



Gas exchange

Revision notes • IB Biology B3.1 gas exchange: exchange surfaces, alveolar lungs, ventilation, lung volumes, leaves, transpiration, stomata and (HL) haemoglobin.

For IB Diploma Biology, Standard Level and Higher Level (first assessment 2025). **HL only** is additional higher level content, for HL students only.

Gas exchange Spec B3.1

Gas exchange and exchange surfaces Spec B3.1.1, B3.1.2, B3.1.3

Every organism must take in oxygen for aerobic respiration and remove carbon dioxide, and photosynthesising organisms do the reverse in the light. **Gas exchange** happens by **diffusion**, so it depends on surface area, distance and the concentration gradient.

Why size makes it harder

- As an organism gets bigger, its volume rises faster than its surface area, so the **surface area-to-volume ratio** decreases. There is less surface for each unit of respiring tissue.
- The distance from the centre of the organism to its exterior also increases, and diffusion is only fast over very short distances.
- Small organisms (for example a unicellular organism or a flatworm) can exchange gases across their whole body surface. Large, active organisms need a specialised gas-exchange surface and a transport system to carry gases to and from every cell.

Properties of gas-exchange surfaces

The four properties of gas-exchange surfaces

Property	Why it helps
Permeable	Oxygen and carbon dioxide can pass through the cells and membranes freely.
Thin tissue layer	A short diffusion distance makes diffusion fast.
Moist	Gases dissolve in the film of water before they diffuse across the surface.
Large surface area	More gas can diffuse across at the same time.

Keeping concentration gradients steep in animals

- Dense networks of blood vessels** (capillaries) lie right next to the exchange surface.
- Continuous blood flow** carries oxygenated blood away and brings deoxygenated blood with a high carbon dioxide concentration, so the gradient never levels out.
- Ventilation** replaces the medium next to the surface: air is pumped in and out of lungs, and water is pumped over the gills of fish.

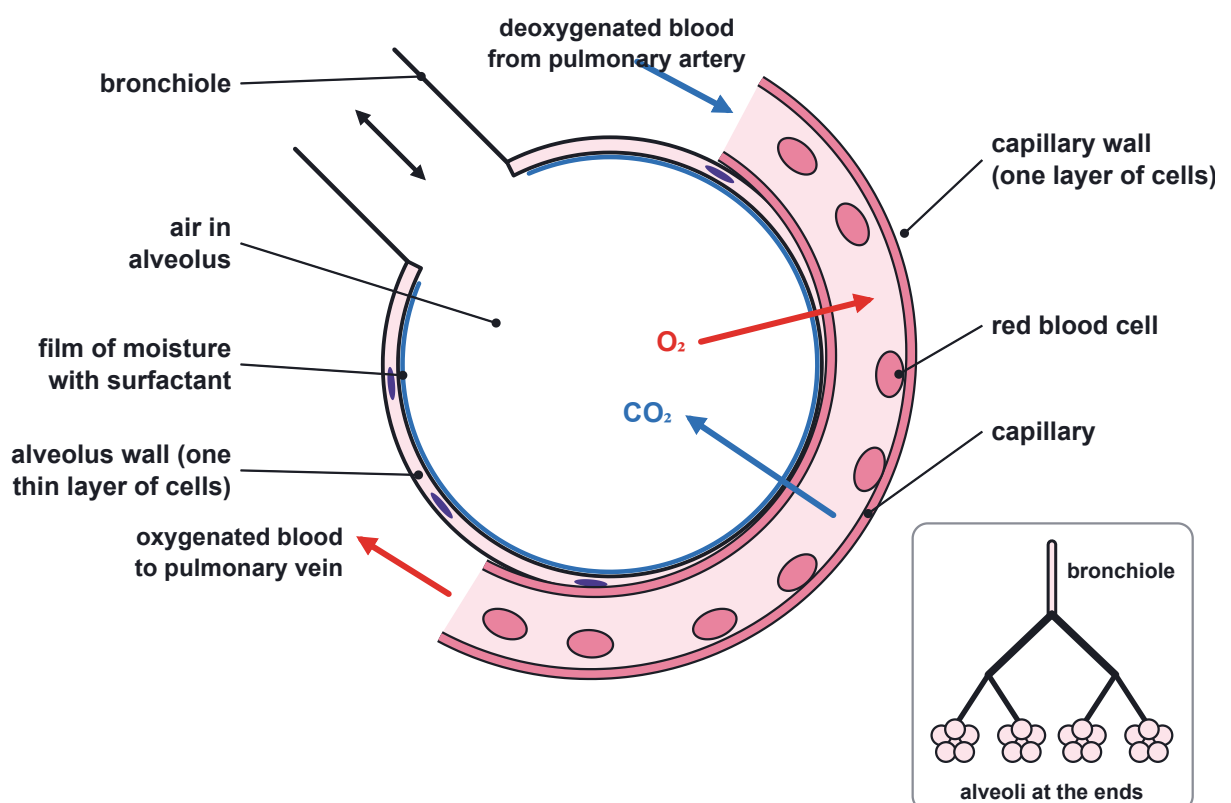
Exam tip: Linking question: how do multicellular organisms solve the problem of access to materials for all their cells? A good answer pairs a large exchange surface with a transport system that delivers to every cell.

