

The heart, blood vessels and haemoglobin

Revision notes · Why animals need a circulation, how blood vessels suit their jobs, the cardiac cycle, and how haemoglobin carries oxygen and carbon dioxide.

For Pearson Edexcel International AS Biology XBI11 and International A Level Biology YBI11. **A Level only** is IA2 content (Units 4 to 6), not needed for the International AS.

The heart, blood vessels and haemoglobin **Spec 1.6-1.9**

Why many animals have a heart and circulation **Spec 1.6**

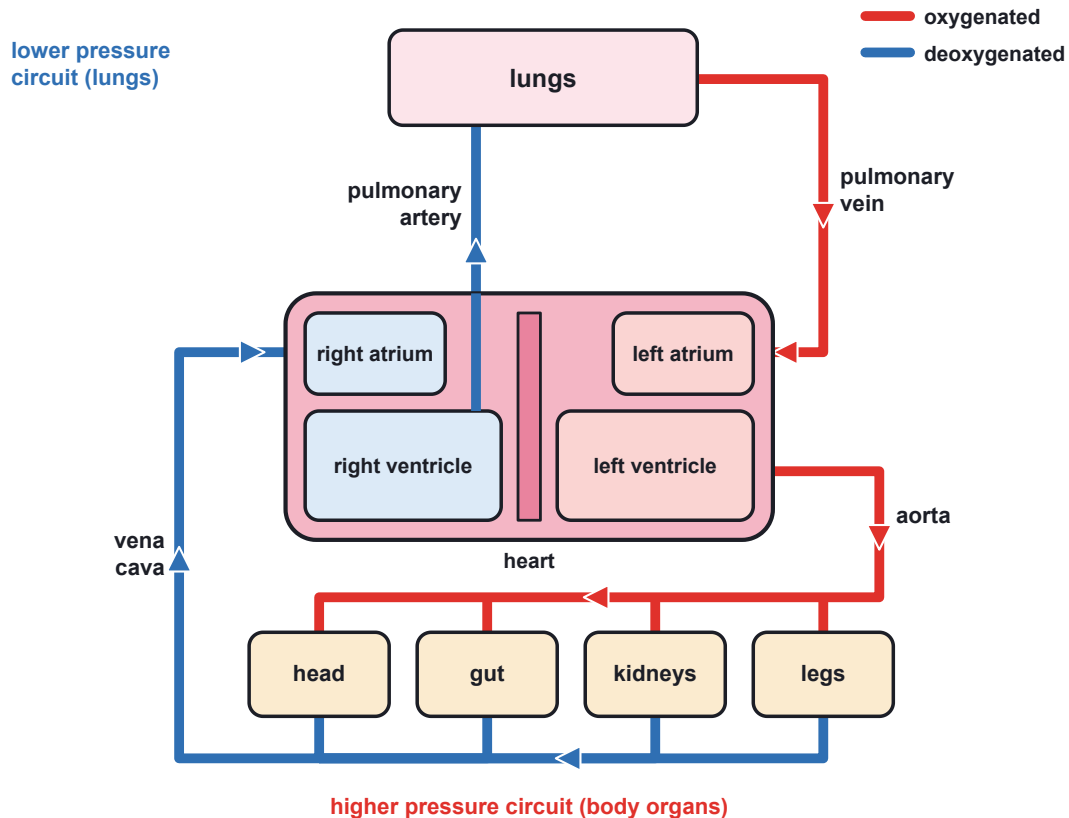
Small organisms, such as single-celled ones, exchange substances by **diffusion** directly across their surface. Their **surface area to volume ratio** is large and the distance from the surface to any part of the cell is tiny, so diffusion is fast enough.

In a large animal this stops working, for three reasons.

- **Surface area to volume ratio falls** as size increases, so the body surface is too small to supply a large volume of cells.
- **Diffusion distances** to cells deep inside the body are long. Diffusion is only fast over very short distances, and the time taken rises sharply as the distance increases.
- A high **metabolic rate** (as in active, warm-blooded animals) means cells use oxygen and glucose, and produce carbon dioxide and wastes, faster than diffusion could move them.

