

Respiration, Muscles and the Internal Environment

revision notes

Respiration, Muscles and the Internal Environment is topic 7 of Pearson Edexcel International A Level Biology (YBI11) and is examined in Unit 5. It covers how cells release energy as ATP, how muscles contract, how the heart and breathing respond to exercise, and how the body keeps its internal environment stable, including the work of the kidney.

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.

1 Stages of respiration Spec 7.1-7.5 A Level only

Aerobic respiration: the overall reaction Spec 7.1

Respiration transfers the chemical energy in a **respiratory substrate** (usually glucose) to ATP, the energy currency of the cell. Aerobic respiration needs oxygen. The overall reaction is shown below.



Two things happen to the substrate. Its carbon atoms are removed as carbon dioxide, which is a waste product (**decarboxylation**). Its hydrogen atoms are removed and picked up by the hydrogen carriers NAD and FAD, which become reduced NAD and reduced FAD (**dehydrogenation**). At the end of the process the hydrogen is reunited with atmospheric oxygen to make water, and this releases a large amount of energy that is used to make ATP.

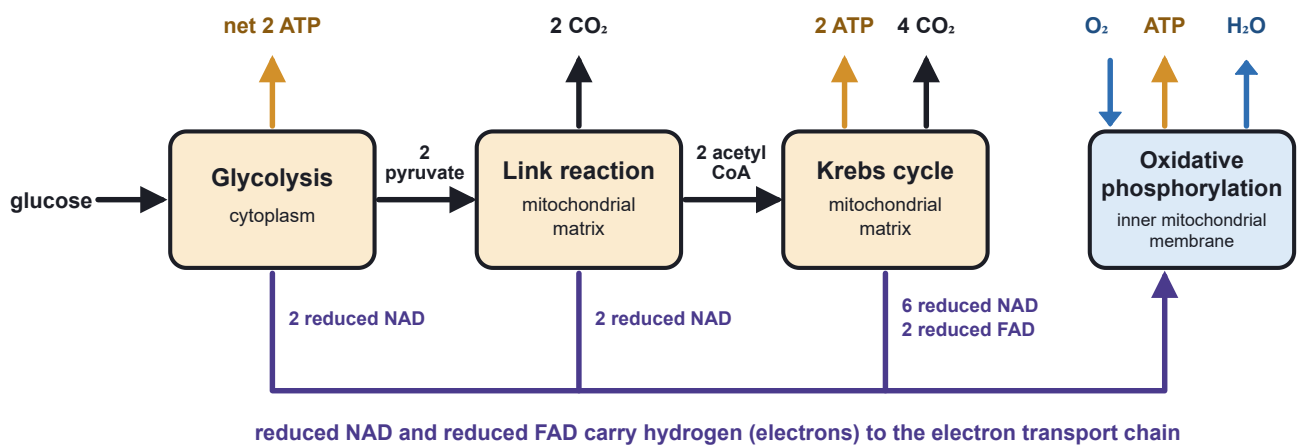
Respiratory substrate	An organic molecule, such as glucose, that is oxidised in respiration to release energy.
Decarboxylation	Removal of carbon dioxide from a substrate molecule.
Dehydrogenation	Removal of hydrogen atoms from a substrate molecule, usually by an enzyme with NAD or FAD as the hydrogen acceptor.

Why respiration is a stepped process

Respiration is not one reaction but a series of small steps. **Each step is controlled and catalysed by a specific intracellular enzyme**, so the names of the individual enzymes are not required.

- Energy is released in small, manageable amounts rather than one large burst.
- More of the energy can be captured in ATP, and less is lost as heat that could damage the cell.
- Each step can be controlled separately, so the cell can speed up or slow down respiration to match its needs.
- Intermediate compounds can be diverted into other metabolic pathways.

Common mistake: The carbon dioxide does not come from the oxygen you breathe in. It comes from the carbon in the substrate, removed by decarboxylation. Oxygen only accepts hydrogen at the end, forming water.



The four stages of aerobic respiration for one glucose molecule. Reduced NAD and reduced FAD carry hydrogen to the electron transport chain.

Glycolysis Spec 7.2

Glycolysis happens in the cytoplasm and does not need oxygen. It is the first stage of both aerobic and anaerobic respiration. Details of the intermediate stages and compounds are not required.

1. Phosphorylation: two ATP molecules each donate a phosphate to the hexose (glucose), making hexose biphosphate. This makes the sugar more reactive and traps it in the cell.
2. Lysis: the hexose biphosphate splits into two molecules of triose phosphate (3C).
3. Oxidation: each triose phosphate is dehydrogenated. The hydrogen is accepted by NAD, forming reduced NAD.
4. ATP formation: four ATP are made in total by **substrate-level phosphorylation**, and each triose phosphate is converted to a molecule of pyruvate (3C).

net yield per glucose = 2 ATP (4 made – 2 used) + 2 reduced NAD + 2 pyruvate

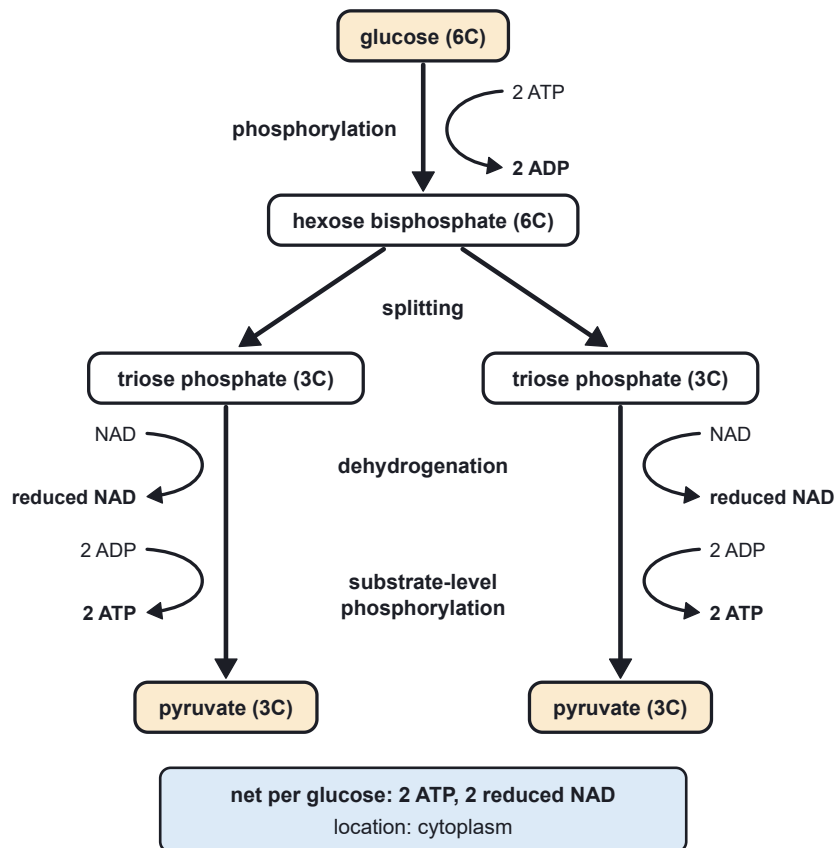
Substrate-level phosphorylation

Formation of ATP by the direct transfer of a phosphate group from a substrate molecule to ADP, without the electron transport chain.

Pyruvate

The 3C product of glycolysis. It enters the mitochondrion in aerobic respiration or is converted to lactate in anaerobic respiration in animals.

Exam tip: Always say net gain of 2 ATP. Four ATP are made, but two were used at the start. Marks are lost for writing 4 ATP.



Glycolysis in the cytoplasm: two ATP are used, four are made, so the **net gain is 2 ATP**.

The link reaction and the Krebs cycle Spec 7.3

Unlike glycolysis, which happens in the cytoplasm, the link reaction and the Krebs cycle take place in the **mitochondria** (the matrix). Pyruvate from glycolysis is actively transported into the matrix. Together they achieve the complete oxidation of glucose. Names of the other compounds are not required.