Adaptations of mammalian lungs Spec B3.1.4

Air enters through the trachea, which divides into two bronchi, one to each lung. Each bronchus divides again and again into a **branched network of bronchioles**, which end in clusters of tiny air sacs called **alveoli**.

Adaptations of the alveolar lungs for gas exchange	
Adaptation	How it helps gas exchange
Branched network of bronchioles	Carries air to and from hundreds of millions of alveoli spread through the whole lung.
High surface area	The very large number of small alveoli gives a huge total surface for diffusion.
Extensive capillary beds	Each alveolus is covered in capillaries, so blood flows close to every part of the surface and keeps the gradient steep.
Thin walls	The alveolus wall and the capillary wall are each one layer of very thin, flattened cells, so the diffusion distance is short.
Surfactant	A fluid secreted by cells in the alveolus wall reduces the surface tension of the water lining, so the alveoli do not stick together and collapse when air is breathed out.
Moist lining	Oxygen dissolves in the film of moisture before it diffuses into the blood.

Oxygen diffuses from the air in the alveolus into the blood, and carbon dioxide diffuses from the blood into the alveolus. Ventilation and continuous blood flow keep both gradients steep.



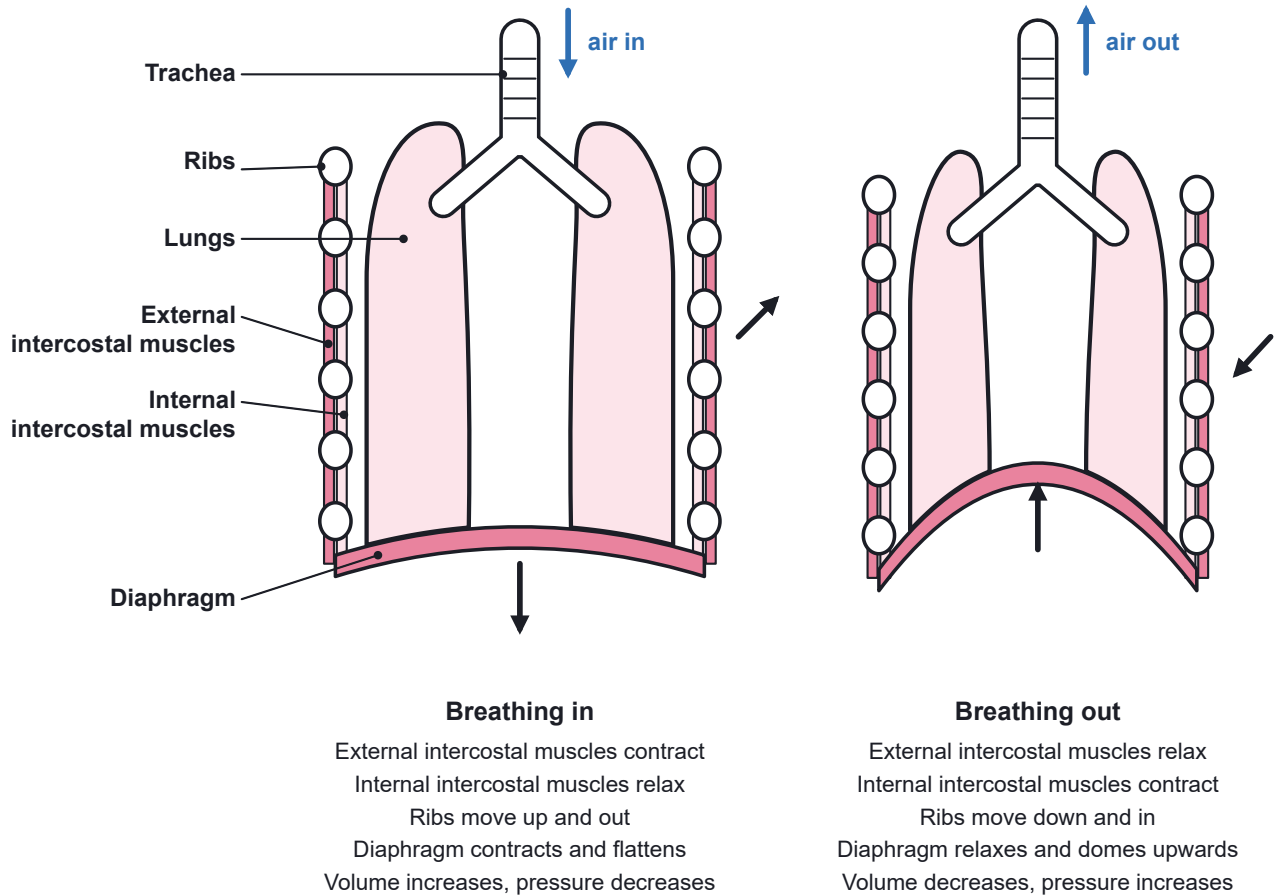
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Gas exchange in an alveolus: **two thin layers of cells** separate the air from the blood, and blood flow keeps the gradients steep.

Common mistake: Surfactant does not help gases dissolve or diffuse. Its job is to lower surface tension so the alveoli stay open.

Ventilation and lung volumes Spec B3.1.5, B3.1.6

Air always flows from higher to lower pressure. Muscles change the **volume of the thorax**, which changes the pressure inside it (pressure and volume are inversely related).