Mass transport solves this problem. A liquid (blood) is moved in bulk, quickly, over long distances through vessels by the pressure generated by a pump (the heart). Blood carries oxygen and nutrients to cells and removes carbon dioxide and wastes. Continually moving blood also keeps concentration gradients steep at the exchange surfaces, which keeps diffusion going.

Mammals have a **closed, double circulation**. Blood stays inside vessels, and passes through the heart twice on each complete circuit: right side of the heart to the lungs, then back to the left side of the heart to be pumped to the rest of the body. Pumping blood to the lungs at lower pressure protects the delicate lung capillaries. Returning it to the heart means the pressure can be raised again before it goes to the body.



Blood passes through the heart **twice** on each complete circuit: once for the lungs and once for the body.

Surface area to volume ratio and size

A cube-shaped organism has sides of 1 cm. Another has sides of 4 cm. Calculate the surface area to volume ratio of each and comment.

1. 1 cm cube: surface area = $6 \times 1^2 = 6 \text{ cm}^2$; volume = $1^3 = 1 \text{ cm}^3$; ratio = 6 : 1

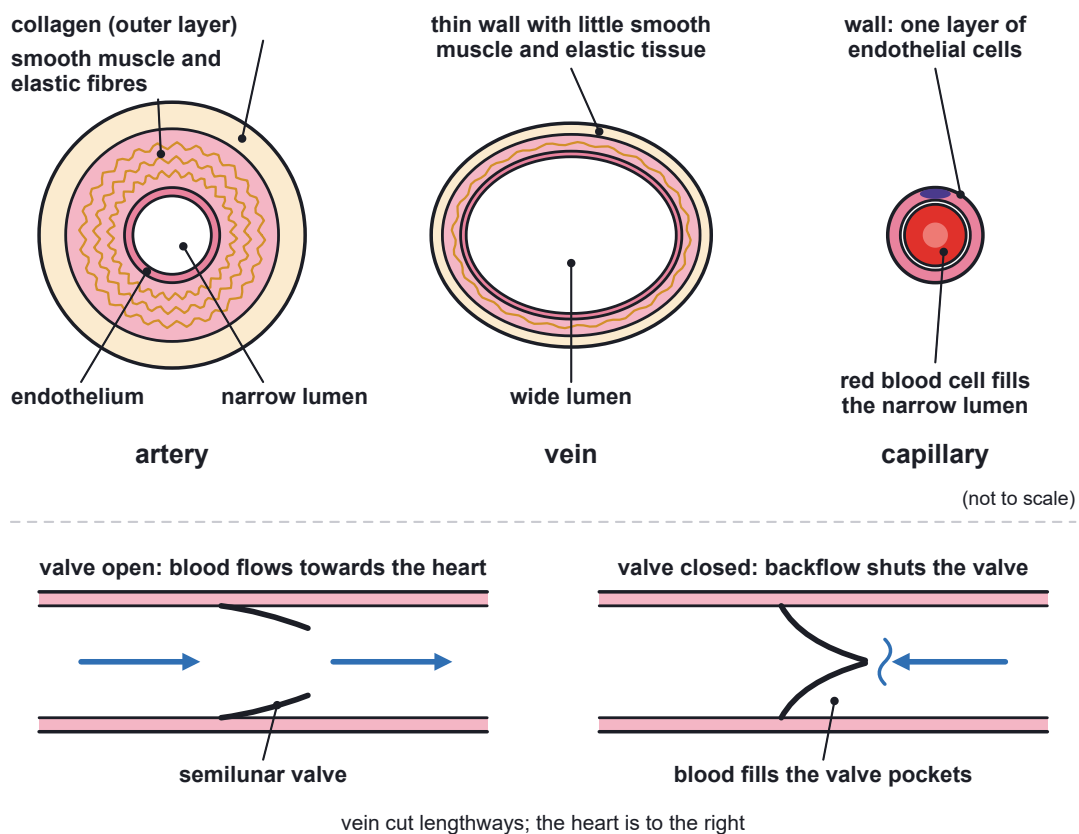
2. 4 cm cube: surface area = $6 \times 4^2 = 96 \text{ cm}^2$; volume = $4^3 = 64 \text{ cm}^3$; ratio = $96 \div 64 = 1.5 : 1$

Answer: 6 : 1 and 1.5 : 1. The larger organism has a much smaller surface area to volume ratio, so diffusion across its surface cannot supply all its cells.