The link reaction

- Pyruvate (3C) is decarboxylated: one carbon is lost as CO_2 .
- It is also dehydrogenated: hydrogen is removed and passed to NAD, forming reduced NAD.
- The remaining 2C acetyl group combines with coenzyme A to form acetyl CoA, which carries it into the Krebs cycle.
- This happens twice per glucose, because glycolysis makes two pyruvate.

The Krebs cycle

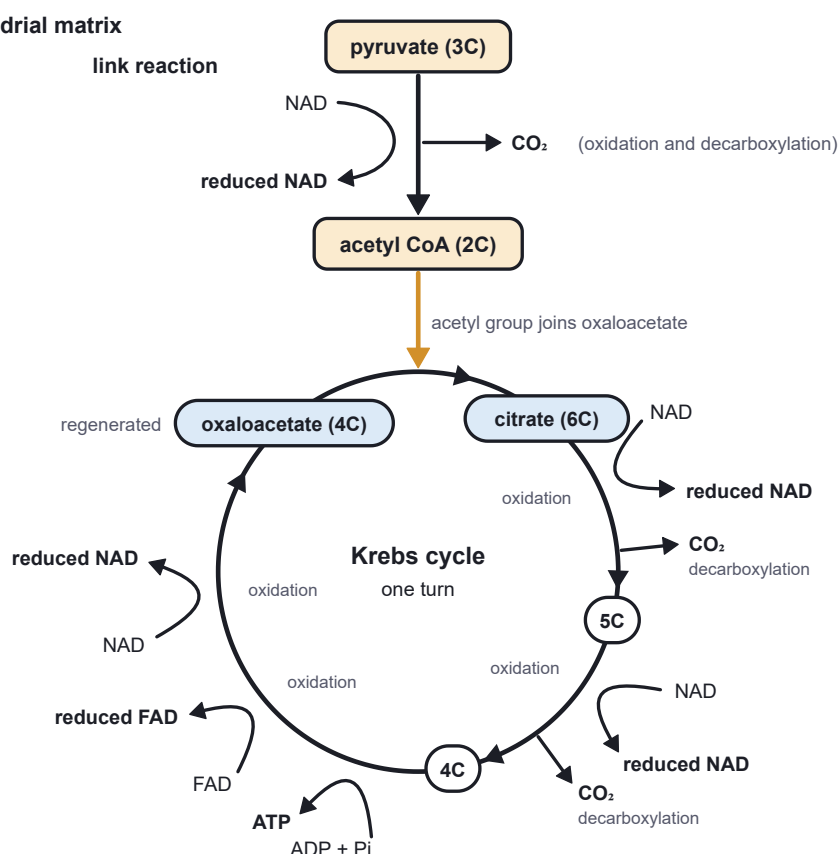
The acetyl group (2C) from acetyl CoA joins a 4C compound to form a 6C compound. The 6C compound is then converted back to the 4C compound in a series of enzyme-controlled steps, so the cycle can start again. In each turn:

- two carbon atoms are lost as CO_2 by **decarboxylation**;
- hydrogen is removed by **dehydrogenation** and accepted by NAD (3 reduced NAD) and by FAD (1 reduced FAD);
- one ATP is made by **substrate-level phosphorylation**.

The cycle turns twice for each glucose molecule, so the totals are doubled.

Products of the link reaction and Krebs cycle per glucose molecule				
Stage	CO ₂	Reduced NAD	Reduced FAD	ATP
Link reaction (2 pyruvate)	2	2	0	0
Krebs cycle (2 turns)	4	6	2	2
Total for both	6	8	2	2

Exam tip: Reduced NAD and reduced FAD are the main products: they carry hydrogen (electrons) to the electron transport chain, where most ATP is made. Only the cycle itself makes ATP directly.



The link reaction and Krebs cycle in the **mitochondrial matrix**, labelled by carbon number.

Oxidative phosphorylation Spec 7.4

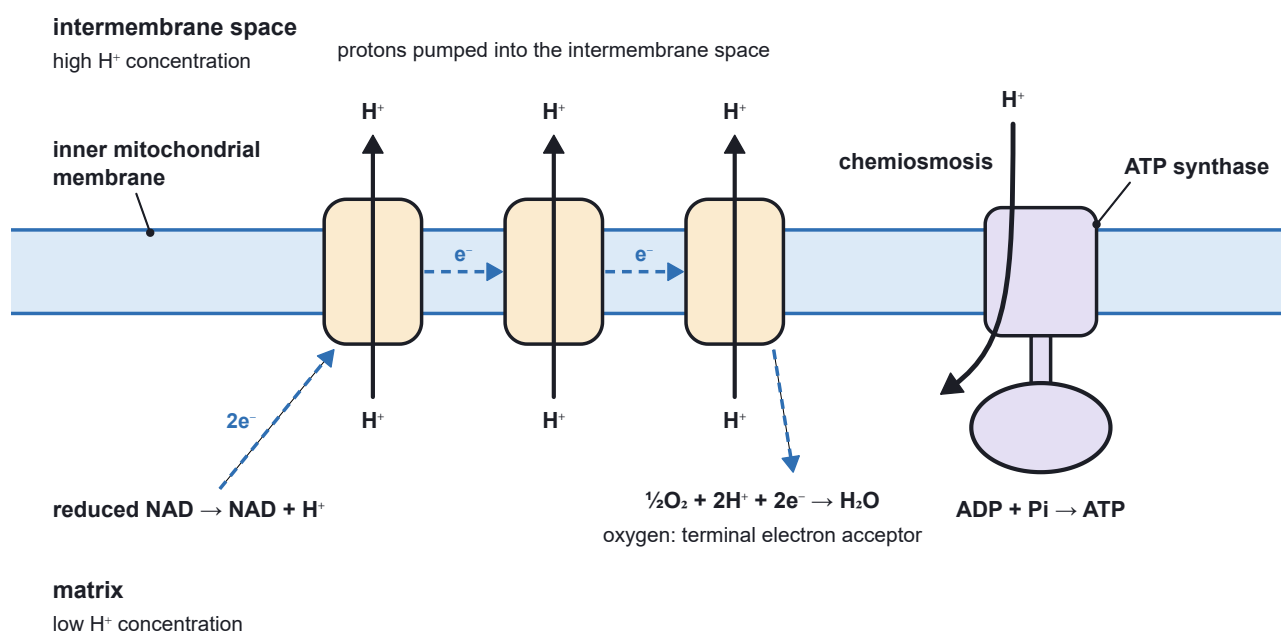
Most ATP is made by **oxidative phosphorylation**, which is linked to the electron transport chain on the inner mitochondrial membrane. The folded cristae give a large surface area for the carriers and ATP synthase.

1. Reduced NAD and reduced FAD deliver hydrogen to the chain. They are oxidised back to NAD and FAD, which can be used again in glycolysis, the link reaction and the Krebs cycle. The hydrogen splits into protons (H⁺) and electrons.
2. The electrons pass along a chain of electron carriers in a series of redox reactions. Each step releases a little energy.
3. This energy is used to pump protons from the matrix into the intermembrane space, building up a high concentration of H⁺ there: a proton gradient across the inner membrane.
4. Protons diffuse back into the matrix down their gradient through channels in the enzyme **ATP synthase**. This flow of protons is called **chemiosmosis**, and it provides the energy to join ADP and inorganic phosphate (Pi) to form ATP.

5. At the end of the chain, oxygen is the final electron acceptor. It combines with electrons and protons to form water.

Summary of aerobic respiration for one glucose molecule				
Stage	Site	ATP made directly	Reduced NAD	Reduced FAD
Glycolysis	Cytoplasm	2 (net)	2	0
Link reaction	Matrix	0	2	0
Krebs cycle	Matrix	2	6	2
Oxidative phosphorylation	Inner membrane	Most of the ATP (from reduced NAD and FAD)	Oxidised	Oxidised

Exam tip: Without oxygen the chain stops. Reduced NAD and reduced FAD are not oxidised, so NAD and FAD run out, and the link reaction and Krebs cycle also stop.



Electrons passing along the chain pump protons across the membrane; protons flow back through **ATP synthase** (chemiosmosis).

