'indirect' method. For this, warm up gently, walk one mile as quickly as you can (note the time taken) and take your pulse immediately after completing the exercise. Then, use the following formula to determine VO_2 max.



Philippe Psaila/SPL

$$\begin{aligned} VO_2 \text{ max } (\text{cm}^3\,\text{min}^{-1}\text{kg}^{-1}) = {} & 132.853 - (0.0769 \times \text{weight in pounds}) \\ & - (0.3877 \times \text{age in years}) + (6.3150 \times \text{sex}^*) \\ & - (3.2649 \times \text{time (in minutes)} - (0.1565 \times \text{final heart rate}) \end{aligned}$$

(*Male = 1, female = 0)

The following tables show VO_2 max values for men and women that represent a range of performance levels.

VO_2 values for men:

	20–29 (yrs)	30–39 (yrs)	40–49 (yrs)	50–59 (yrs)	60–69
Low	<38	<34	<30	<25	<21
Quite low	39–34	35–39	31–35	26–31	22–26
Average	44–51	40–47	36–43	32–39	27–35
High	52–56	48–51	44–47	40–43	36–39
Very high	>57	>52	>48	>44	>40

VO_2 values for women:

	20–29 (yrs)	30–39 (yrs)	40–49 (yrs)	50–65 (yrs)
Low	<28	<27	<25	<21
Quite low	29–34	28–33	26–31	22–28
Average	35–43	34–41	32–40	29–36
High	44–48	42–47	41–45	37–41
Very high	>49	>48	>46	>42

Summary

Structure

- The human breathing system comprises:
  - the airways in the lungs (bronchi, bronchioles, alveoli) and those outside the lungs (trachea, larynx, nasal and mouth cavities)
  - the structures that surround the lungs and assist in the mechanisms of breathing movements (ribs, intercostal muscles and diaphragm)

Mechanism

- Inhalation and exhalation occur because breathing movements create pressure differences between the atmosphere and the air in the lungs.
- Inhalation is brought about because the contraction of the external intercostal muscles and contraction of the diaphragm muscle increase the volume of the thorax, which reduces pressure in the thorax.
- Exhalation is brought about because the contraction of the internal intercostal muscles and the relaxation of the diaphragm muscle decrease the volume of the thorax and this increases pressure in the thorax.
- Inhalation draws air though the nasal cavity and pharynx, along the trachea, bronchi and bronchioles, and into the alveoli, where gas exchange takes place. Exhalation forces air from the alveoli back along the same route.

Gas exchange

- In the alveoli, oxygen diffuses from the alveolar air into the red blood cells (where it combines with haemoglobin), and carbon dioxide diffuses from the blood plasma into the alveolar air.
- Diffusion in the alveoli is efficient (in terms of Fick's law) because:
  - the many alveoli provide a large surface area
  - continuous ventilation and circulation maintain a high concentration difference between alveolar air and the blood
  - the extremely thin walls of the alveoli and capillaries (consisting only of squamous epithelium on a basement membrane) provide a short diffusion distance
- Gas exchange is also more efficient because the alveoli are moist; this aids the diffusion of carbon dioxide in particular.
- The partial pressure of a gas is the contribution made by that gas to the total pressure of a system. It is a useful way of comparing concentrations of gases between a gaseous medium and a liquid medium.
- The volume of air moved in and out of the lungs with each breath is the tidal volume.
- At rest, the tidal volume is about 500 cm^3, but the inspiratory reserve volume and the expiratory reserve volume can increase this to about 4500 cm^3.
- There is about 1200 cm^3 air that is never exhaled, which forms the residual volume.

Control

- pulmonary ventilation rate = rate of breathing × tidal volume

Questions

Multiple-choice

1 Pulmonary ventilation rate is equal to:
A breathing rate × residual volume
B breathing rate × tidal volume
C tidal volume ÷ breathing rate
D residual volume ÷ breathing rate

2 Diffusion of oxygen and carbon dioxide in the alveoli is rapid because there is:
A a large surface area, a low concentration difference and a short diffusion pathway
B a small surface area, a high concentration difference and a short diffusion pathway
C a large surface area, a high concentration difference and a long diffusion pathway
D a large surface area, a high concentration difference and a short diffusion pathway