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Inspiration and expiration change the volume of the thorax. The breathing-out panel shows forced expiration: in quiet expiration the internal intercostal muscles stay relaxed. The abdominal muscles (not drawn) also contract in forced expiration.

Muscle actions during ventilation		
Structure	Inspiration (breathing in)	Expiration (breathing out)
Diaphragm	Contracts and flattens, moving down	Relaxes and is pushed back up into a dome (by elastic recoil and the abdominal organs; in forced expiration also by the abdominal muscles)
External intercostal muscles	Contract, pulling the ribcage up and out	Relax
Internal intercostal muscles	Relax	Relaxed in quiet expiration; contract in forced expiration, pulling the ribcage down and in
Abdominal muscles	Relax, so abdominal organs can be pushed down	Relaxed in quiet expiration; contract in forced expiration, pushing abdominal organs and the diaphragm up
Ribs	Move up and out	Move down and in (by gravity and elastic recoil in quiet expiration; pulled by the internal intercostals in forced expiration)
Thorax volume and pressure	Volume increases, pressure falls below atmospheric, air flows in	Volume decreases, pressure rises above atmospheric, air flows out

Quiet expiration (breathing out at rest) is mainly passive: the diaphragm and external intercostal muscles relax, and the stretched lungs and chest wall recoil elastically, so thorax volume falls. **Forced expiration** (during exercise, coughing, or when measuring vital capacity or expiratory reserve) is active: the internal intercostal muscles and the abdominal muscles contract, so more air is pushed out, faster.

Common mistake: Do not say the internal intercostal muscles contract in every breath out. They contract only in forced expiration; quiet expiration relies on muscle relaxation and elastic recoil.