Anaerobic respiration and lactate Spec 7.2, 7.5

When oxygen is in short supply, as in muscle during vigorous exercise, the electron transport chain cannot work. Reduced NAD cannot be oxidised, so there would be no NAD for glycolysis. Anaerobic respiration solves this.

- Glycolysis continues, giving a net gain of 2 ATP per glucose.
- Pyruvate accepts hydrogen from reduced NAD and is converted to **lactate**.
- This reforms NAD, so glycolysis can carry on making ATP, although only a small amount compared with aerobic respiration.

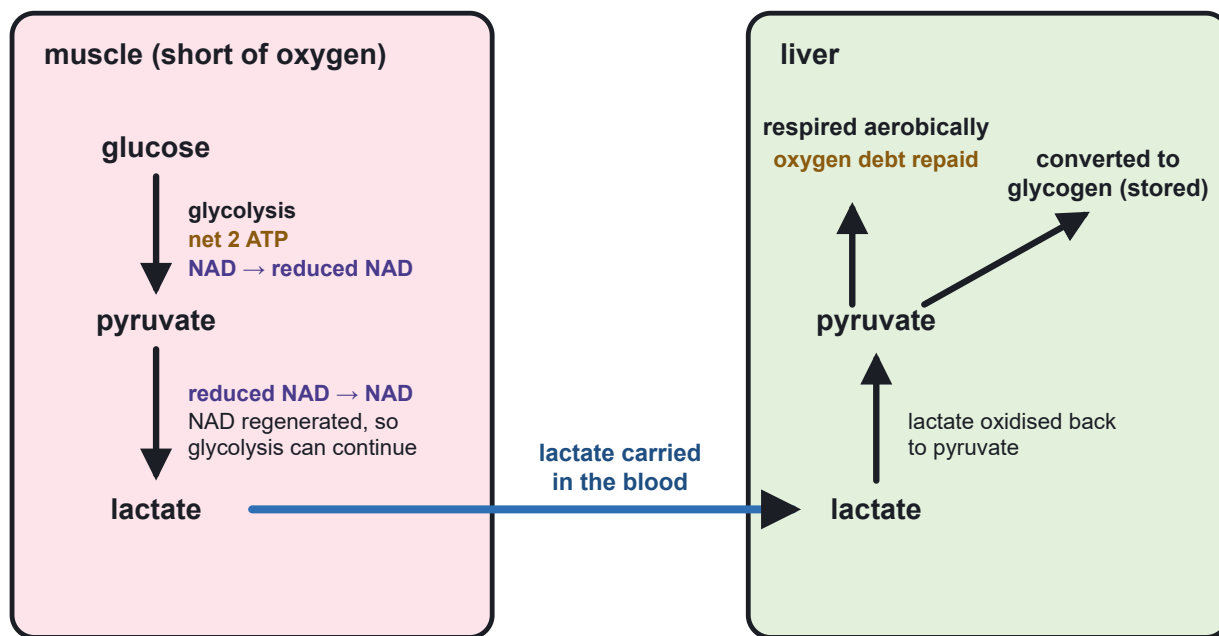
Lactate lowers the pH of the muscle cells, which interferes with enzyme action and contributes to muscle fatigue.

What happens to lactate

- Lactate diffuses out of the muscle cells into the blood and is carried to the liver.

2. When enough oxygen is available again, in the liver the lactate is oxidised back to pyruvate.
3. Some pyruvate enters aerobic respiration (link reaction, Krebs cycle and oxidative phosphorylation) to release ATP; the rest is converted to glucose and then glycogen for storage.
4. Extra oxygen is taken in for some time after the exercise. This is why breathing stays fast and deep: the **oxygen debt** is being repaid.

Common mistake: Lactate does not build up because there is 'no oxygen' in the cell. It forms because pyruvate has to accept hydrogen so that NAD is regenerated. Say that glycolysis would stop without it.



Lactate formed in muscle is carried to the **liver** for removal.

Quick check

1. In which part of the cell does glycolysis take place?
2. How many ATP molecules are made by glycolysis, net, per glucose molecule?
3. What are the products of the link reaction?
4. What is the role of oxygen in aerobic respiration?
5. Why does glycolysis stop if pyruvate cannot be converted to lactate in anaerobic conditions?

2 Respiratory quotient and respiration practicals Spec 7.6-7.8 A Level only

Respiratory quotient (RQ) Spec 7.6

The **respiratory quotient (RQ)** compares the carbon dioxide produced with the oxygen consumed by an organism or tissue over the same time.

$$\text{RQ} = \text{volume of CO}_2 \text{ produced} \div \text{volume of O}_2 \text{ consumed}$$

RQ has no units, because it is a ratio. Its value depends on the substrate being respired, because different substrates contain different proportions of oxygen.

Typical RQ values		
Substrate respired	Typical RQ	Reason
Carbohydrate (glucose)	1.0	6CO ₂ produced for 6O ₂ used
Lipid	about 0.7	Lipids have little oxygen in the molecule, so more O ₂ is needed per CO ₂ released
Protein	about 0.9	Between lipid and carbohydrate

A mixture of substrates gives a value between those shown. An RQ greater than 1.0 means that more CO₂ is being produced than O₂ used, so some anaerobic respiration may be taking place in the tissue (for example, in yeast).

Calculating RQ

A sample of germinating seeds uses 40 cm³ of oxygen and produces 36 cm³ of carbon dioxide in 10 minutes. Calculate the RQ and suggest which substrate was respired.

1. $\text{RQ} = \text{volume of CO}_2 \text{ produced} \div \text{volume of O}_2 \text{ consumed}$
2. $\text{RQ} = 36 \div 40$

Answer: RQ = 0.9, which suggests that protein (or a mixture of substrates) is being respired.

Maths skill: RQ is a ratio, so no units. Write the working as 'CO₂ produced ÷ O₂ consumed' and state what the answer suggests about the substrate.

Core practical 15: redox indicator and yeast Spec 7.7

Core practical: Core practical 15: use an artificial hydrogen carrier (redox indicator) to investigate respiration in yeast.

During respiration, dehydrogenase enzymes remove hydrogen from the substrate and normally pass it to NAD. A **redox indicator** (for example methylene blue or DCPIP) can accept this hydrogen instead, so it acts as an artificial hydrogen carrier. When it is reduced, it changes colour (blue to colourless). The faster the yeast respire, the faster the indicator is decolourised.

1. Make a suspension of yeast in a glucose solution of known concentration.
2. Place equal volumes of the suspension in boiling tubes in water baths at different temperatures (the independent variable), and let them reach the temperature.
3. Add the same volume of the redox indicator to each tube and mix. A layer of oil may be added to exclude oxygen, which would re-oxidise the indicator.

4. Start a stopwatch and record the time taken for the blue colour to disappear, or until it matches a colour standard.
5. Repeat at each temperature and calculate a mean. Rate of reaction is proportional to $1 \div \text{time}$.
 - Independent variable: temperature (or glucose concentration, or yeast concentration).
 - Dependent variable: time for the indicator to lose its colour.
 - Control variables: volume and concentration of yeast, glucose and indicator; pH; the colour end-point used.
 - Control experiment: boiled and cooled yeast should not decolourise the indicator.
 - Risks: hot water can scald; use a thermometer and a water bath that is not boiling. Methylene blue stains skin and clothes; wear eye protection and gloves, and wipe up spills.
 - Limitation: judging the colour end-point is subjective, so use the same colour standard, or a colorimeter for the endpoint.

Exam tip: If asked why the indicator changes colour, say that it accepts hydrogen released by the dehydrogenase enzymes in place of NAD, so a faster colour change means a faster rate of respiration.

Core practical 16: respirometer and RQ Spec 7.8

Core practical: Core practical 16: use a simple respirometer to determine the rate of respiration and RQ of a suitable material (such as germinating seeds or small invertebrates).

A simple respirometer is a sealed tube containing the organisms and connected to a capillary tube containing a drop of coloured fluid. As the organisms respire, the gas volume in the tube changes and the fluid moves.

