

Cambridge AS & A Level · Biology 9700 · Notes

Transport in mammals

AS

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What you need to know

By the end of this topic you should be able to:

The circulatory system

1. **State that mammals have a closed double circulation**, made of a heart, blood, and blood vessels: arteries, arterioles, capillaries, venules and veins.
2. **Describe what the main vessels of the pulmonary and systemic circulations do**: the pulmonary artery, pulmonary vein, aorta and vena cava.
3. **Recognise arteries, veins and capillaries** in microscope slides, photomicrographs and electron micrographs, and **draw plan diagrams** of arteries and veins in transverse section (TS) and longitudinal section (LS).
4. **Explain how the structure** of muscular arteries, elastic arteries, veins and capillaries **suits each one's job**.
5. **Recognise and draw red blood cells, monocytes, neutrophils and lymphocytes** from slides, photomicrographs and electron micrographs.
6. **State that water is the main component of blood and tissue fluid**, and link two of its properties to transport: it is a **solvent**, and it has a **high specific heat capacity**.
7. **State what tissue fluid does, and describe how it forms** in a capillary network.

Transport of oxygen and carbon dioxide

8. **Describe how red blood cells carry oxygen and carbon dioxide**, including the roles of haemoglobin and carbonic anhydrase, and the formation of haemoglobinic acid and carbaminohaemoglobin.
9. **Describe the chloride shift and explain why it matters**.
10. **Describe how plasma carries carbon dioxide**.
11. **Describe and explain the oxygen dissociation curve** of adult haemoglobin.
12. **Explain why the shape of the curve matters** at the partial pressures of oxygen in the lungs and in respiring tissues.
13. **Describe the Bohr shift and explain why it matters**.

The heart

14. **Describe the outside and inside structure** of the mammalian heart.
15. **Explain the differences in wall thickness** between the atria and the ventricles, and between the left and right ventricles.
16. **Describe the cardiac cycle**, linking the blood pressure changes in systole and diastole to the opening and closing of the valves.
17. **Explain the roles of the sinoatrial node, the atrioventricular node and the Purkyne tissue** in the cardiac cycle. Nervous and hormonal control of the heart are **not** needed.

Understand it

In a large, active mammal most cells are too far from the lungs and gut for diffusion alone, so blood is pumped round by **mass flow**, and diffusion only works over the last short distance, from capillary to cell.

A closed double circulation

- **Closed**: the blood stays inside blood vessels all the way round. It leaves the vessels only as the fluid that forms tissue fluid.
- **Double**: on each complete trip round the body, the blood passes **through the heart twice**.
 - The **pulmonary circulation** takes blood from the heart to the **lungs** and back.
 - The **systemic circulation** takes blood from the heart to the **rest of the body** and back.

The advantage: blood that has lost pressure in the lungs is **pumped again at high pressure** to the body, while the lungs get a **lower pressure** that doesn't damage their thin capillaries.

On the way out, blood goes **artery** → **arteriole** → **capillary** → **venule** → **vein** and back to the heart.

Vessel	Carries	From → to
Pulmonary artery	Deoxygenated blood	Right ventricle → lungs
Pulmonary vein	Oxygenated blood	Lungs → left atrium
Aorta	Oxygenated blood, at the highest pressure	Left ventricle → all of the body (through its branches)
Vena cava	Deoxygenated blood, at the lowest pressure	Body → right atrium

Arteries carry blood **away from the heart** and veins **towards** it, whatever its oxygen content.

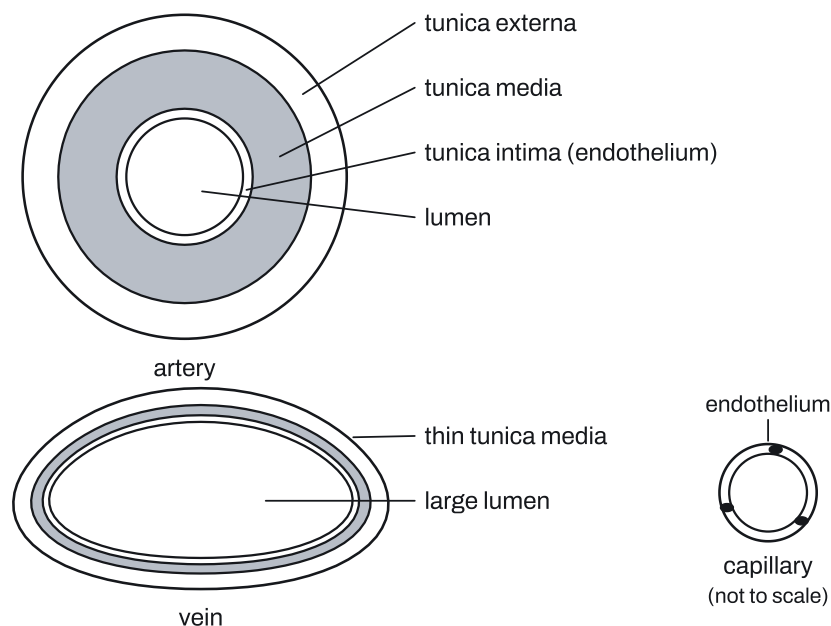
Blood pressure is highest in the aorta and falls all the way round: it drops most in the **arterioles** and capillaries (where the vessels are narrow and there are so many of them), and is lowest in the **vena cava**. The pulmonary artery has a lower pressure than the aorta, because the right ventricle pumps less forcefully. In arteries, the pressure rises and falls with each heartbeat; in veins it is low and steady.

Blood vessels

The walls of arteries and veins have three layers:

- **Tunica intima** (inner layer): the **endothelium**, one layer of thin, flat cells, which gives a smooth lining so blood flows with little friction. In arteries it sits on a layer of elastic tissue.
- **Tunica media** (middle layer): **smooth muscle** and **elastic fibres**, in different amounts in different vessels.
- **Tunica externa** (outer layer, also called the adventitia): mostly **collagen** fibres, which are strong and stop the vessel over-stretching or bursting.

A **capillary** wall is just the endothelium, one cell thick.



Vessel	Structure	How it suits the job
Elastic artery (the aorta, the pulmonary artery)	Thick wall; tunica media with many elastic fibres and less smooth muscle; small lumen	Blood arrives in surges at high pressure: the elastic fibres stretch so the wall doesn't burst, then recoil between beats, pushing blood on, keeping the pressure up and smoothing the flow.
Muscular artery (further from the heart, to organs)	Tunica media with much more smooth muscle and fewer elastic fibres	The smooth muscle contracts or relaxes to narrow or widen the lumen , changing how much blood goes to each organ.
Arteriole	Mostly smooth muscle, thin wall, narrow lumen	Controls the flow into each capillary bed ; the pressure falls a lot here.
Capillary	Wall one endothelial cell thick ; lumen about the width of one red blood cell ; gaps between the cells (pores or fenestrations); huge network	Short diffusion distance ; red cells pass slowly, close to the wall; the gaps let fluid out to form tissue fluid; a large surface area close to every cell.