Lung volumes

Tidal volume	The volume of air breathed in or out in one normal breath.
Inspiratory reserve volume	The extra volume of air that can be breathed in by force after a normal inspiration.
Expiratory reserve volume	The extra volume of air that can be breathed out by force after a normal expiration.
Vital capacity	The largest volume of air that can be breathed out after the deepest possible breath in: tidal volume + inspiratory reserve + expiratory reserve.

Some air always stays in the lungs (the residual volume), so a spirometer cannot measure it and vital capacity is less than total lung volume.

Practical skill: Measure lung volumes with a digital spirometer, or by breathing out through a tube into an upturned, water-filled, calibrated bottle and reading the volume of water displaced. Repeat each measurement three times and use the mean.

Reading a spirometer trace

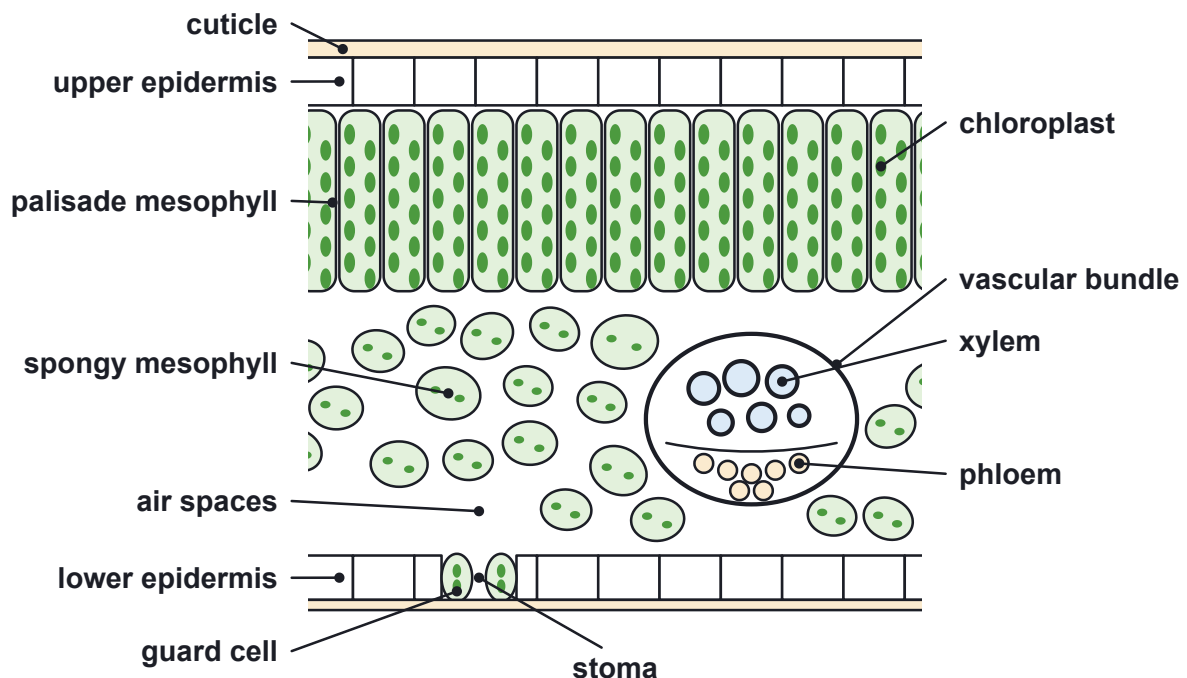
On a spirometer trace, a normal breath goes from 2.3 dm³ to 2.8 dm³. The deepest breath in reaches 5.8 dm³ and the deepest breath out falls to 1.2 dm³. Find the tidal volume, inspiratory reserve, expiratory reserve and vital capacity. (Practice data.)

1. Tidal volume = $2.8 - 2.3 = 0.5 \text{ dm}^3$
2. Inspiratory reserve = $5.8 - 2.8 = 3.0 \text{ dm}^3$
3. Expiratory reserve = $2.3 - 1.2 = 1.1 \text{ dm}^3$
4. Vital capacity = $5.8 - 1.2 = 4.6 \text{ dm}^3$ (check: $0.5 + 3.0 + 1.1 = 4.6 \text{ dm}^3$)

Answer: TV 0.5 dm³, IRV 3.0 dm³, ERV 1.1 dm³, VC 4.6 dm³

Gas exchange in leaves Spec B3.1.7, B3.1.8

In the light a leaf takes in carbon dioxide for photosynthesis and releases oxygen. The challenge is to let gases in and out without losing too much water.