1. Place the organisms (for example germinating seeds or woodlice) in the tube on a gauze or platform, above a small tube of potassium hydroxide solution (or soda lime) that absorbs the CO_2 they produce. Keep the organisms from touching the potassium hydroxide.
2. Set up a control tube, with an equal volume of glass beads or dead / boiled seeds in place of the organisms, to correct for changes in air temperature and pressure.
3. Place the apparatus in a water bath at constant temperature and wait about 10 minutes for the temperature to equalise.
4. Close the tap or bung, introduce a drop of coloured fluid and mark its position. Measure the distance it moves in a set time.
5. Repeat without the potassium hydroxide to find the net change in gas volume.

With KOH present, CO_2 is absorbed, so the fluid moves towards the organisms by a distance that shows the oxygen consumed. Without KOH, O_2 is still used up but CO_2 is released, so the movement is smaller (zero if $\text{RQ} = 1$, or away from the organisms if RQ is above 1) and shows the oxygen consumed minus the carbon dioxide produced. The volume of gas is calculated from the capillary's radius: $\text{volume} = \pi r^2 \times \text{distance moved}$.

Rate of respiration and RQ

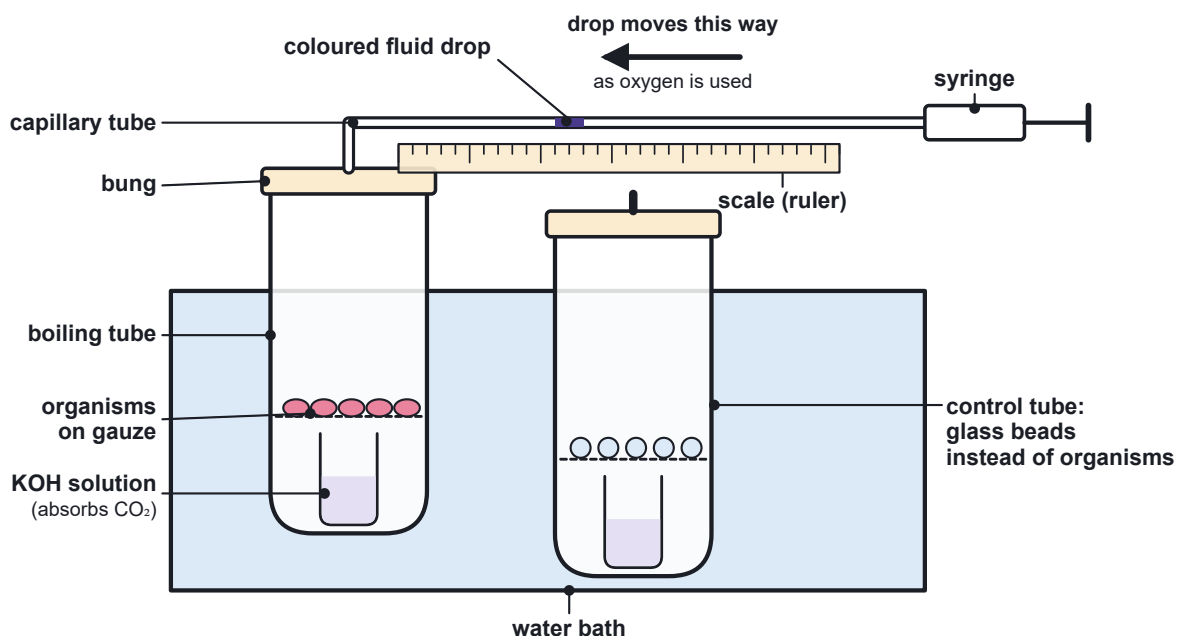
In a respirometer, the fluid in a capillary tube of radius 0.5 mm moved 24 mm in 5 minutes with potassium hydroxide present. Without potassium hydroxide it moved 6 mm in 5 minutes. Calculate the rate of oxygen uptake and the RQ.

1. Volume of O_2 consumed = $\pi r^2 \times \text{distance} = \pi \times 0.5^2 \times 24 = 18.85 \text{ mm}^3$
2. Rate of O_2 uptake = $18.85 \div 5 = 3.77 \text{ mm}^3 \text{ min}^{-1}$
3. Without KOH, net volume decrease = $\pi \times 0.5^2 \times 6 = 4.71 \text{ mm}^3$, which is O_2 consumed – CO_2 produced
4. CO_2 produced = $18.85 - 4.71 = 14.14 \text{ mm}^3$
5. $RQ = CO_2 \text{ produced} \div O_2 \text{ consumed} = 14.14 \div 18.85$

Answer: Rate of oxygen uptake = $3.77 \text{ mm}^3 \text{ min}^{-1}$ (accept 3.8). $RQ = 0.75$, so the organism is probably respiring mostly lipid or a mixture of substrates.

- Variables: independent variable e.g. temperature or type of organism; dependent variable distance moved by the fluid in a set time. Control the mass of organisms, temperature, time and the volume of apparatus.
- Divide by the mass of the organisms to compare rates, e.g. $\text{mm}^3 O_2 \text{ g}^{-1} \text{ min}^{-1}$.
- Risks: potassium hydroxide is corrosive, so wear eye protection and gloves and prevent contact with the organisms. Handle animals gently and return them to their habitat, and wash hands after handling germinating seeds.

Core practical: The respirometer works because CO_2 is absorbed. Be clear which gas each reading refers to: with KOH the movement is due to O_2 used; without KOH the movement is O_2 used minus CO_2 produced.



As oxygen is used and CO_2 is absorbed by the KOH, the drop moves towards the organisms; the syringe resets it.

Quick check

- 1 . What is the formula for the respiratory quotient?
- 2 . What is the typical RQ when carbohydrate is respired?
- 3 . In Core practical 15, why does the redox indicator change colour?
- 4 . In a respirometer, what is the purpose of potassium hydroxide?

3 Muscles and movement

Spec 7.9-7.11

A Level only

Muscles, tendons, the skeleton and ligaments Spec 7.9

Skeletal muscles are attached to bones by **tendons**. Tendons are strong, inelastic bands of collagen, so the force of the muscle contracting is transmitted directly to the bone without being lost by stretching.

Ligaments join bone to bone at a joint. They are strong and slightly elastic, and they hold the bones in place and stabilise the joint. The skeleton provides rigid levers, and the joint acts as the pivot.

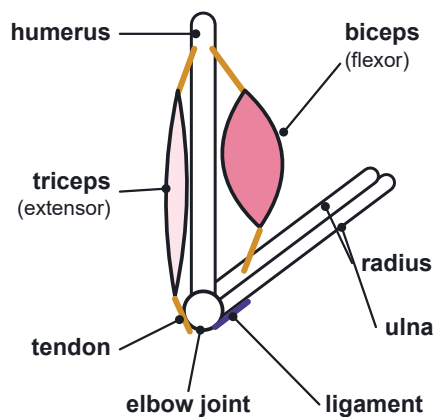
A muscle can only pull when it contracts. It cannot push. To move a joint in both directions, muscles work in **antagonistic pairs**: when one muscle of the pair contracts, the other relaxes and is stretched.

Antagonistic muscles at the elbow

Feature	Biceps	Triceps
Type of muscle	Flexor	Extensor
Action when it contracts	Bends (flexes) the elbow, decreasing the angle	Straightens (extends) the elbow, increasing the angle
Attached to	Radius (by a tendon)	Ulna (by a tendon)
State while the other contracts	Relaxes when the triceps contracts	Relaxes when the biceps contracts

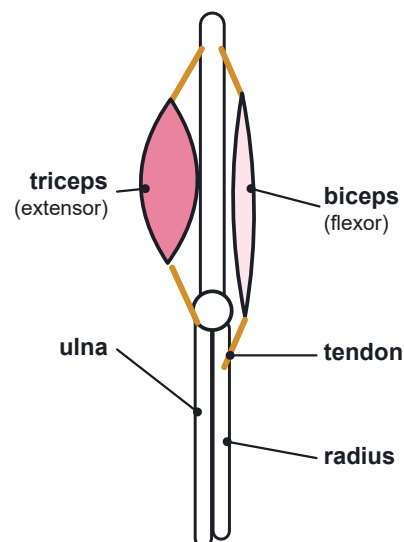
A **flexor** is a muscle whose contraction bends a joint; an **extensor** is a muscle whose contraction straightens a joint. Another example is the hamstring (flexor of the knee) and quadriceps (extensor of the knee).