Vessel	Structure	How it suits the job
Vein	Thin wall; thin tunica media with little muscle and elastic tissue; large lumen ; valves ; collagen outer layer	Low pressure, so no thick wall is needed; the large lumen gives low resistance and holds a lot of blood; valves stop backflow ; nearby skeletal muscles squeeze veins to push blood on.

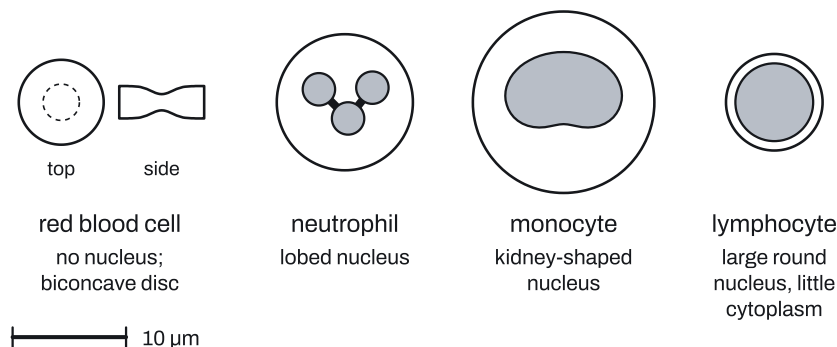
Recognising vessels in slides and micrographs

- **Artery**: round, with a **thick** wall and a **small** lumen for its size; the endothelium often looks **wavy** (folded).
- **Vein**: **thin** wall for its size, a **large** lumen, often squashed or an irregular shape; you may see a valve in LS.
- **Capillary**: tiny; in an electron micrograph you see one or two thin endothelial cells round a lumen that may hold a single red blood cell.

Plan diagrams show only the **outlines of the layers**, never cells, in the right proportions with ruled label lines. In LS, an artery shows thick walls either side of a narrow lumen; a vein shows thin walls, a wide lumen and valves.

Blood cells

Blood is **plasma** (mostly water, with dissolved substances) plus cells.



Cell	How to recognise it	Job
Red blood cell (erythrocyte)	Small (about 7–8 µm), biconcave disc , paler in the middle; no nucleus , no mitochondria	Carries oxygen (and some carbon dioxide)
Neutrophil	Nucleus with several lobes (usually 2–5); grainy cytoplasm; larger than a red cell	Phagocyte: engulfs and digests pathogens
Monocyte	Largest white cell; large kidney- or bean-shaped nucleus	Phagocyte: moves into tissues and becomes a macrophage
Lymphocyte	About the size of a red cell or a bit larger; large round nucleus that almost fills the cell, with only a thin rim of cytoplasm	Immune response (B- and T- lymphocytes)

How a red blood cell's structure suits it:

- **No nucleus** or organelles: more room for **haemoglobin** (but it **cannot divide or make proteins**).
- **Biconcave**: large **surface area to volume ratio**, short distance to the centre, so fast diffusion.
- **Small and flexible**: squeezes through capillaries against the wall, so a short diffusion distance to the tissues.

To **draw** blood cells: clean outlines, correct relative sizes, the right nucleus shape, no shading.

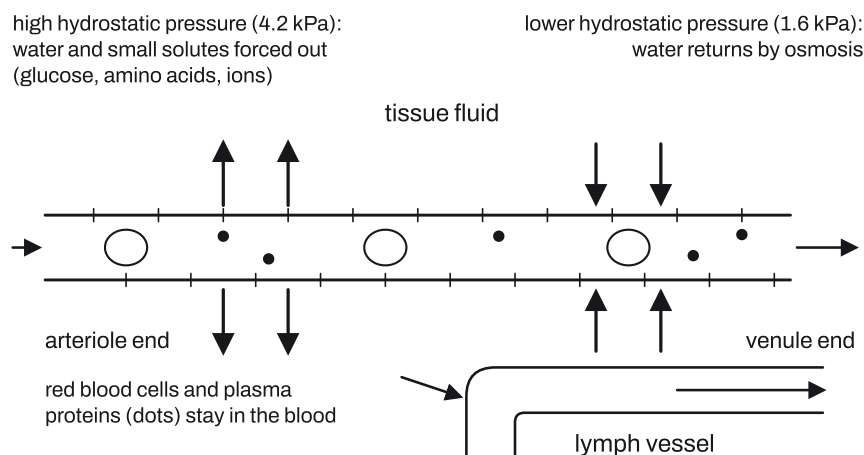
Water in blood

Water is the main component of both blood plasma and tissue fluid. Two of its properties matter here:

- **Solvent**. Water is **polar** (δ^- oxygen, δ^+ hydrogens), so it surrounds and dissolves ions and polar molecules (the δ^- oxygen is attracted to Na^+ , the δ^+ hydrogens to Cl^-). Glucose, amino acids, ions, urea, hormones and hydrogencarbonate ions are carried dissolved in plasma.
- **High specific heat capacity**. A lot of energy is needed to change its temperature, so blood **stays at a steady temperature** and can **carry heat** from active organs (liver, muscles) round the body.

Tissue fluid

Tissue fluid is the liquid that bathes every cell. It forms from blood plasma leaking out of the capillaries.



How it forms:

1. At the **arteriole end** the blood's **hydrostatic pressure** (from the heart) is **high**, higher than that of the tissue fluid.
2. This forces **water and small solutes** (glucose, amino acids, fatty acids, ions, oxygen) **out** through the **gaps between the endothelial cells**. This is a kind of filtration (ultrafiltration).
3. **Red blood cells, platelets and the large plasma proteins stay in the blood**: they are too big to pass through the gaps. Some white blood cells (such as neutrophils) can squeeze out.

4. The plasma proteins that stay behind give the blood a **lower (more negative) water potential** than the tissue fluid. This pulls water back **in** by **osmosis** all along the capillary.
5. Along the capillary the hydrostatic pressure **falls**. At the **venule end** it is now lower than the osmotic pull, so there is a **net movement of water back into the blood** by osmosis, carrying some solutes such as carbon dioxide and urea.
6. Not all of the fluid returns (about 90% does). The rest drains into blind-ended **lymph vessels** and is called **lymph**; it is later returned to the blood.

What tissue fluid does:

- It gives cells **watery surroundings** with a steady water potential.
- It is the **medium for exchange**: oxygen, glucose, amino acids and ions pass from it into cells; carbon dioxide and wastes such as urea pass from cells into it and on into the blood.
- Phagocytes move about in it, and hormones travel through it to their target cells.

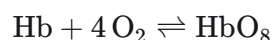
Compared with plasma, tissue fluid has the same small solutes but **much less protein** (not **none**) and **no red blood cells**, with few white cells.

Oedema, a build-up of tissue fluid, happens when blood pressure is **too high** or the blood has **too little plasma protein** (for example from a protein-poor diet), so less water returns by osmosis.