3 To bring about inhalation:
A external intercostal muscles contract, internal intercostal muscles relax, diaphragm muscle contracts
B external intercostal muscles contract, internal intercostal muscles contract, diaphragm muscle relaxes
C external intercostal muscles relax, internal intercostal muscles relax, diaphragm muscle contracts
D external intercostal muscles relax, internal intercostal muscles contract, diaphragm muscle relaxes

4 During gas exchange in the alveoli, oxygen must diffuse through:
A the alveolar epithelium
B the interstitial space
C the membrane of a red blood cell
D all of the above

5 The tidal volume is:
A the total volume of air in the lungs
B the volume inhaled added to the volume exhaled in one breath
C the volume of air inhaled and then exhaled in one breath
D the maximum volume of air that can be inhaled in one breath

6 The partial pressure of a gas is:
A the proportion by volume of a gas in a mixture of gases
B the part of the total pressure that a gas exerts due to its molecules colliding with each other
C the part of the overall pressure of a mixture of gases that is due to that gas
D the pressure of a gas when only some of its molecules exert a force

7 When air is exhaled, it:

A diffuses out down a concentration gradient

B is drawn out because of the higher pressure in the atmosphere

C is forced out because of the higher pressure in the lungs

D is drawn in because of the lower pressure in the lungs

8 Following exercise, the pulmonary ventilation rate falls only slowly because

A the partial pressure of oxygen in the blood is high

B the levels of lactate are still high

C the levels of lactate are still low

D the partial pressure of oxygen in the blood is low

9 Ventilating the lungs means:

A inhaling

B exhaling

C inhaling and exhaling

D exchanging gases

10 When compared with inhaled air, exhaled air:

A has a higher concentration of oxygen, a lower concentration of carbon dioxide and is more moist

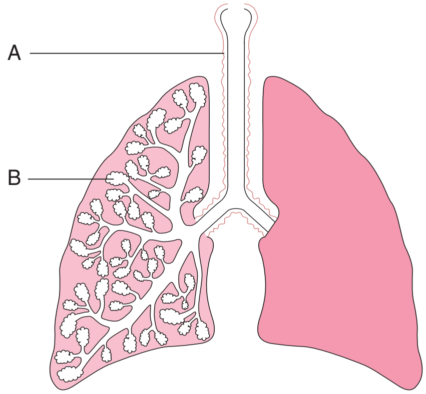
B has a higher concentration of oxygen, a lower concentration of carbon dioxide and is drier

C has a lower concentration of oxygen, a higher concentration of carbon dioxide and is more moist

D has a lower concentration of oxygen, a higher concentration of carbon dioxide and is drier

Examination-style

1 **(a)** The diagram below shows the main components of the human breathing system.



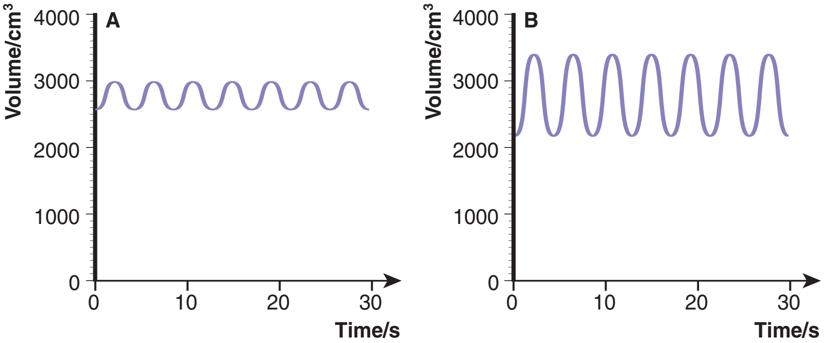
(i) Name the structures labelled A and B. (*2 marks*)

(ii) Explain why contraction of the external intercostal muscles and contraction of the diaphragm muscle cause air to be drawn into the lungs. (*3 marks*)

(b) Use Fick's law to explain why gas exchange in the alveoli is efficient. (*4 marks*)

Total: 9 marks

2 The diagram shows two spirometer traces taken from the same person at different times.



(a) **(i)** What is the tidal volume shown in trace A? (*1 mark*)

(ii) From trace B, calculate the pulmonary ventilation rate. Show your working. (*2 marks*)

(b) Suggest reasons for the difference in breathing shown by the two traces. Explain your answer. (*4 marks*)