Maths skill: Surface area to volume ratio: for a cube of side L , surface area = $6L^2$ and volume = L^3 . Write the ratio as surface area : volume, and give units for the areas and volumes you calculate.

Arteries, veins and capillaries Spec 1.7

Structure and function of blood vessels			
Feature	Artery	Vein	Capillary
Direction of blood flow	Away from the heart	Towards the heart	Between arteries and veins (through tissues)
Blood pressure	High	Low	Falls along the capillary
Wall	Thick, with collagen, smooth muscle and elastic fibres	Thin, with little muscle or elastic tissue	One layer of flattened endothelial cells
Lumen	Narrow	Wide	Very narrow (about the width of a red blood cell)
Valves	None (except at the heart)	Present	None
Main function	Carry blood away from the heart at high pressure	Return blood to the heart	Exchange of substances between blood and cells



Wall thickness and lumen size match the **pressure** in each vessel; valves in veins stop backflow.

Arteries

Blood leaves the heart in a high-pressure surge. The wall of an artery contains **collagen** fibres, which give strength and prevent bursting, and **elastic fibres**, which stretch as the surge passes and then recoil. This elastic recoil evens out the pressure pulse so blood flows smoothly. **Smooth muscle** in the wall can contract to narrow the lumen. The inner lining (endothelium) is smooth, which reduces friction.

Veins

By the time blood reaches the veins its pressure is low, so the walls can be thin, with little muscle or elastic tissue. The wide lumen offers little resistance to flow. **Valves** (semilunar valves) stop blood

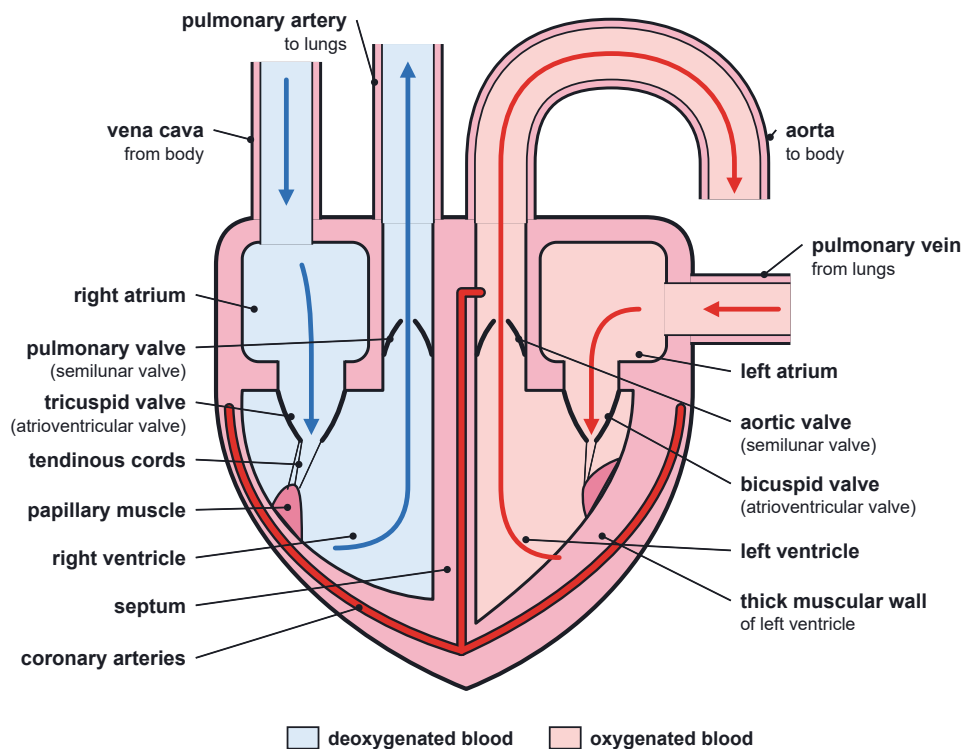
flowing backwards. Blood is helped towards the heart by contractions of the surrounding skeletal muscles squeezing the veins, and by pressure changes in the chest during breathing.