Haemoglobin

Haemoglobin is a **globular protein** with **quaternary structure**, made of **four polypeptide chains**: **two α -globin** and **two β -globin** chains, held together by hydrogen bonds, ionic bonds and hydrophobic interactions between the chains. Each chain carries one **haem group**, which contains an **iron ion (Fe^{2+})**.

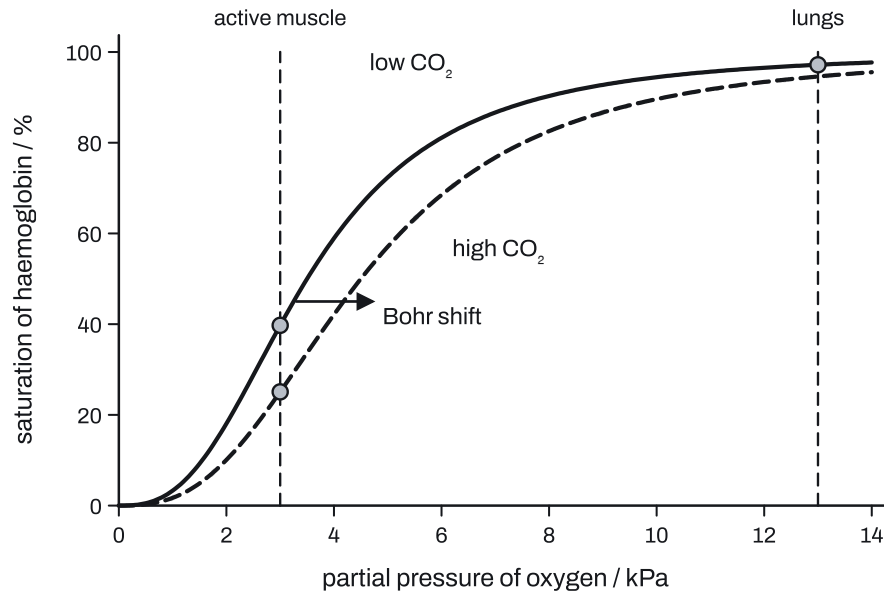
- Each Fe^{2+} can bind **one oxygen molecule** (two oxygen atoms), so one haemoglobin molecule carries up to **four O_2 molecules** (eight oxygen atoms). Fully loaded it is **oxyhaemoglobin**:



- **Cooperative binding**: when the first O_2 binds, the shape of the whole molecule changes slightly, which makes it **easier for the next O_2 molecules to bind**. Likewise, once one O_2 leaves, the others leave more easily.
- Its hydrophilic R groups on the outside make it **soluble**, so it can be packed at a high concentration in the red cell's cytoplasm.
- Carbon monoxide also binds to the haem, very strongly, so it stops that haem carrying oxygen.

The oxygen dissociation curve

The **partial pressure of oxygen** (pO_2 , in kPa) measures how much oxygen there is. The **oxygen dissociation curve** shows the **percentage saturation** of haemoglobin with oxygen at each pO_2 . For adult haemoglobin it is **S-shaped (sigmoid)**.



Why it is S-shaped:

- **Low pO₂: shallow**, because the first O₂ binds with difficulty.
- **Middle: steep**, because once one O₂ has bound the molecule changes shape and the rest bind easily (**cooperative binding**).
- **High pO₂: levels off** near 100%, as almost every haem is already loaded.

Why the shape matters:

- **In the lungs** (pO₂ about 13 kPa, the flat top) haemoglobin is **almost fully saturated** (about 97% here), and a small fall in pO₂ hardly changes loading.
- **In respiring tissues** (about 5 kPa at rest, lower when active) the curve is **steep**, so a **small fall in pO₂ releases a lot of oxygen**: about 72% saturated at 5 kPa but only about 18% at 2 kPa. The harder a tissue works, the more oxygen it gets.

Affinity is how strongly haemoglobin holds oxygen: a curve **to the left = higher affinity** (loads at lower pO₂, releases less easily); **to the right = lower affinity** (releases more easily).

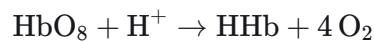
The Bohr shift

When there is **more carbon dioxide**, the dissociation curve moves **to the right**: haemoglobin's **affinity for oxygen is lower**, so it releases more oxygen at the same pO₂. This is the **Bohr shift** (or Bohr effect). What directly causes it is the **fall in pH** (more hydrogen ions).

How it happens:

1. Respiring cells make carbon dioxide, which diffuses into the red blood cells.
2. **Carbonic anhydrase** catalyses: $\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3$ (carbonic acid).
3. Carbonic acid dissociates: $\text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^-$.

4. The **H⁺ binds to haemoglobin**, forming **haemoglobinic acid (HHb)**. This **changes the shape** of the haemoglobin, **lowering its affinity** for oxygen, so it **releases its oxygen**, which diffuses out to the cells.



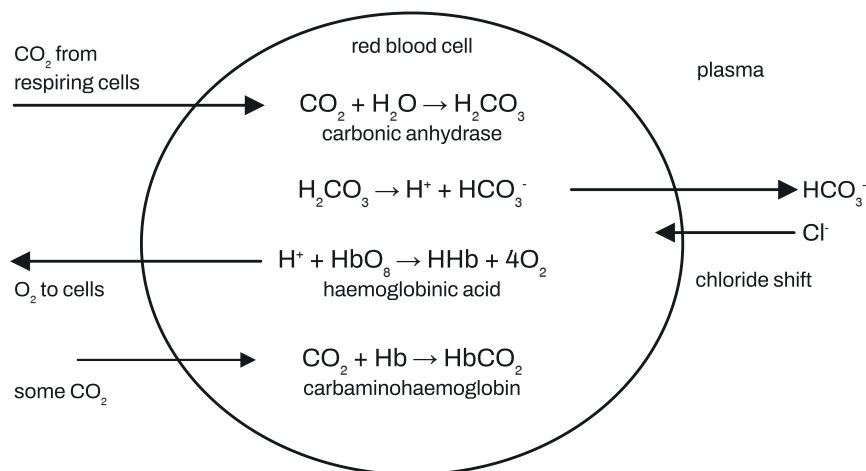
Why it matters:

- Tissues that respire fastest make the most carbon dioxide, so they get **the most oxygen**, exactly where it is needed.
- In the **lungs**, carbon dioxide is being lost, so the curve is back to the left and haemoglobin **loads oxygen fully**.
- Taking up the H⁺ also **buffers** the blood: it stops the pH of the blood falling too far.

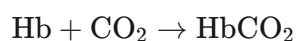
The reverse is also examined: if a person **breathes very fast and deeply**, the blood loses carbon dioxide, so less carbonic acid and fewer H⁺ are made, less haemoglobinic acid forms, haemoglobin keeps a **higher affinity**, and **less oxygen is released** to the tissues.