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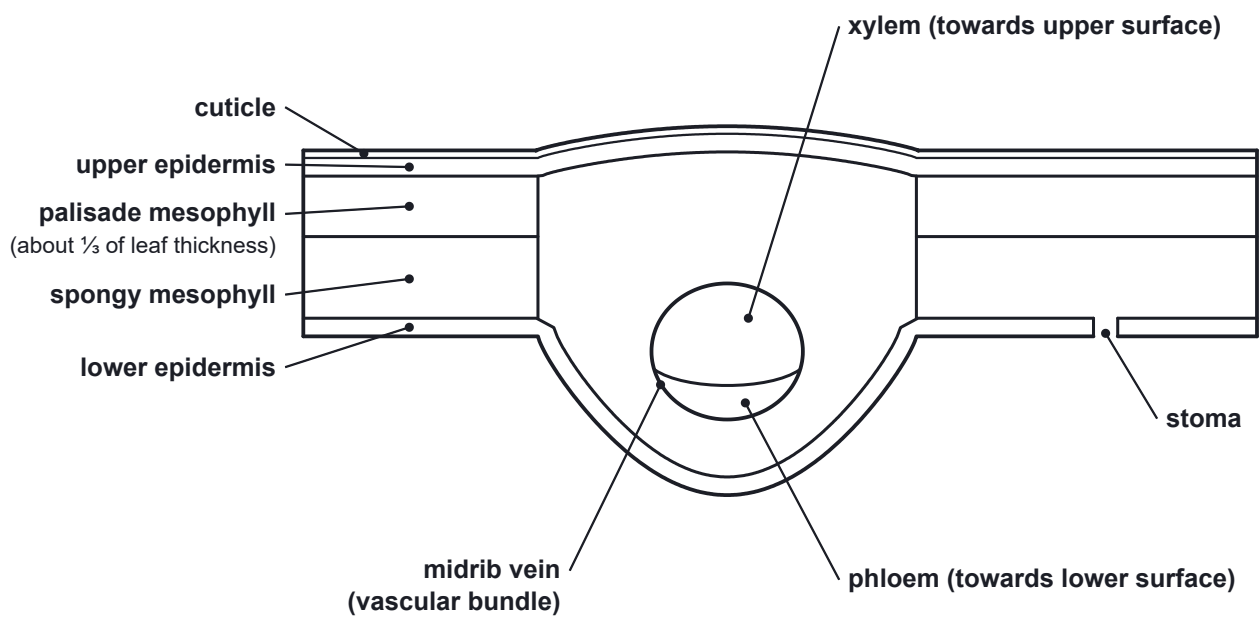
Tissues of a dicotyledonous leaf, drawn with cells. A plan diagram shows the same tissues as outlines only.

Adaptations of a leaf for gas exchange

Structure	Adaptation
Waxy cuticle	Waterproof layer on the epidermis that reduces water loss by evaporation.
Epidermis	A single, tightly packed layer of cells that secretes the cuticle and protects the leaf; it is transparent, so light reaches the mesophyll.
Stomatal guard cells	Pairs of guard cells open the stoma between them to let CO ₂ in and O ₂ out, and close it to reduce water loss.
Air spaces	Connect the stomata with the mesophyll so gases diffuse quickly through the leaf.
Spongy mesophyll	Loosely packed cells with moist walls give a large surface area for gas exchange.
Veins	Xylem brings water to replace the water lost; phloem carries away the sugars made in photosynthesis.

Plan diagram of a leaf

A **plan diagram** shows the distribution of tissues as areas outlined by single lines, with no individual cells drawn. Draw it large, use a sharp pencil, no shading, and label with ruled lines that do not cross.



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Plan diagram of a dicotyledonous leaf: tissues as outlines only. In the vein, **xylem is towards the upper surface**.