Capillaries

Capillaries form dense networks close to almost every cell. Their wall is a single layer of flattened endothelial cells, so the **diffusion distance is very short**. Gaps between the cells allow small molecules and fluid to pass. The lumen is so narrow that red blood cells are squeezed through in single file, which brings them close to the wall. Together, the capillaries have a very large total cross-sectional area, so blood flows slowly. This gives time for exchange of oxygen, carbon dioxide, glucose and wastes.

Exam tip: Explain each feature with 'so': thick elastic wall so it withstands high pressure and recoils; one cell thick so a short diffusion distance. A list of features without the reason will not get the mark.

Structure of the mammalian heart Spec 1.8



The left ventricle has the **thickest wall** because it pumps blood to the whole body.

Major blood vessels of the heart

Vessel	Carries blood	From	To
Vena cava	Deoxygenated	Body	Right atrium
Pulmonary artery	Deoxygenated	Right ventricle	Lungs
Pulmonary vein	Oxygenated	Lungs	Left atrium
Aorta	Oxygenated	Left ventricle	Body
Coronary arteries	Oxygenated	Base of the aorta	Heart muscle (cardiac muscle)

- The **atria** have thin walls because they only pump blood a short distance into the ventricles.
- The **ventricles** have thicker, muscular walls to pump blood out of the heart. The **left ventricle** has the thickest wall because it pumps blood to the whole body at high pressure. The right ventricle pumps blood only to the nearby lungs at lower pressure, which protects the lung capillaries.
- The **septum** separates the left and right sides, so oxygenated and deoxygenated blood do not mix.

- **Atrioventricular valves** (tricuspid on the right, bicuspid on the left) stop blood flowing back from the ventricles into the atria. They are held in position by **tendinous cords** attached to papillary muscles, so that they are not pushed inside out when the ventricles contract.
- **Semilunar valves** at the start of the aorta and pulmonary artery stop blood flowing back from the arteries into the ventricles.
- The **coronary arteries** supply the cardiac muscle with oxygen and glucose. Blockage of a coronary artery causes a heart attack.

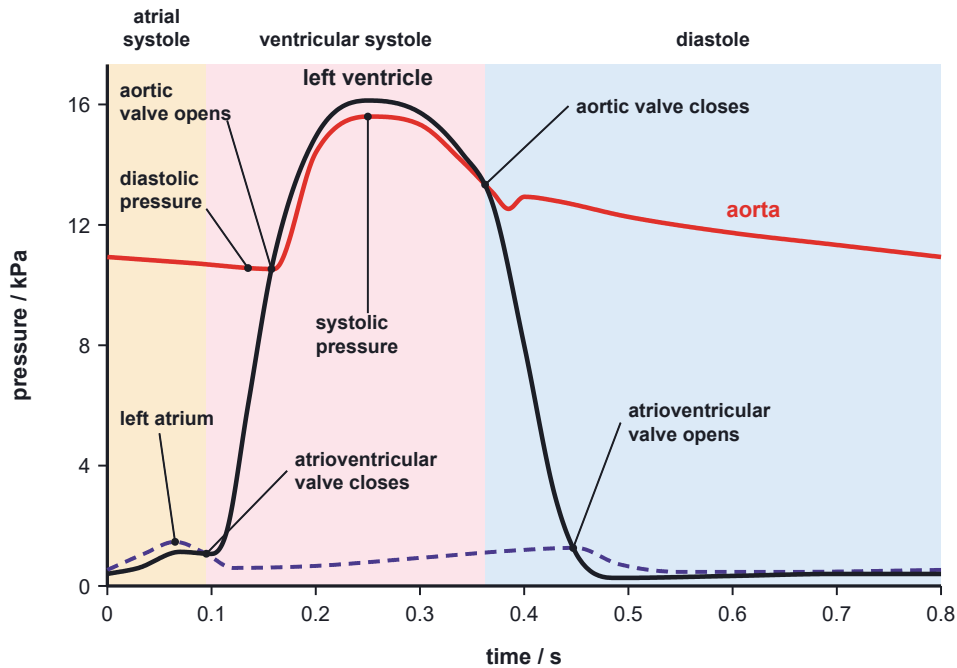
Practical: Recommended additional practical (not a core practical): investigate the structure of a mammalian heart by dissection. Cut across the ventricles to compare wall thickness, find the valves and tendinous cords, and identify the vessels. Wear gloves and eye protection, use a sharp scalpel on a dissecting board, cut away from your hand and disinfect surfaces afterwards.