Carbon dioxide transport and the chloride shift

Carbon dioxide travels in the blood in three ways.



1. **As hydrogencarbonate ions (HCO_3^-)**, which is how **most** carbon dioxide is carried. They are made inside red blood cells (steps 1–3 above), which contain **carbonic anhydrase**; then most of them diffuse out and are carried **in the plasma**.
2. **As carbaminohaemoglobin**: some carbon dioxide combines with the **amine ($-\text{NH}_2$) groups** of the globin chains of haemoglobin. This does not need carbonic anhydrase.



3. **Dissolved in the plasma**: a small amount travels as CO_2 in solution.

The role of plasma: it carries the **hydrogencarbonate ions** (the main form) and the **dissolved carbon dioxide**. Carbon dioxide reacts with water only very slowly in plasma itself, because plasma has **no carbonic anhydrase**; that is why the red cells do the conversion.

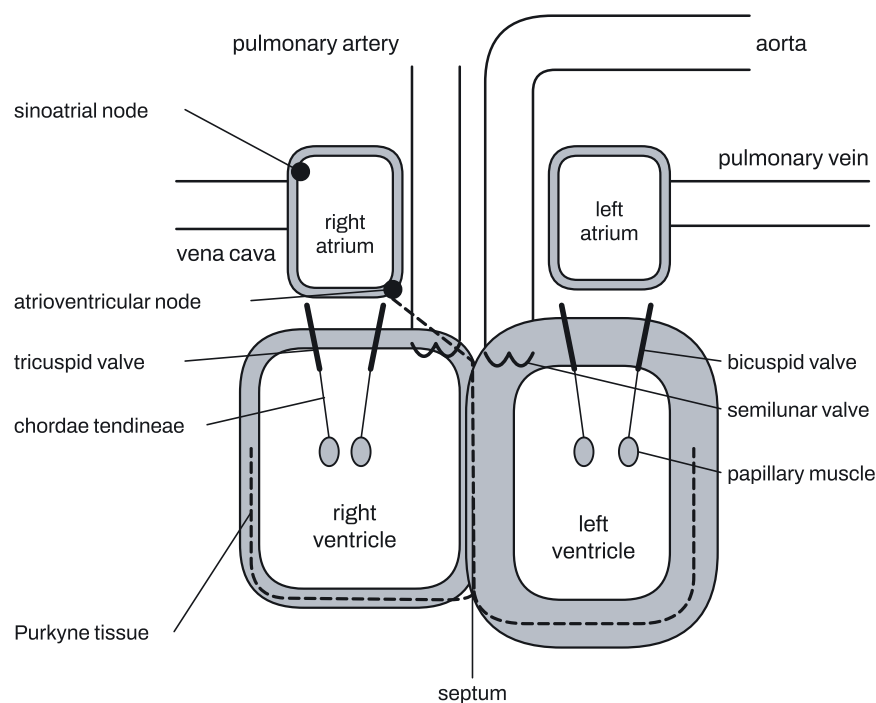
The chloride shift

- As hydrogencarbonate ions build up inside the red cell, they **diffuse out** into the plasma, through a **transport protein** in the cell surface membrane.
- Losing negative ions would leave the inside of the cell positively charged. To balance this, **chloride ions (Cl⁻) diffuse in** from the plasma through the same protein, in exchange.
- Why it matters:** it keeps the red cell **electrically neutral** (balances the charge), and by removing HCO₃⁻ it lets carbonic acid keep dissociating, so **more carbon dioxide can be converted** and carried. So blood leaving respiring tissues has **fewer chloride ions** in its plasma.

In the lungs, everything goes backwards. Oxygen binds to haemoglobin, which releases H⁺ from haemoglobinic acid and CO₂ from carbaminohaemoglobin. HCO₃⁻ diffuses back into the red cells (and Cl⁻ moves out); $\text{H}^+ + \text{HCO}_3^- \rightarrow \text{H}_2\text{CO}_3$, and carbonic anhydrase turns it back into CO₂ + H₂O. The carbon dioxide diffuses into the alveoli and is breathed out.

The structure of the heart

The heart is made of **cardiac muscle**. Outside, you see the **atria** on top, the larger **ventricles** below, the large vessels, and the **coronary arteries** (branches of the aorta) over the surface, which **supply the heart muscle itself**.



Inside:

- Four chambers:** two **atria** receive blood, two **ventricles** pump it out. **The heart's right side is on the left of the page.**
- The **septum** separates the right side (deoxygenated blood) from the left (oxygenated), so they never mix.

- **Atrioventricular (AV) valves** between each atrium and ventricle: the **tricuspid** valve on the right and the **bicuspid** (mitral) valve on the left. They stop blood flowing back into the atria when the ventricles contract.
- **Chordae tendineae** (tendons) join the AV valve flaps to **papillary muscles** in the ventricle wall. They hold the flaps so the valves **don't turn inside out** when the ventricles contract.
- **Semilunar valves** at the base of the **pulmonary artery** and the **aorta**. They stop blood flowing back into the ventricles when the ventricles relax.

The route of blood: vena cava → right atrium → tricuspid valve → right ventricle → semilunar valve → pulmonary artery → lungs → pulmonary vein → left atrium → bicuspid valve → left ventricle → semilunar valve → aorta → body.

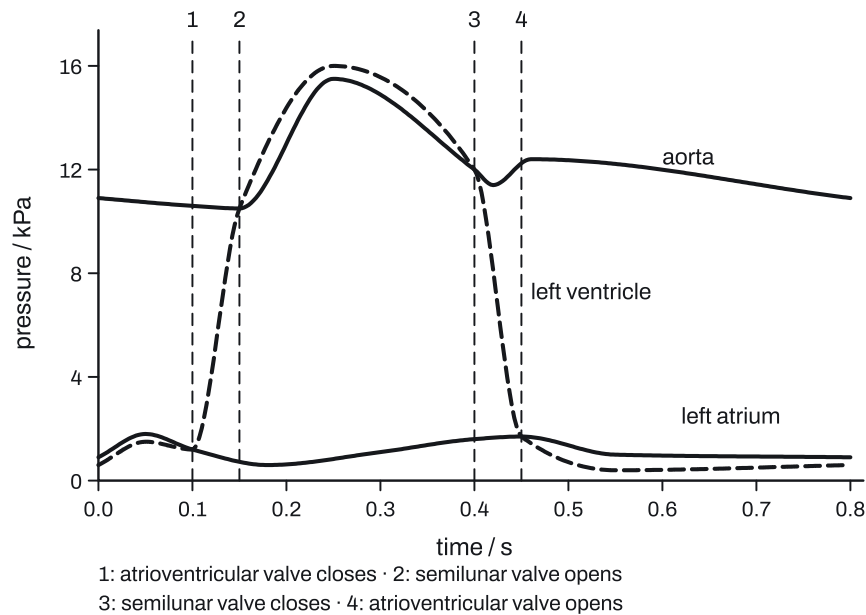
Why the walls differ in thickness

- **Atria vs ventricles.** The atria only push blood a **short distance**, down into the ventricles, at **low pressure**, so they have **thin** walls. The ventricles push blood **out of the heart** and all the way round a circulation, so they need **thicker** walls with more muscle to contract with more force and make a higher pressure.
- **Left vs right ventricle.** The **left** ventricle pumps blood round the **whole systemic circulation**: a long distance with a lot of **resistance** to overcome, so it needs a **high pressure** and has a **much thicker** wall. The **right** ventricle pumps only to the **lungs**, which are close by. A lower pressure is also safer for the thin lung capillaries. Both ventricles pump the **same volume** per beat.