Common mistake: Do not say that the relaxed muscle 'pushes'. It is the contracting muscle that pulls, and the relaxed antagonist is stretched. Tendons join muscle to bone; ligaments join bone to bone.



arm bent

biceps contracts, triceps relaxes



arm straight

triceps contracts, biceps relaxes

An antagonistic pair: the muscle that contracts **pulls**, and the other relaxes (darker pink = contracted).

Structure of a skeletal muscle fibre Spec 7.10(i)

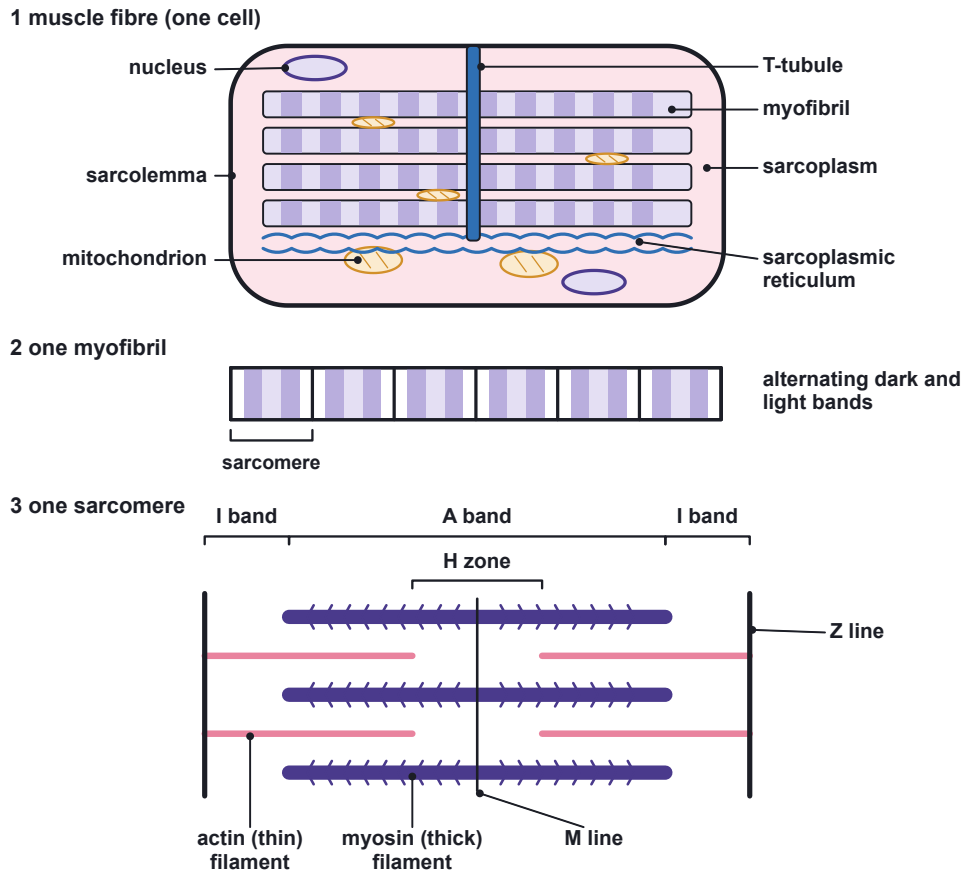
A skeletal muscle fibre is a single, long, cylindrical cell with many nuclei. Its cell surface membrane is the **sarcolemma** and its cytoplasm is the **sarcoplasm**. The sarcolemma folds inwards to form T-tubules (transverse tubules), which carry action potentials deep into the fibre.

- Myofibrils: long, thin, cylindrical bundles of protein filaments that run along the length of the fibre and cause contraction.
- Sarcoplasmic reticulum: a network of membranes around each myofibril that stores calcium ions (Ca^{2+}).
- Many mitochondria: lying between the myofibrils, to supply the ATP needed for contraction.
- Many nuclei, lying just under the sarcolemma.

The sarcomere

Each myofibril is divided along its length into repeating units called **sarcomeres**, from one Z line to the next. Two kinds of filament lie in the sarcomere: thick filaments of **myosin** and thin filaments of **actin** (with the proteins troponin and tropomyosin). Their arrangement gives the striped (striated) appearance under the microscope.

Bands of a sarcomere		
Region	Appearance	What is present
A band	Dark	The full length of the myosin filaments (including where actin overlaps them)
I band	Light	Actin filaments only (no myosin)
H zone	Lighter region in the middle of the A band	Myosin only (no actin overlap)
Z line	Thin dark line	Boundary of the sarcomere; actin is attached here
M line	Centre of the sarcomere	Myosin filaments held together



From fibre to **sarcomere**: each myofibril is a chain of sarcomeres.

Exam tip: In a contracted muscle the A band stays the same length, but the I band and H zone get shorter. Examiners often test this.

Fast and slow twitch muscle fibres Spec 7.10(ii)

Skeletal muscle contains two main types of fibre, and their proportions differ between muscles and between people. Their structure matches their role.

Fast twitch and slow twitch fibres		
Feature	Slow twitch	Fast twitch
Speed of contraction	Slow	Fast
Force produced	Lower	Higher
Resistance to fatigue	High: contract for long periods	Low: tire quickly as lactate builds up
Main way of making ATP	Aerobic respiration	Anaerobic glycolysis (producing lactate)
Mitochondria	Many	Fewer
Myoglobin (stores oxygen)	A lot, so the fibres look red	Little, so the fibres look pale / white
Capillary supply	Dense	Fewer
Glycogen store	Lower	Higher
Sarcoplasmic reticulum	Less extensive	More extensive: releases Ca^{2+} quickly
Used for	Posture and endurance, e.g. marathon running	Sprinting and lifting heavy weights

Exam tip: Link each structural feature to its function. 'Many mitochondria' is not enough; add 'for aerobic respiration to make ATP for a long time'.

Contraction and the sliding filament theory Spec 7.11

Muscle contracts when the thin actin filaments slide between the thick myosin filaments, pulling the Z lines closer together. The filaments themselves do not shorten.

Roles of the proteins and ions

- **Actin**: thin filament with binding sites for myosin heads.
- **Tropomyosin**: fibrous protein that lies along actin and covers the myosin-binding sites when the muscle is relaxed.
- **Troponin**: a protein attached to tropomyosin that binds Ca^{2+} .
- **Myosin**: thick filament with globular heads that bind actin and act as an ATPase enzyme.
- **Ca^{2+}** : released from the sarcoplasmic reticulum; triggers the change that exposes the binding sites.
- **ATP**: provides energy for the myosin head to move, and allows it to detach.

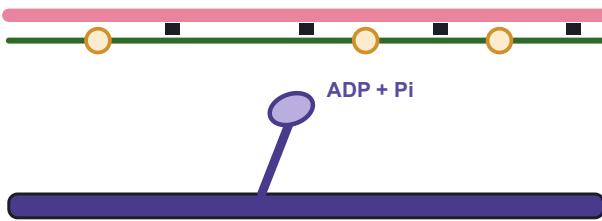
1. An action potential arrives at the neuromuscular junction and spreads along the sarcolemma and down the T-tubules.
2. This causes the sarcoplasmic reticulum to release Ca^{2+} into the sarcoplasm.
3. Ca^{2+} binds to troponin, changing its shape. This pulls tropomyosin away from the myosin-binding sites on actin.
4. A myosin head (with ADP and P_i attached) binds to actin, forming an actin-myosin cross-bridge.
5. The head changes shape, tilting and pulling the actin filament towards the centre of the sarcomere. ADP and P_i are released. This is the power stroke.
6. A new ATP binds to the myosin head, which detaches from the actin.
7. Myosin ATPase hydrolyses ATP to ADP and P_i , releasing energy that returns the head to its original position, ready to bind again further along the actin.
8. Steps 4 to 7 repeat while Ca^{2+} and ATP are available, and the filaments slide past each other.