The cardiac cycle Spec 1.8

Systole is contraction. **Diastole** is relaxation. The cycle repeats about 70 times a minute at rest. Valves have no muscle: they open when pressure behind them is higher than in front, and shut when pressure in front is higher.

1. **Atrial systole**: the atria contract. Atrial pressure is higher than ventricular pressure, so the atrioventricular valves are open and the last of the blood is pushed into the ventricles. The semilunar valves are shut.
2. **Ventricular systole**: the ventricles contract. Ventricular pressure rises above atrial pressure, so the atrioventricular valves shut (the first heart sound). When ventricular pressure exceeds the pressure in the aorta and pulmonary artery, the semilunar valves open and blood is forced out into the arteries.
3. **Cardiac diastole**: the ventricles relax and pressure falls. Arterial pressure is now higher, so the semilunar valves shut (the second heart sound). Blood from the vena cava and pulmonary veins flows into the relaxed atria. When ventricular pressure falls below atrial pressure, the atrioventricular valves open and blood flows into the ventricles.

Summary of the cardiac cycle				
Stage	Atria	Ventricles	Atrioventricular valves	Semilunar valves
Atrial systole	Contract	Relaxed, filling	Open	Closed
Ventricular systole	Relaxed, filling	Contract	Closed	Open (once pressure exceeds arterial pressure)
Cardiac diastole	Relaxed, filling	Relaxed, filling	Open	Closed



Each valve opens or closes when the pressure on one side becomes higher than on the other.

Length of the cardiac cycle

A person's resting heart rate is 75 beats per minute. Calculate the time for one cardiac cycle.

1. There are 60 seconds in a minute
2. Time for one cycle = $60 \div \text{heart rate} = 60 \div 75$

Answer: 0.8 s

Exam tip: When asked why a valve opens or closes, always compare the pressures on each side of it, and say which is higher. For example: 'ventricular pressure is higher than atrial pressure, so the atrioventricular valve shuts'.

Haemoglobin and the transport of oxygen and carbon dioxide Spec 1.9(i)

Transport of oxygen

Haemoglobin (Hb) is a protein with a quaternary structure: four polypeptide chains, each with a **haem group** containing an Fe^{2+} ion. Each haem group can combine reversibly with one oxygen molecule, so one haemoglobin molecule can carry four O_2 molecules. Haemoglobin is packed inside red blood cells.