The cardiac cycle

One heartbeat is one **cardiac cycle**. **Systole** means contraction; **diastole** means relaxation. At 75 beats per minute, a cycle lasts 0.8 s.

The one rule for valves: blood always moves from **higher to lower pressure**, and a valve **opens** when the pressure **behind** it is higher than the pressure **in front** of it. It **closes** when the pressure in front becomes higher, because the blood would then flow backwards and pushes the flaps shut.



1. **Atrial systole** (0–0.1 s). The atria contract; the AV valves are **open**, so the last blood is pushed into the **ventricles**. The semilunar valves are **closed** (arterial pressure is higher than ventricular).
2. **Ventricular systole** (0.1–0.4 s). The ventricles contract, from the **bottom (apex) upwards**, and the atria relax.
 - Ventricular pressure > atrial pressure: the **AV valves close** (line 1). With all valves shut, ventricular pressure rises very fast.
 - Ventricular pressure > pressure in the aorta (or pulmonary artery): the **semilunar valves open** (line 2) and blood is pushed out.
3. **Diastole** (0.4–0.8 s). The ventricles and atria both relax.
 - Ventricular pressure < aortic pressure: the **semilunar valves close** (line 3).
 - Very soon after, ventricular pressure < atrial pressure: the **AV valves open** (line 4).
 - Blood from the veins flows through the atria into the ventricles, which fill passively.

Aortic pressure never falls near zero, because the **elastic recoil** of its wall keeps squeezing blood on during diastole. The right side has the same pattern at much **lower** pressures.

Controlling the heartbeat

Cardiac muscle is **myogenic**: the heartbeat starts in the heart muscle itself, without needing nerve impulses.

1. The **sinoatrial node (SAN)**, a patch of specialised muscle in the **wall of the right atrium** (near where the vena cava enters), sends out a **wave of electrical excitation** at regular intervals. It is the heart's **pacemaker**: it sets the rate.
2. The wave spreads **across the walls of both atria**, so they contract together: **atrial systole**.
3. A band of **non-conducting fibrous tissue** between the atria and ventricles **stops the wave** passing straight into the ventricle walls.

4. The only way through is the **atrioventricular node (AVN)**, in the **septum where the atria meet the ventricles**. The AVN **delays** the wave by about **0.1 s**. This gives the atria time to **finish contracting** and the ventricles time to **fill** before the ventricles contract.
5. The AVN passes the wave into the **Purkyne tissue** (Purkyne fibres), which carries it quickly **down the septum** to the **base (apex) of the ventricles**, then up through the ventricle walls.
6. So both ventricles contract **together**, starting **from the apex upwards**, which squeezes the blood up and out into the arteries: **ventricular systole**.

Key facts and formulas

None of these are in the syllabus's list of mathematical formulae, so they are all "Learn it".

Formula	Status
$\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$ (catalysed by carbonic anhydrase, in red blood cells)	Learn it
$\text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^-$	Learn it
$\text{HbO}_8 + \text{H}^+ \rightarrow \text{HHb} + 4 \text{O}_2$ (haemoglobinic acid)	Learn it
$\text{Hb} + \text{CO}_2 \rightarrow \text{HbCO}_2$ (carbaminohaemoglobin)	Learn it
$\text{Hb} + 4 \text{O}_2 \rightleftharpoons \text{HbO}_8$: 4 O ₂ per haemoglobin, one per haem (Fe ²⁺)	Learn it
Chloride shift: HCO_3^- out of the red cell, Cl^- in	Learn it
A valve opens when the pressure behind it is higher than the pressure in front	Learn it
Heart rate (beats per minute) = $\frac{60}{\text{length of one cardiac cycle in s}}$	Learn it
Percentage change = $\frac{\text{new} - \text{original}}{\text{original}} \times 100$	Learn it
Net pressure out of a capillary = (hydrostatic pressure in blood – hydrostatic pressure in tissue fluid) – the inward pull caused by the plasma proteins	Learn it
Magnification = $\frac{\text{image size}}{\text{actual size}}$ (1 mm = 1000 µm)	Learn it
Curve to the left: higher affinity for O ₂ ; curve to the right: lower affinity (Bohr shift)	Learn it

How to do it

We have tagged 206 questions on this topic from 2021–2025: 165 multiple choice on Paper 1 and 41 structured questions on Paper 2. 37 of them mix types, so the counts add up to 260.

Question type	Questions
Explain carbon dioxide transport (carbonic anhydrase, haemoglobinic acid, carbaminohaemoglobin, chloride shift)	38
Relate pressure changes to valves and stages of the cardiac cycle	31
Relate blood vessel structure to function; identify vessels	29
Describe heart structure, wall thickness and the route of blood	26
Describe tissue fluid formation and composition	24
Describe control of the heartbeat (SAN, AVN, Purkyne tissue)	23
Identify and describe blood cells	19
Explain the Bohr shift	17
Describe the circulation and blood pressure in the main vessels	15
Interpret oxygen dissociation curves and changes in affinity	13
Describe haemoglobin's structure and how it binds oxygen	9
Calculate from pressure or dissociation data	6
Explain adaptation to high altitude	6
Relate properties of water to transport	4

1. Explain carbon dioxide transport (38 questions)

Write the steps from "Carbon dioxide transport and the chloride shift" in order, **naming every substance**: CO_2 diffuses in $\rightarrow$ carbonic anhydrase $\rightarrow$ carbonic acid $\rightarrow \text{H}^+$ and $\text{HCO}_3^- \rightarrow$ haemoglobinic acid (O_2 released, pH buffered) $\rightarrow \text{HCO}_3^-$ out, Cl^- in $\rightarrow$ some carbaminohaemoglobin, a little dissolved in plasma.

Variations you will meet:

- **Carbonic anhydrase** catalyses only $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$. An **inhibitor** means less carbonic acid, fewer H^+ and HCO_3^- , less haemoglobinic acid, less O_2 released and less chloride shift; carbaminohaemoglobin is not directly affected.
- **Most CO_2** travels as **hydrogencarbonate ions** in the plasma.
- **Lungs or respiring tissue?** In the lungs every reaction runs the **other way** ($\text{HCO}_3^- + \text{H}^+ \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$; $\text{HHb} \rightarrow \text{Hb} + \text{H}^+$; $\text{Hb} + 4\text{O}_2 \rightarrow \text{HbO}_8$).
- **What rises in a red cell** as CO_2 enters: carbonic acid, H^+ , HCO_3^- , haemoglobinic acid and chloride ions; oxyhaemoglobin falls. So these are highest at **high CO_2 and low pO_2** on a dissociation graph, and deoxygenated plasma has **fewer chloride ions**.