When stimulation stops, Ca^{2+} is actively pumped back into the sarcoplasmic reticulum using ATP. Troponin returns to its original shape, tropomyosin covers the binding sites again, and the muscle relaxes.

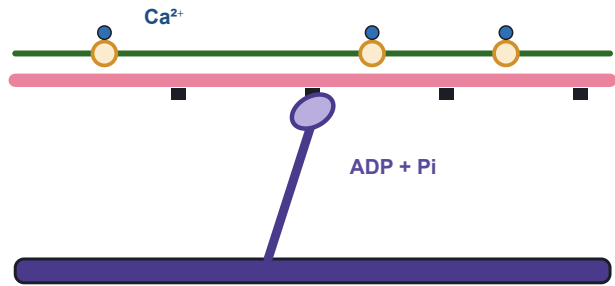
Changes in a sarcomere during contraction	
Part	Change
Sarcomere (Z line to Z line)	Gets shorter
I band	Gets shorter
H zone	Gets shorter (or disappears)
A band	Stays the same length

Common mistake: ATP is needed to detach the myosin head from actin, as well as to move it. Without ATP the heads stay attached, as in rigor mortis.

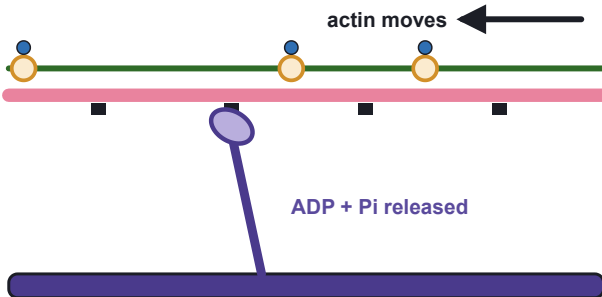
1 Relaxed: tropomyosin blocks the binding sites on actin



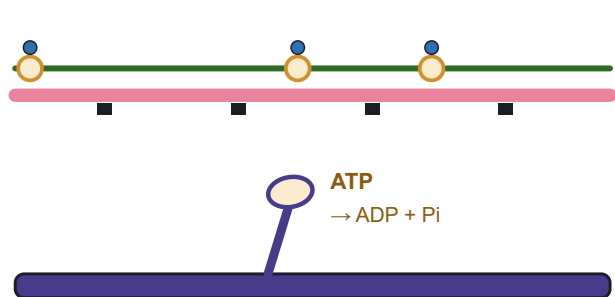
2 Ca^{2+} binds troponin, tropomyosin moves; myosin head (ADP + Pi) forms a cross-bridge



3 Power stroke: head swivels, actin pulled towards the M line; ADP + Pi released

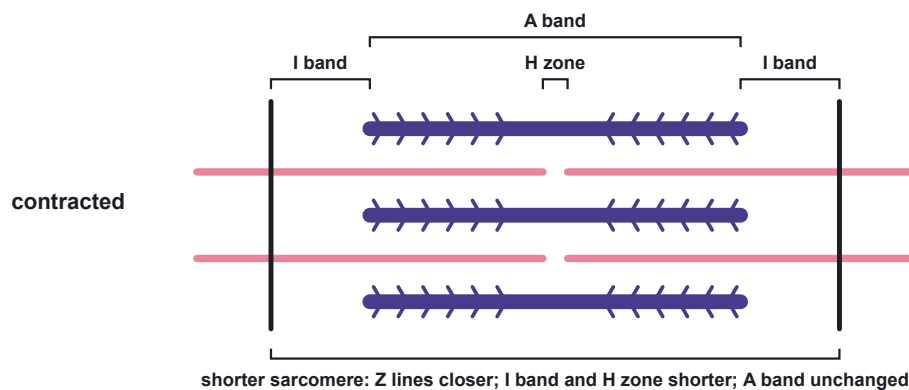
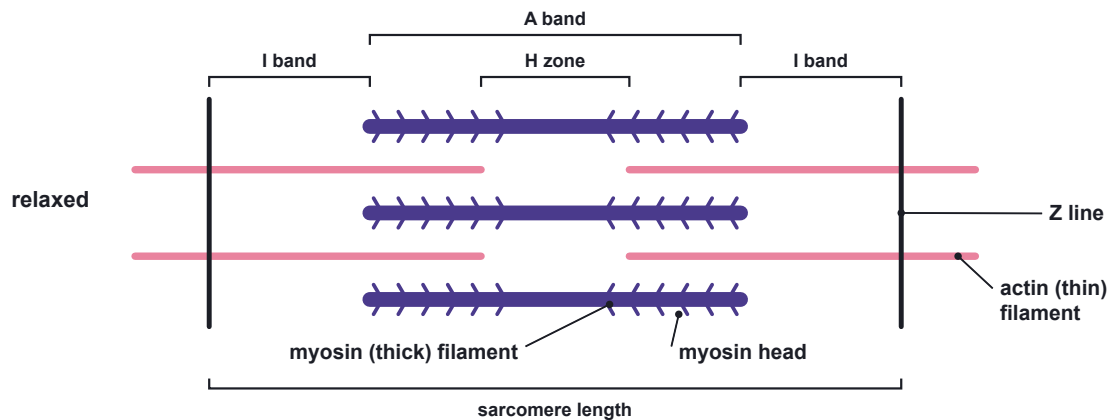


4 ATP binds and the head detaches; ATPase hydrolyses ATP, head re-cocks



actin myosin tropomyosin troponin Ca^{2+} ion myosin-binding site on actin

The **cross-bridge cycle**: calcium ions expose the binding sites, and ATP is needed to detach the head.



In contraction the **I band and H zone shorten**; the A band does not change.

Quick check

- 1 . What is the difference between a tendon and a ligament?
- 2 . What is an antagonistic muscle pair?
- 3 . Which part of a sarcomere stays the same length when a muscle contracts?
- 4 . What does calcium bind to in muscle contraction?
- 5 . Why do fast twitch fibres tire quickly?

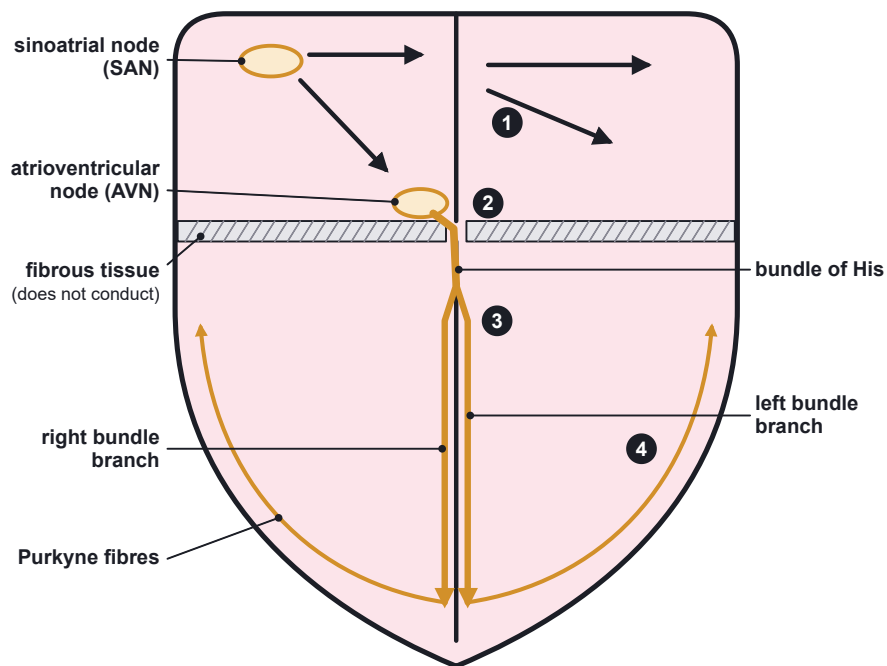
4 The heart, ventilation and exercise Spec 7.12-7.15 A Level only

Cardiac muscle and the coordination of the heartbeat Spec 7.12(i), 7.12(ii)

Cardiac muscle is **myogenic**: it can initiate its own contraction without a nerve impulse, so the heart beats even if its nerves are cut. Nerves only change the rate.