Total: 7 marks

3 **(a)** Explain what is meant by the terms:

(i) tidal volume

(ii) inspiratory reserve volume

(iii) vital capacity (*3 marks*)

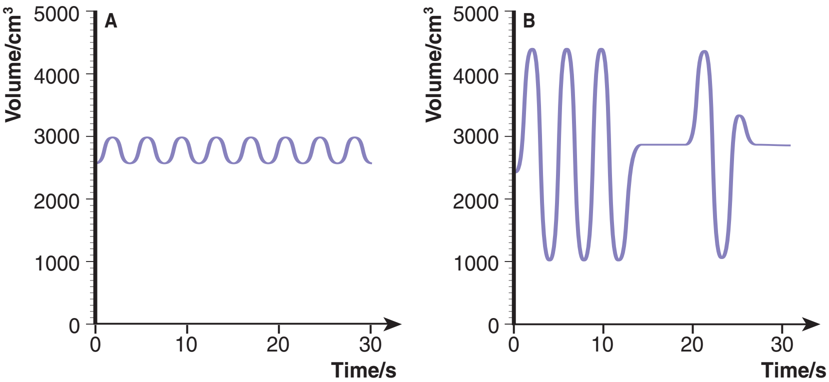
(b) When a person suffers a serious chest wound, a condition known as pneumothorax can result. In this condition, air rushes into the space between the two pleural layers surrounding one of the lungs.

(i) What effect will the wound have on the pressure of the air between the two pleural layers? Explain your answer. (*2 marks*)

(ii) Explain why the lung affected by pneumothorax can no longer be ventilated. (*3 marks*)

Total: 8 marks

4 The diagram shows two spirometer traces. Trace A shows a normal breathing pattern of a person at rest. Trace B shows an abnormal pattern of breathing at rest.



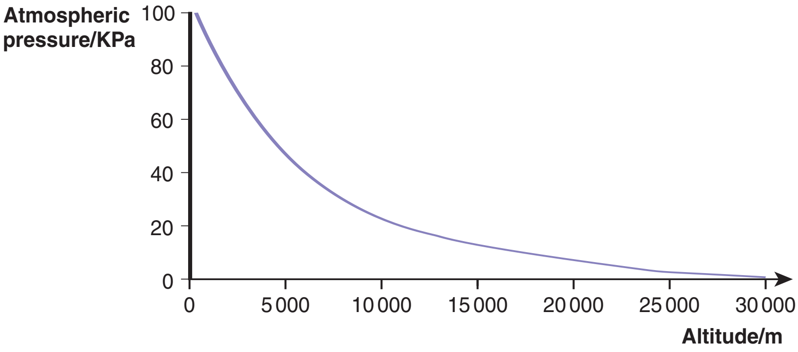
(a) Calculate the pulmonary ventilation rate shown by trace A. *(2 marks)*

(b) Describe two ways in which the pattern of breathing shown by trace B differs from that shown in trace A. *(2 marks)*

(c) The pattern of breathing shown in trace B is sometimes found in brain-damaged patients, where the nervous control of breathing fails and then begins again. Suggest how brain damage might produce this abnormal pattern of breathing. *(3 marks)*

Total: 7 marks

5 The graph below shows the atmospheric pressure at different altitudes.



(a) Describe the change in atmospheric pressure between sea level and 1000 m. *(2 marks)*

(b) Assuming that oxygen makes up 21% of the atmosphere at all altitudes, calculate the partial pressure of oxygen at:

(i) sea level *(1 mark)*

(ii) an altitude of 5000 m *(1 mark)*

(c) Gas exchange takes place in the alveoli. Most of the oxygen absorbed diffuses into red blood cells and combines with haemoglobin to form oxyhaemoglobin.

(i) Explain why oxygen combining with haemoglobin does not affect the concentration gradient of oxygen between the alveolar air and the blood. *(2 marks)*

(ii) Suggest why people who live at high altitudes have more red blood cells per cm^3 blood than people who live at sea level. *(3 marks)*

(iii) Use Fick's law to explain the benefit, to a person who has just reached a high altitude, of breathing more quickly. *(3 marks)*

(d) Explain to a person not adapted to living at such altitudes, why exercise is more difficult at higher altitudes. *(3 marks)*

Total: 15 marks