- **Fill in a diagram or passage:** use full names. For an unfamiliar animal (for example one with carbonic anhydrase but no chloride shift), say what each remaining step still does.

2. Relate pressure changes to valves and stages of the cardiac cycle (31 questions)

1. **Name the stage:** a small atrial peak = atrial systole; high ventricle pressure = ventricular systole; everything low = diastole.
2. **Find where the lines cross:** ventricle crosses atrium → AV valve; ventricle crosses artery → semilunar valve. Use the valve rule to say open or shut.

Variations you will meet:

- **Times from a graph:** the ventricle is fullest just as the AV valve closes, emptiest as the semilunar valve closes. "Both sets of valves shut" means two gaps added together (Example 2).
- **A written sequence** from the pulmonary vein to the aorta: give each valve movement with its **pressure comparison**, as in Example 2 (c).
- **Ventricle volume graphs:** volume rises in diastole and atrial systole, is steady while all valves are shut, and falls once the semilunar valves open.
- **Valve positions seen from above:** AV open, semilunar shut = atrial systole or late diastole; AV shut, semilunar open = ventricular systole.
- **"At the start of ventricular diastole":** the ventricles relax, the semilunar valves close first, and very soon after (once ventricular pressure falls below atrial pressure) the **AV valves open**. Cambridge multiple-choice questions phrased this way expect **"the atrioventricular valves open"** (9700/13/O/N/24 Q31). The semilunar valves never **open** in diastole.

3. Relate blood vessel structure to function; identify vessels (29 questions)

Give each **feature with its job** in one sentence, from the table in "Blood vessels".

Variations you will meet:

- **Identify a vessel** from a micrograph, plan diagram or bar chart: much elastic tissue = elastic artery; much smooth muscle = muscular artery or arteriole; thin wall, large lumen = vein; endothelium only = capillary. **Every** vessel has an endothelium.
- **An arteriole** needs **smooth muscle** to change the blood flow.
- **Aorta vs muscular artery:** compare the **proportions** of elastic fibres and smooth muscle, then link to the aorta's surges of blood.
- **Vein valves** are just "valves" (not "semilunar valves").
- **Membranes crossed** by CO₂ going from tissue fluid through an endothelial cell into plasma: **2** (in and out of one cell).

4. Describe heart structure, wall thickness and the route of blood (26 questions)

Orient the diagram (the heart's right side is on the left of the page; the thick ventricle is the left), label from the heart diagram, and for wall thickness give the comparison **and** the reason (distance, pressure, resistance).

Variations you will meet:

- **Features of the left side and their job**, for example from a photograph: thick ventricle wall (high pressure for the systemic circulation), thin atrial wall (short distance), bicuspid and semilunar valves (prevent backflow), chordae tendineae (stop the valve turning inside out).
- **A bar chart of wall thickness**: the atria are thinnest, then the right ventricle, then the left ventricle.
- **Vessels entering the atria**: vena cava and pulmonary vein. The coronary arteries supply the heart muscle.
- **Septal defects**. Pressure is higher on the left, so blood flows **left to right** through the hole.
 - **Ventricular septal defect (VSD)**: during ventricular systole blood flows from the left ventricle into the right ventricle.
 - **Atrial septal defect (ASD)**: oxygenated blood flows from the left atrium into the right atrium. So blood in the **pulmonary artery** has **more oxygen** and a **higher pressure**; blood in the **aorta** has about the **same** oxygen but a **lower pressure**, because less blood is pumped to the body. The body receives **less oxygen overall**, so it makes **more red blood cells** to compensate (9700/11/O/N/24 Q30, 9700/13/M/J/25 Q30).
- **A heart with one shared ventricle** (as in an amphibian): oxygenated and deoxygenated blood mix, and the lungs and body can't get different pressures.

5. Describe tissue fluid formation and composition (24 questions)

Give the steps from "Tissue fluid" in order, ending with **osmosis** at the venule end and drainage into lymph.

Variations you will meet:

- **Most tissue fluid returns by osmosis** into the blood, not by active transport.
- **Tick tables**: blood, tissue fluid and lymph all contain water, glucose, ions, CO₂, some proteins (such as antibodies) and white cells; only blood has **red cells** and plenty of **large plasma proteins**. Lymph can also carry lipids.
- **Two functions**: exchange medium for O₂, CO₂, nutrients and wastes; watery surroundings for cells; a route for phagocytes and hormones.
- **Oedema**: high blood pressure, or low plasma protein (poor diet, liver or kidney disease).
- **Numbers**: use the net pressure formula (Example 3).

6. Describe control of the heartbeat (23 questions)

Give the six steps from "Controlling the heartbeat" in order, saying **where** each structure is.

Variations you will meet:

- **Role of the AVN:** the only route to the ventricles; its **delay** lets the atria empty and the ventricles fill first.
- **Role of the Purkyne tissue:** carries the wave down the septum to the apex, so both ventricles contract **together, from the bottom up**.
- **Locate the AVN:** in the **septum where the atria meet the ventricles** (not just anywhere in the right atrium).
- **Faults (Paper 2 "suggest"):** a damaged SAN (for example from a blocked coronary artery branch) gives a slow or irregular beat; an **extra pathway that bypasses the AVN** removes the delay, so the ventricles contract before they have filled and the **rate rises**; **heart block** (AVN or Purkyne tissue not passing the wave on) slows the ventricles.

7. Identify and describe blood cells (19 questions)

Look at the **nucleus** first (none = red cell; lobed = neutrophil; kidney-shaped in a large cell = monocyte; round, filling the cell = lymphocyte), then the **size**. A description such as "very large, U-shaped nucleus" is a monocyte. A mature red cell **can't divide or make proteins** (no nucleus or ribosomes) but can still do active transport. A disease that raises one cell type shows as many more of that cell in a smear.

8. Explain the Bohr shift (17 questions)

Define it (more CO_2 , lower pH $\rightarrow$ lower affinity $\rightarrow$ curve right $\rightarrow$ more O_2 released), explain it with the chain in "The Bohr shift", and say why it matters.

Variations you will meet:

- **The direct cause** is the **hydrogen ions**, not CO_2 molecules or HCO_3^- .
- **Most oxygen released** at **low pH and high pCO_2** . Carbonic anhydrase **speeds up** the Bohr shift.
- **The reverse case** (hyperventilation, less CO_2): less O_2 released (see "The Bohr shift").
- **Sketch** the shifted curve: the same S-shape to the right, meeting the original near the top.