1. The **sinoatrial node (SAN)**, a patch of cardiac muscle cells in the wall of the right atrium, is the pacemaker. It generates a wave of depolarisation (excitation) at regular intervals.
2. The wave spreads across the walls of both atria, which contract together (atrial systole).
3. A layer of non-conducting fibrous tissue between the atria and the ventricles stops the wave passing directly to the ventricles.
4. The wave reaches the **atrioventricular node (AVN)**. The AVN delays it for about 0.1 s, giving the atria time to empty and the ventricles time to fill.
5. The wave then passes down the **bundle of His**, which runs through the septum to the apex (bottom) of the heart.
6. The bundle divides into **Purkyne fibres**, which carry the wave up the walls of both ventricles. The ventricles contract from the apex upwards (ventricular systole), forcing blood out through the arteries.

Exam tip: Explain the delay at the AVN: it makes sure the atria have finished contracting before the ventricles contract, so the ventricles fill fully.



- 1 impulse spreads over both atria from the SAN: atria contract
- 2 delay of about 0.1 s at the AVN: atria finish contracting first
- 3 impulse passes down the bundle of His and its branches in the septum
- 4 Purkyne fibres carry it up the ventricle walls: ventricles contract from the apex

The wave of excitation: SAN, then a **0.1 s delay at the AVN**, then the bundle of His, branches and Purkyne fibres.

Electrocardiograms (ECGs) Spec 7.12(iii)

An **electrocardiogram (ECG)** is a trace of the electrical changes produced by the heart, recorded by electrodes on the skin. One heartbeat gives a repeating pattern of waves.

Parts of a normal ECG

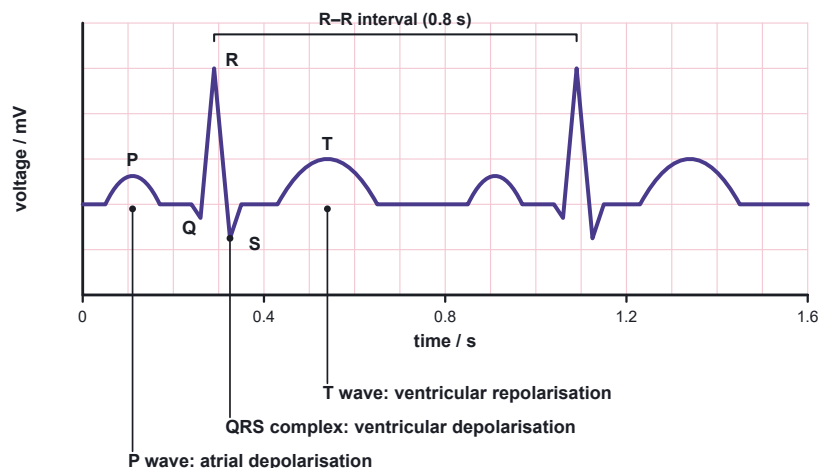
Feature	What it shows
P wave	Depolarisation of the atria (just before atrial systole)
QRS complex	Depolarisation of the ventricles (just before ventricular systole)
T wave	Repolarisation of the ventricles (as they relax)
R-R interval	Time for one complete heartbeat

$$\text{heart rate (beats per minute)} = 60 \div \text{time for one heartbeat (R-R interval, in seconds)}$$

Abnormal rhythms shown on an ECG

Condition	ECG appearance
Tachycardia	Regular pattern, but a rapid heart rate (above 100 beats per minute): short R-R intervals
Bradycardia	Regular pattern, but a slow heart rate (below 60 beats per minute): long R-R intervals
Ectopic heartbeat	An extra or early beat, then a longer gap before the next normal beat
Atrial fibrillation	Irregular, rapid atrial activity: no clear P waves and an irregular R-R interval

Maths skill: To find heart rate from an ECG, measure the time between two R peaks from the scale given, then divide 60 by it. For example, an R-R interval of 0.8 s gives 75 beats per minute.



Tachycardia

fast heart rate: short R-R intervals



Bradycardia

slow heart rate: long R-R intervals



Ectopic beat

early extra beat, wide QRS, no P wave



Atrial fibrillation

irregular R-R, no clear P waves



A normal ECG, and what **abnormal rhythms** look like.

Cardiac output and the control of heart rate and ventilation Spec 7.13

$$\text{cardiac output} = \text{stroke volume} \times \text{heart rate}$$

Stroke volume is the volume of blood pumped out of a ventricle in one beat (cm^3). Heart rate is in beats per minute. Cardiac output is in $\text{cm}^3 \text{ min}^{-1}$ (or $\text{dm}^3 \text{ min}^{-1}$).

Cardiac output

At rest, a person's stroke volume is 75 cm^3 and heart rate 70 beats per minute. During exercise, stroke volume is 120 cm^3 and heart rate 150 beats per minute. Calculate the change in cardiac output.

1. Resting cardiac output = $75 \times 70 = 5250 \text{ cm}^3 \text{ min}^{-1}$
2. Exercise cardiac output = $120 \times 150 = 18\,000 \text{ cm}^3 \text{ min}^{-1}$
3. Change = $18\,000 - 5250$

Answer: $12\,750 \text{ cm}^3 \text{ min}^{-1}$ ($12.75 \text{ dm}^3 \text{ min}^{-1}$) increase. An increase of 243% ($12\,750 \div 5250 \times 100$).

Maths skill: Write the unit with every answer and check the units match (cm^3 with $\text{cm}^3 \text{ min}^{-1}$).

Percentage change = $\text{change} \div \text{original} \times 100$.

Controlling heart rate

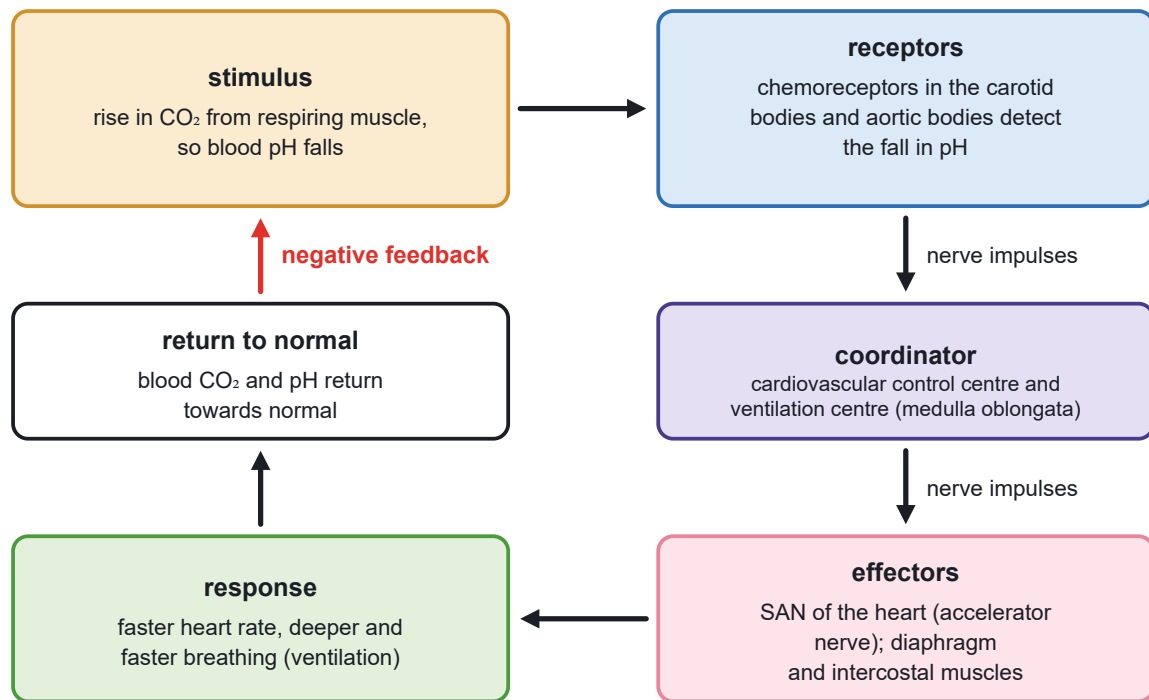
The **cardiovascular control centre** in the medulla oblongata of the brain receives information from receptors and signals to the SAN along two nerves:

- Chemoreceptors in the carotid arteries and aorta, and in the medulla, detect a fall in blood pH (caused by a rise in CO_2 concentration, which forms carbonic acid). Baroreceptors in the aorta and carotid arteries detect blood pressure.
- A rise in CO_2 (low pH) in exercise: impulses along sympathetic nerves (the accelerator pathway) to the SAN increase heart rate and stroke volume.
- A rise in blood pressure, or low CO_2 : impulses along the vagus (parasympathetic) nerve to the SAN decrease heart rate.
- During exercise, stretch receptors in the muscles and joints also detect movement and send impulses to the cardiovascular control centre, so heart rate rises as soon as exercise starts. Adrenaline released into the blood increases heart rate as well.