Exam tip: In the vein, xylem is towards the upper surface and phloem towards the lower surface. Examiners check this in leaf plan diagrams.

Transpiration and stomatal density Spec B3.1.9, B3.1.10

Water evaporates from the moist walls of mesophyll cells into the air spaces, then water vapour diffuses out through open stomata. Because stomata must be open for CO₂ to enter, **transpiration is a consequence of gas exchange**.

Factors affecting the rate of transpiration

Factor	Effect on rate	Reason
Light intensity	Increases	Stomata open in the light for photosynthesis.
Temperature	Increases	More evaporation from cell walls and faster diffusion of water vapour.
Humidity	Decreases	Moist air outside lowers the water vapour concentration gradient.
Wind speed	Increases	Moving air removes water vapour from around the stomata, keeping the gradient steep.
Soil water availability	Decreases if water is short	Guard cells lose turgor and stomata close.

The rate of transpiration can be estimated with a potometer, which measures water uptake by a cut shoot.

Stomatal density

$$\text{stomatal density} = \text{number of stomata} \div \text{area of field of view (mm}^2\text{)}$$

Practical skill: To make a leaf cast, paint clear nail varnish on the lower epidermis, let it dry, lift it off with clear tape and stick it to a slide. Count stomata at high power in several fields of view, or count them on a micrograph with a known scale.

Calculating stomatal density

At high power the field of view has a diameter of 0.40 mm. Counts of stomata in five fields of view are 24, 27, 22, 26 and 26. Calculate the mean stomatal density. (Practice data.)

1. Mean count = $(24 + 27 + 22 + 26 + 26) \div 5 = 125 \div 5 = 25$
2. Radius = $0.40 \div 2 = 0.20 \text{ mm}$
3. Area = $\pi r^2 = 3.14 \times 0.20^2 = 0.126 \text{ mm}^2$
4. Density = $25 \div 0.126 = 198.4$

Answer: about 200 stomata per mm^2 ($2.0 \times 10^2 \text{ mm}^{-2}$)

Maths skill: Repeated counts vary because biological material is variable. Replicate counts and a mean increase the reliability of the data; the range or standard deviation shows the spread.

Haemoglobin, the Bohr shift and oxygen dissociation curves Spec B3.1.11, B3.1.12, B3.1.13

HL only

Adult haemoglobin is made of four polypeptide chains (two alpha and two beta), each with a **haem group** containing an iron ion that binds one O_2 molecule. One haemoglobin molecule carries up to four O_2 molecules.

Cooperative binding

When the first O_2 binds, the conformation of the whole molecule changes, so the remaining haem groups bind O_2 more easily. This is **cooperative binding**. In the same way, when one O_2 is released, the others are released more easily.

Oxygen dissociation curves

An oxygen dissociation curve plots percentage saturation of haemoglobin against partial pressure of oxygen (pO_2 , kPa). It shows the affinity of haemoglobin for oxygen at different oxygen concentrations.