9. Describe the circulation and blood pressure in the main vessels (15 questions)

Define **closed** and **double**, then rank the pressures: aorta > arteries > arterioles > capillaries > veins > vena cava, with the pulmonary artery below the aorta. In **diastole** the aorta is still very high (elastic recoil), the pulmonary artery high, the pulmonary vein and vena cava low. **Systolic** pressure is the highest arterial pressure, when the ventricles contract.

10. Interpret oxygen dissociation curves and changes in affinity (13 questions)

Read saturation at the lung and tissue pO_2 (the difference is the O_2 released), then decide on affinity: **left = higher, right = lower**. Link it to the animal: animals of **low-oxygen places** (altitude, burrows) have curves to the **left**; **small, very active mammals** have curves to the **right**, so O_2 is released readily. A substance that means a higher pO_2 is needed for 50% saturation shifts the curve **right**. Temperature and pH are kept constant when measuring a curve because both change affinity.

11. Describe haemoglobin's structure and how it binds oxygen (9 questions)

Use "Haemoglobin": **two α and two β chains**, a **haem with Fe^{2+}** on each, **one O_2 per haem** (four per molecule), **cooperative binding**, full loading at high pO_2 . Oxygen and carbon monoxide bind to haem; CO_2 binds to the globin.

12. Calculate from pressure or dissociation data (6 questions)

- **Percentage change**: for example a fall from 12.0 kPa to 5.0 kPa is $\frac{12.0-5.0}{12.0} \times 100 = 58.3\%$.
- **Heart rate** = $60 \div$ cycle length in s; **time with all valves shut** = the two gaps added (Example 2).
- **Net pressure out of a capillary**: if blood is at 4.0 kPa and tissue fluid at 0.5 kPa, the outward difference is 3.5 kPa; if the water potential of the blood is -3.0 kPa and of the tissue fluid -1.2 kPa, the inward pull is 1.8 kPa, so the net pressure out is $3.5 - 1.8 = 1.7$ kPa. Try **9700/13/O/N/23 Q31**.
- **Oxygen released**: saturation at lung pO_2 minus saturation at tissue pO_2 (Example 4).

13. Explain adaptation to high altitude (6 questions)

Lower pO_2 at altitude $\rightarrow$ haemoglobin less saturated $\rightarrow$ over weeks the body makes **more red blood cells** (more haemoglobin per volume), so the blood carries about as much oxygen. Animals adapted over generations (such as the llama) have **higher-affinity** haemoglobin: a curve to the **left**. With a data table, describe the trend with figures, then explain.

14. Relate properties of water to transport (4 questions)

Use "Water in blood": **solvent** (polar, so ions and polar molecules dissolve and are carried; not lipids) and **high specific heat capacity** (steady temperature, carries heat).

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
 - **A1** accuracy mark: for a correct answer; it needs the M mark before it.
 - **B1** mark for a correct result on its own, with no method needed.
-

Example 1

- (a) Describe how carbon dioxide produced by respiring muscle cells is transported to the lungs. **[5]**
- (b) Explain the importance of the chloride shift. **[2]**

(a) Carbon dioxide diffuses into the plasma and into the red blood cells. **B1** In the red cells, the enzyme **carbonic anhydrase** catalyses the reaction of carbon dioxide with water to form **carbonic acid**. **B1** Carbonic acid dissociates into **hydrogen ions** and **hydrogencarbonate ions**. **B1** The hydrogencarbonate ions diffuse out of the red cells and are carried **in the plasma** (the main form). **B1** Some carbon dioxide combines with the amine groups of haemoglobin to form **carbaminohaemoglobin**, and a little is carried **dissolved in the plasma**. **B1**

(b) As hydrogencarbonate ions (negative) leave the red cell, **chloride ions** diffuse in to replace them, which **keeps the charge balanced** (the cell stays electrically neutral). **B1** Removing the hydrogencarbonate ions lets more carbonic acid dissociate, so **more carbon dioxide can be converted and carried**. **B1**

Example 2

The graph in "The cardiac cycle" shows the pressure in the left side of a person's heart during one cycle, which lasts 0.8 s.

(a) Calculate the heart rate, in beats per minute. **[1]**

(b) Use the graph to find the total time in one cycle during which the atrioventricular and semilunar valves are both closed. **[2]**

(c) Explain what happens to the valves at 0.10 s and at 0.15 s. **[3]**

(d) Explain why the pressure in the aorta does not fall below about 10 kPa. **[2]**

(a) $60 \div 0.8 = 75$ beats per minute. **B1**

(b) Both are shut from 0.10 s (AV valve closes) to 0.15 s (semilunar valve opens), and from 0.40 s (semilunar valve closes) to 0.45 s (AV valve opens). **M1** Total = $0.05 + 0.05 = 0.10$ s. **A1**

(c) At 0.10 s the ventricle contracts and its pressure becomes **higher than the pressure in the atrium**, so the **atrioventricular (bicuspid) valve closes**, stopping backflow into the atrium. **B1** The pressure in the ventricle then rises quickly. **B1** At 0.15 s it becomes **higher than the pressure in the aorta**, so the **semilunar valve opens** and blood is forced into the aorta. **B1**

(d) The aorta's wall has many **elastic fibres**. They **stretch** when blood is pushed in during ventricular systole. **B1** During diastole they **recoil**, squeezing the blood onwards and keeping the pressure high. **B1**

Example 3

The hydrostatic pressure of the blood is 4.2 kPa at the arteriole end of a capillary and 1.6 kPa at the venule end. The hydrostatic pressure of the tissue fluid is 0.2 kPa. The plasma proteins give an inward pull (by osmosis) equal to 3.0 kPa all along the capillary.

(a) Calculate the percentage decrease in the hydrostatic pressure of the blood along the capillary. Give your answer to 1 decimal place. **[1]**

(b) Calculate the net pressure at each end of the capillary, and use it to explain how tissue fluid forms and returns. [4]

(c) A child's diet is very low in protein, and the pull from the plasma proteins falls to 2.0 kPa. Explain why fluid builds up in the child's tissues. [3]

(a) $\frac{4.2 - 1.6}{4.2} \times 100 = 61.9\%$ decrease. **B1**

(b) Arteriole end: $4.2 - 0.2 - 3.0 = +1.0$ kPa, outwards. **M1** Venule end: $1.6 - 0.2 - 3.0 = -1.6$ kPa, that is 1.6 kPa **inwards**. **A1** At the arteriole end the high hydrostatic pressure **forces water and small solutes out** through the gaps in the capillary wall, forming tissue fluid; plasma proteins are too large and stay in. **B1** At the venule end the hydrostatic pressure has fallen below the pull of the plasma proteins, which lower the water potential of the blood, so **water returns by osmosis**. **B1**

(c) Less plasma protein means the water potential of the blood is **higher** (less negative). **B1** The net pressure at the venule end is now $1.6 - 0.2 - 2.0 = -0.6$ kPa, so **less water returns** by osmosis. **B1** More tissue fluid forms than returns (more than the lymph can drain), so it builds up: **oedema**. **B1**

Example 4

Use the two dissociation curves in "The oxygen dissociation curve". In the lungs the pO_2 is 13 kPa and the carbon dioxide concentration is low. In an actively respiring muscle the pO_2 is 3 kPa and the carbon dioxide concentration is high.