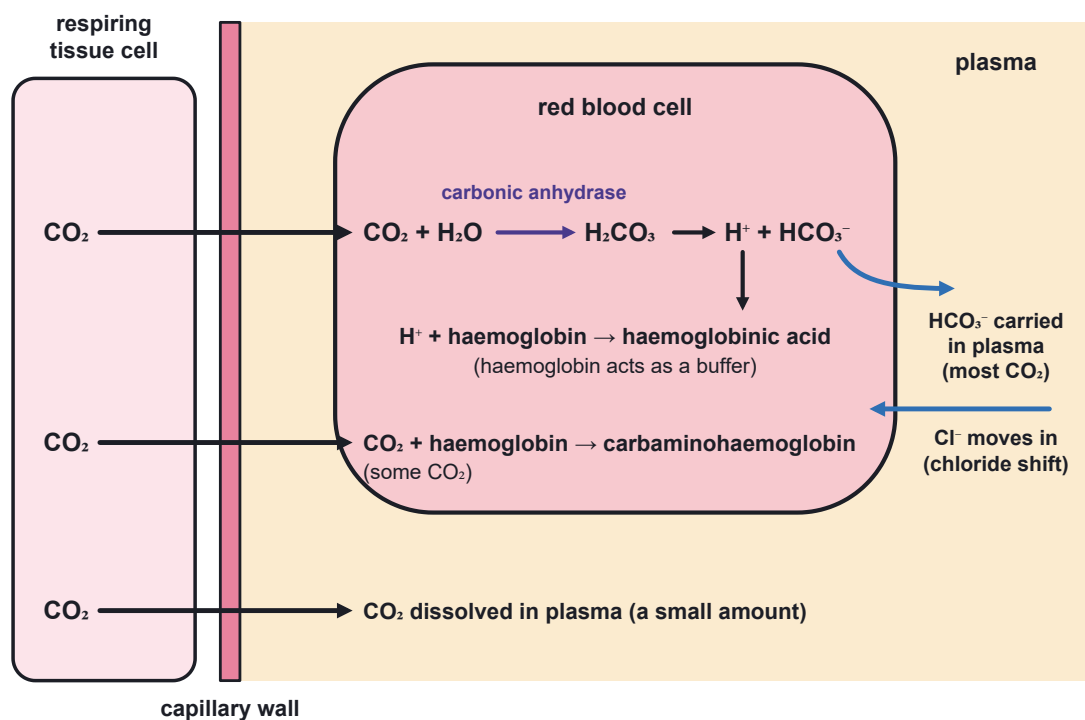
In the lungs the partial pressure of oxygen is high, so oxygen **loads** onto haemoglobin, forming **oxyhaemoglobin**. In respiring tissues the partial pressure of oxygen is low, so oxygen is released (**unloaded**) and diffuses into cells.

Transport of carbon dioxide

How carbon dioxide is carried in blood

Form	Approximate share	Where and how
Hydrogencarbonate ions (HCO_3^-)	Most (about 70 to 85 %)	Formed inside red blood cells and carried in plasma
Carbaminohaemoglobin	About 10 to 20 %	CO_2 binds directly to haemoglobin
Dissolved CO_2	About 5 %	Dissolved in plasma

1. CO_2 from respiring tissues diffuses into red blood cells.
2. The enzyme **carbonic anhydrase** catalyses $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$ (carbonic acid), which dissociates: $\text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^-$.
3. HCO_3^- diffuses out of the red blood cell into the plasma. Chloride ions (Cl^-) move in to balance the charge (the chloride shift).
4. H^+ ions bind to haemoglobin, forming haemoglobinic acid. Haemoglobin therefore acts as a **buffer**, preventing a large fall in pH in the red blood cell.
5. In the lungs the reactions run in reverse and CO_2 diffuses out of the blood into the alveoli.