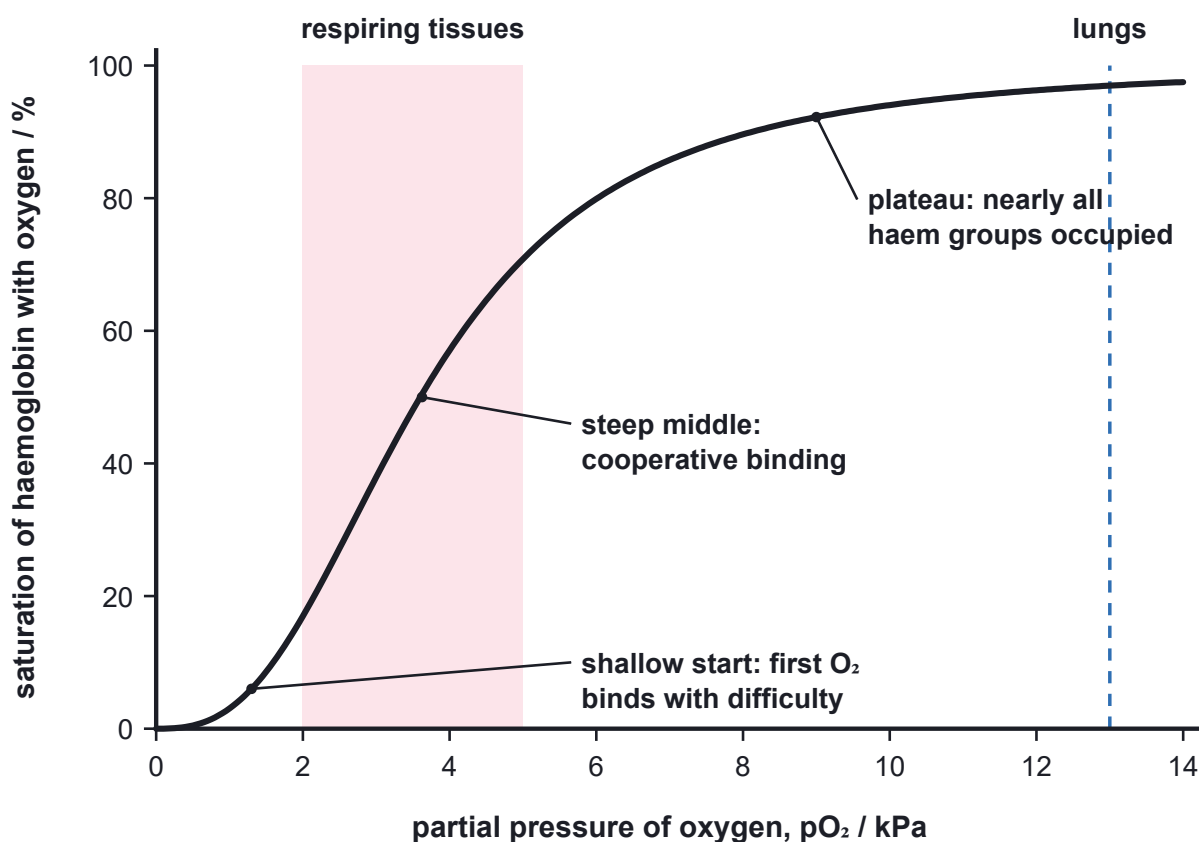
- At low pO_2 the curve is shallow: binding the first O_2 is difficult.
- In the middle the curve is steep: cooperative binding makes each further O_2 bind more easily.
- At high pO_2 the curve levels off: almost all haem groups are occupied, so in the lungs (about 13 kPa) haemoglobin is nearly saturated even if pO_2 falls a little.
- The steep part matches the pO_2 in respiring tissues, so a small drop in pO_2 releases a large amount of oxygen.

Bohr shift

Carbon dioxide binds **allosterically** to haemoglobin, at sites other than the haem groups (the amino groups at the ends of the globin chains), and this lowers its affinity for oxygen. CO_2 also reacts with water in red blood cells to form carbonic acid, and the hydrogen ions released bind to haemoglobin as well, lowering its affinity further. So a rise in CO_2 (and the fall in pH that goes with it) moves the dissociation curve to the right: the **Bohr shift**. At the same pO_2 , haemoglobin is then less saturated, so more oxygen dissociates. Actively respiring tissues produce more CO_2 , so haemoglobin releases more oxygen exactly where it is needed. In the lungs CO_2 is low, so affinity is higher and oxygen loading is efficient.