(a) Using the **low CO₂** curve only, find the percentage saturation at 13 kPa and at 3 kPa, and the percentage of the haemoglobin's oxygen capacity released in the muscle. [2]

(b) Blood loads in the lungs at low CO₂ but unloads in the muscle at high CO₂. Find the percentage released now, and calculate the percentage increase compared with (a). [3]

(c) Explain why the high carbon dioxide concentration in the muscle changes the curve in this way. [4]

(a) At 13 kPa: 97%. At 3 kPa: 40%. **M1** Released: $97 - 40 = 57\%$. **A1**

(b) Unloading on the high CO₂ curve at 3 kPa: 25%. Released: $97 - 25 = 72\%$. **B1** Increase = $\frac{72 - 57}{57} \times 100 = 26.3\%$. **M1 A1**

(c) Carbon dioxide diffuses into the red blood cells, where **carbonic anhydrase** catalyses its reaction with water to form **carbonic acid**. **B1** Carbonic acid dissociates into **hydrogen ions** and hydrogencarbonate ions. **B1** The hydrogen ions **bind to haemoglobin**, forming **haemoglobinic acid**; this changes the **shape** of the haemoglobin and **lowers its affinity** for oxygen. **B1** So more oxygen is released at the same pO_2 and the curve moves to the right: the **Bohr shift**, which gives more oxygen to the most active tissues. **B1**

Common mistakes

- **Leaving out "ions".** Write "**chloride ions**" and "**hydrogencarbonate ions**", never "chloride" or "chlorine". Examiners check for the word.
- **Getting the chloride shift's reason wrong.** Chloride ions move in to **balance the negative hydrogencarbonate ions leaving**, not to balance the hydrogen ions, and not because carbon dioxide is lost.
- **Saying carbonic anhydrase releases oxygen** or "breaks down carbon dioxide". It only makes carbonic acid. The oxygen is released because the **H⁺ bind to haemoglobin** to form **haemoglobinic acid**; say so, by name.
- **Using abbreviations when a name is asked for.** If a question asks you to name the compound, write "haemoglobinic acid", not "HHb" (and spell it correctly). Define an abbreviation before you use it.
- **Mixing up the AVN and the Purkyne tissue.** The AVN **delays** the wave; the Purkyne tissue **carries** it to the apex. Mention the **non-conducting tissue** between atria and ventricles, which many answers leave out, and write "wave of excitation" or "electrical impulse", not "nerve impulse".
- **Saying a valve closes "because of high pressure".** Say which two pressures are compared: the AV valve closes **when the pressure in the ventricle is higher than in the atrium**.
- **Saying tissue fluid has no protein.** It has **less** protein: the large plasma proteins stay in the blood, but small proteins (such as some hormones and antibodies) get out.
- **Writing "high heat capacity".** It must be "high **specific** heat capacity".
- **Muddling elastic and muscular arteries.** Elastic fibres **stretch and recoil**; smooth muscle **contracts** to change the lumen. The difference between the aorta and a muscular artery is the **proportion** of elastic fibres and smooth muscle, not the thickness of the tunica media.
- **Saying the left ventricle "withstands high pressure".** Its thick muscle **makes** the high pressure, to push blood round the systemic circulation.
- **Mixing up affinity and the direction of the shift.** Right = **lower** affinity = **more** oxygen released.

How to get the marks

- **"Describe"** a process (the cardiac cycle, tissue fluid formation, CO₂ transport): give the steps **in order**, with the correct names of vessels, valves and substances. Each correct step is usually a mark.
- **"Explain"** (the Bohr shift, the chloride shift, the role of the AVN): give the **reason** for each step, as a chain ("more H⁺, **so** more haemoglobinic acid, **so** lower affinity, **so** more oxygen released").
- **Structure and function:** every feature needs its matching job in the same sentence ("valves, **to** prevent backflow"). A list of features alone scores little.
- **Pressure and valves:** always compare **two named pressures** ("ventricle higher than aorta, so the semilunar valve opens").
- **Reading graphs:** quote values **with units** (kPa, s, %) read from the graph, and show subtraction or division for any calculation. Give percentages to the accuracy asked (often 1 decimal place or whole numbers).

- **Name the side:** for a heart question about the left side, say **bicuspid** (left atrioventricular) and **aortic** semilunar valve, and name the **pulmonary vein** and **aorta**.
- **"Suggest":** use the ideas in this note to explain the new situation (a heart defect, a new pathway, an unusual animal's haemoglobin).
- **Drawings:** plan diagrams show layers only, with no cells; cell drawings need clean lines, correct proportions and the nucleus shape, with ruled label lines that touch the structure.

Quick check

1. A red blood cell takes 1.5 s to pass along a capillary 0.6 mm long. Calculate its mean speed in $\mu\text{m s}^{-1}$.
2. One cardiac cycle lasts 0.75 s. Calculate the heart rate in beats per minute.
3. In a blood smear, one white cell has a nucleus divided into three lobes, and another has a round nucleus that fills almost all of the cell. Name each cell.
4. Explain why the wall of the left ventricle is thicker than the wall of the right ventricle.
5. A student's drawing of a red blood cell is 40 mm across. The real cell is $7.5 \mu\text{m}$ across. Calculate the magnification of the drawing, to the nearest whole number.

Answers

1. $0.6 \text{ mm} = 600 \text{ }\mu\text{m}$; $\text{speed} = 600 \div 1.5 = 400 \text{ }\mu\text{m s}^{-1}$.
2. $60 \div 0.75 = 80$ beats per minute.
3. The lobed nucleus is a **neutrophil**; the large round nucleus with little cytoplasm is a **lymphocyte**.
4. The left ventricle pumps blood round the **whole systemic circulation**, which is long and has high **resistance**, so it must contract with more force to make a **higher pressure**. The right ventricle pumps only to the **lungs**, which are close, and a lower pressure avoids damaging the lung capillaries.
5. $40 \text{ mm} = 40\,000 \text{ }\mu\text{m}$; $\text{magnification} = 40\,000 \div 7.5 = \times 5333$.

Past questions to try

- [9700/22/M/J/23 Q1](#): the roles of the SAN and AVN, and the timing of the cardiac cycle.
- [9700/22/O/N/21 Q2](#): how tissue fluid forms and what is in it.
- [9700/23/M/J/24 Q3](#): the features of arteries, capillaries and veins.
- [9700/21/M/J/23 Q5](#): a capillary in muscle, carbon dioxide transport and the Bohr shift.