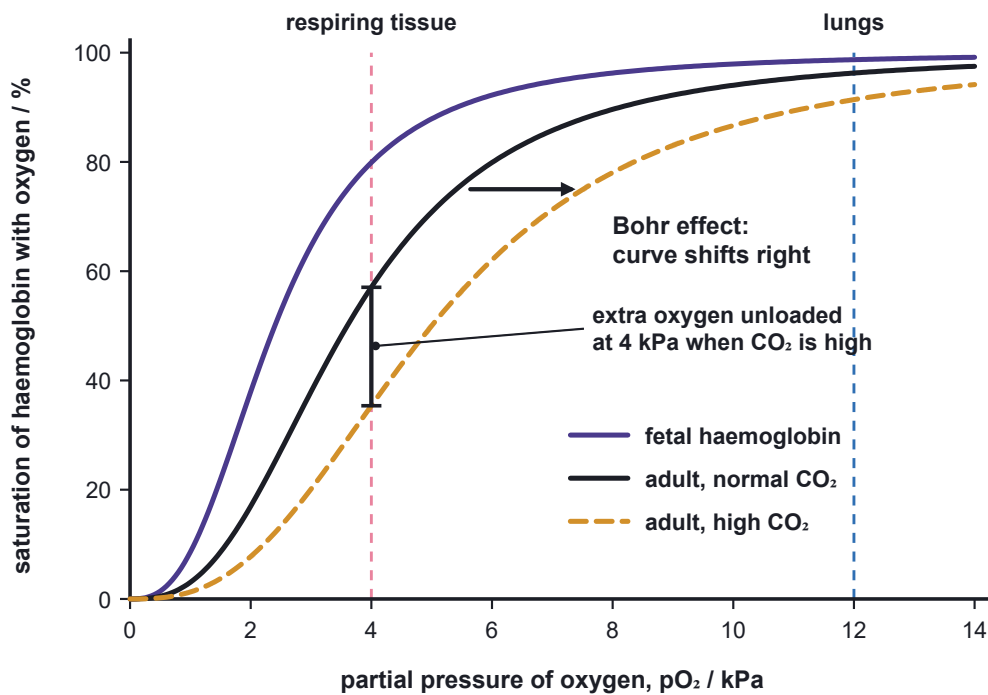


Most carbon dioxide travels as **hydrogencarbonate ions** in the plasma.

Common mistake: Most carbon dioxide is carried as hydrogencarbonate ions in the plasma, not on haemoglobin. Haemoglobin's role in carbon dioxide transport is to combine with H^+ ions (buffering) and to carry some CO_2 directly.

The oxygen dissociation curve, the Bohr effect and fetal haemoglobin Spec 1.9(ii)

The **oxygen dissociation curve** shows the percentage saturation of haemoglobin with oxygen (y-axis) against the partial pressure of oxygen, pO_2 , in kPa (x-axis). The curve is **S-shaped** (sigmoid).



High CO_2 shifts the curve **to the right**, so more oxygen is unloaded; fetal haemoglobin lies to the left.

Why the curve is S-shaped

- At low pO_2 the curve is shallow. The first oxygen molecule is hard to bind because the haem groups are inside the protein.
- Once one oxygen molecule binds, the haemoglobin changes shape slightly, making it easier for the next ones to bind. This **cooperative binding** gives the steep middle section.
- At high pO_2 the curve levels off because haemoglobin is almost saturated: few haem groups are still free, so a further rise in pO_2 adds little more oxygen.

In the lungs (high pO_2) haemoglobin is about 95 % or more saturated. In respiring tissues (low pO_2) it is much less saturated, because it releases oxygen. The steep part of the curve is at the pO_2 of respiring tissues, so a small fall in pO_2 makes a large amount of oxygen unload.

The Bohr effect

Respiring tissues release CO_2 . CO_2 forms carbonic acid, which dissociates to release H^+ ions, so a higher partial pressure of CO_2 lowers the pH. Haemoglobin changes shape, its **affinity** for oxygen falls, and the curve shifts to the **right**. This is the **Bohr effect**. At a given pO_2 the haemoglobin is then less saturated, so **more oxygen is unloaded** where it is needed most, in active tissues. In the lungs, where CO_2 is removed, the affinity rises again and oxygen loads easily.

Fetal haemoglobin

Fetal haemoglobin has a **higher affinity** for oxygen than adult haemoglobin at all partial pressures. Its curve lies to the **left** of the adult curve. In the placenta the pO_2 is low, so the mother's haemoglobin unloads oxygen, and the fetal haemoglobin, which is still highly saturated at this low pO_2 , loads it. Oxygen is therefore transferred from mother to fetus.

Percentage saturation of haemoglobin (typical rounded values for practice)

pO ₂ / kPa	Adult Hb (%)	Fetal Hb (%)
2	17	33
4	57	76
6	80	90
8	90	95
10	94	97
12	96	98

Exam tip: 'Shift to the right' means lower affinity, so more oxygen is released at the same pO₂. Describe a shift in terms of percentage saturation at a stated pO₂, and use values from the graph if one is given.

Quick check

1. Why does a large animal need a circulatory system?
2. Why is the left ventricle wall thicker than the right?
3. What are the three stages of the cardiac cycle?
4. How many oxygen molecules can one haemoglobin molecule carry?
5. What happens to the oxygen dissociation curve when CO₂ concentration increases?

Quick check answers

The heart, blood vessels and haemoglobin

- 1 . Its surface area to volume ratio is small and diffusion distances are long, so diffusion alone is too slow to supply all cells.
- 2 . It pumps blood to the whole body at high pressure, whereas the right ventricle only pumps to the lungs.
- 3 . Atrial systole, ventricular systole and cardiac diastole.
- 4 . Four, one on each haem group.
- 5 . It shifts to the right (Bohr effect), so haemoglobin releases more oxygen.