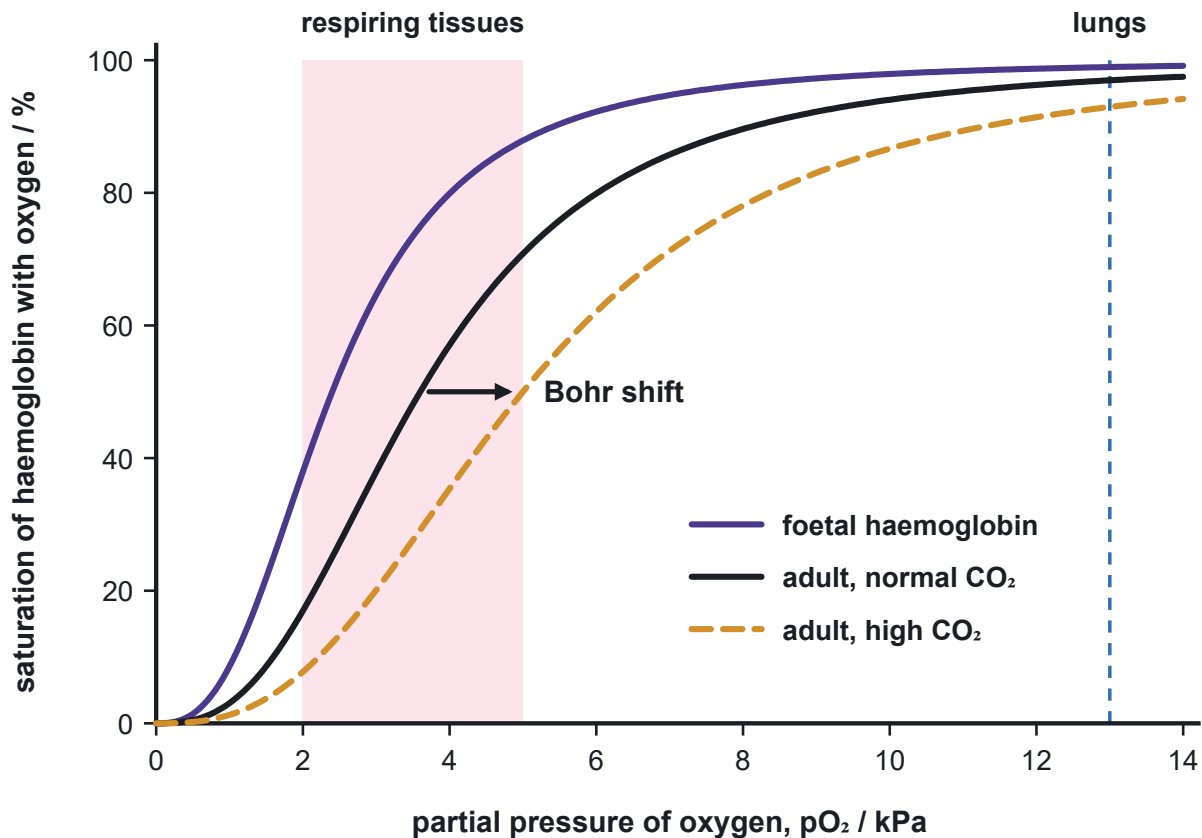
Foetal and adult haemoglobin

Foetal haemoglobin has two gamma chains in place of the beta chains, and a **higher affinity for oxygen** than adult haemoglobin. Its curve lies to the left of the adult curve, so in the placenta, at a pO_2 where maternal haemoglobin releases oxygen, foetal haemoglobin takes it up.



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The sigmoid curve of adult haemoglobin: the **steep middle (cooperative binding)** matches the pO_2 of respiring tissues. Curve shape is illustrative.



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High CO_2 moves the curve right (the Bohr shift, lower affinity); foetal haemoglobin lies to the left (higher affinity). Curves are illustrative.

Exam tip: Curve to the left means higher affinity (loads more easily); curve to the right means lower affinity (unloads more easily). Always say what happens to affinity.

Common mistake: The Bohr shift does not mean CO_2 competes with oxygen for the haem groups. CO_2 and hydrogen ions bind elsewhere on the globin and change the molecule's shape, lowering its affinity for oxygen.

Quick check

1. What happens to the surface area-to-volume ratio as an organism grows larger?
2. What is the function of surfactant in the alveoli?
3. Which three volumes add up to the vital capacity?
4. Why does increased humidity reduce the rate of transpiration?
5. **HL only** In which direction does high carbon dioxide shift the oxygen dissociation curve?

Quick check answers

Gas exchange

1. It decreases.
2. It reduces surface tension so the alveoli do not stick together and collapse when air is breathed out.
3. Tidal volume, inspiratory reserve volume and expiratory reserve volume.
4. It reduces the concentration gradient of water vapour between the air spaces and the outside air.
5. To the right (lower affinity, more oxygen released): the Bohr shift.