Controlling ventilation

The **ventilation centre** (breathing centre) in the medulla oblongata controls the rate and depth of breathing. During exercise, more CO_2 is made by respiration, and chemoreceptors detect the fall in pH. The ventilation centre sends more frequent impulses along nerves to the diaphragm and the external intercostal muscles, so breathing becomes faster and deeper. Stretch receptors in the lungs send impulses back to the centre to stop over-inflation.

The combined increase in ventilation and cardiac output delivers oxygen to the muscles quickly and removes CO_2 rapidly from them, keeping the blood CO_2 concentration and pH within narrow limits. This is a negative feedback system.



Control of heart rate and ventilation in exercise is **negative feedback**.

Adrenaline and the fight or flight response Spec 7.14

In a threatening situation, the brain stimulates the adrenal glands (above the kidneys) to release **adrenaline** into the blood. It reaches its target cells, which have specific receptors on their cell surface membrane. This prepares the body for **fight or flight**.

- Heart: increases heart rate and stroke volume, so cardiac output rises and more oxygen and glucose reach the muscles.
- Lungs: widens the bronchioles and increases ventilation rate and depth, so more oxygen enters the blood.
- Liver: stimulates the conversion of glycogen to glucose, raising blood glucose concentration as a substrate for respiration.
- Blood vessels: dilates arterioles supplying skeletal muscles and constricts arterioles to the gut and skin, redirecting blood to muscles.
- Eyes: dilates the pupils so more light enters.
- Metabolic rate increases.

Exam tip: Link each effect to its purpose: for example, 'increases heart rate, so more oxygen and glucose are delivered to muscles for aerobic respiration'.

Core practical 17: exercise and spirometer traces Spec 7.15

Core practical: Core practical 17: investigate the effects of exercise on tidal volume, breathing rate, respiratory minute ventilation, and oxygen consumption using data from spirometer traces.

A spirometer is a chamber containing air or oxygen, with a lid that rises and falls as the person breathes in and out through a mouthpiece. The movements are recorded as a trace. Soda lime in the circuit absorbs the CO₂ breathed out, so the total volume of gas in the chamber falls as oxygen is consumed and the trace slopes downwards.

What to measure from a spirometer trace

Measurement	How to find it from the trace
Tidal volume	Volume of air breathed in or out in one breath (at rest or during exercise): the height from a trough to the next peak
Breathing rate	Number of peaks (breaths) per minute
Respiratory minute ventilation	Tidal volume $\times$ breathing rate ($\text{dm}^3 \text{ min}^{-1}$)
Oxygen consumption	The gradient (slope) of the trace over a set time, drawn through the peaks or troughs ($\text{dm}^3 \text{ min}^{-1}$)

$$\text{minute ventilation} = \text{tidal volume} \times \text{breathing rate}$$

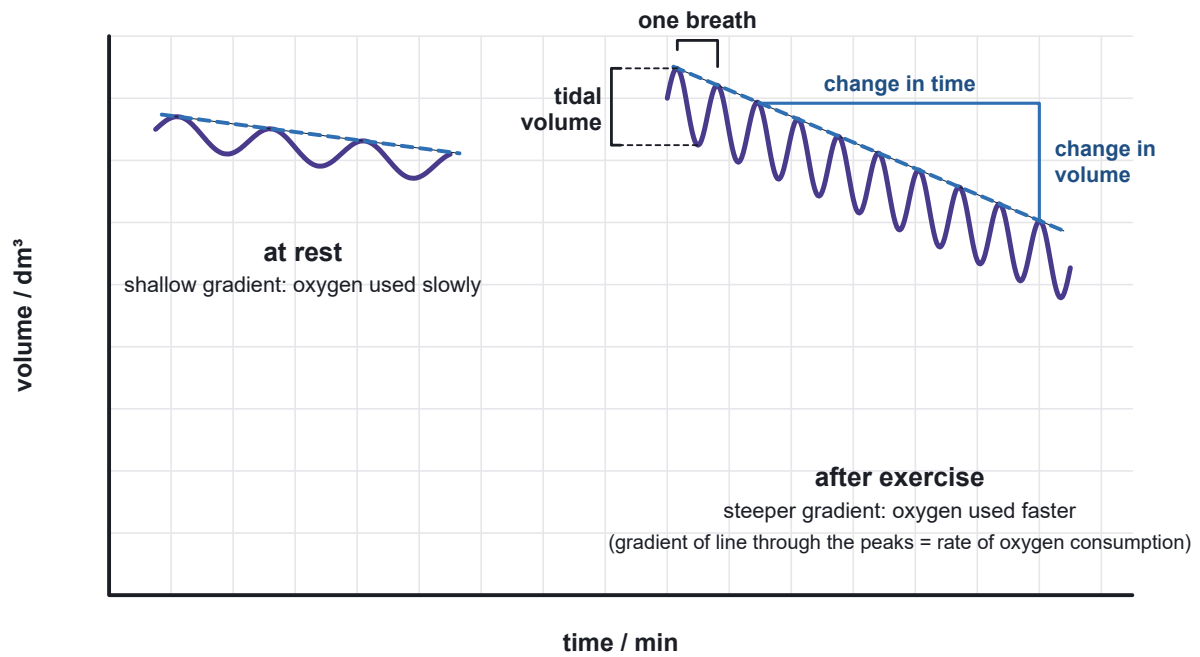
Spirometer trace

At rest, a spirometer trace shows a tidal volume of 0.5 dm^3 and 14 breaths per minute. The trace falls from 3.0 dm^3 to 2.4 dm^3 in two minutes. Calculate the minute ventilation and the rate of oxygen consumption.

1. Minute ventilation = $0.5 \times 14 = 7.0 \text{ dm}^3 \text{ min}^{-1}$
2. Fall in the trace = $3.0 - 2.4 = 0.6 \text{ dm}^3$
3. Rate = $0.6 \div 2 = 0.3 \text{ dm}^3 \text{ min}^{-1}$

Answer: Minute ventilation $7.0 \text{ dm}^3 \text{ min}^{-1}$; oxygen consumption $0.3 \text{ dm}^3 \text{ min}^{-1}$.

1. Fill the spirometer chamber with medical-grade oxygen, check the soda lime is fresh and the mouthpiece is sterilised. The volunteer wears a nose clip.
 2. Record a trace at rest for a few minutes.
 3. The volunteer exercises for a set time (for example stepping or cycling), then breathes through the spirometer again and a trace is recorded at once. Repeat with different levels of exercise, with a rest period between.
 4. Process the traces for tidal volume, breathing rate, minute ventilation and oxygen consumption. Both ventilation and oxygen consumption increase with exercise.
- Safety and ethics: the volunteer gives informed consent and can stop at any time; check for asthma, heart conditions or other health problems before exercise; use a clean mouthpiece to avoid cross-infection; the soda lime is corrosive and oxygen is a fire risk, so keep flames away.
 - Control variables: the same person, the same type and duration of exercise, the same starting volume in the chamber, the same time of day, and the same amount of rest.



The gradient of a line through the **peaks** gives the rate of oxygen consumption.

Quick check

1. What does myogenic mean?
2. Where is the sinoatrial node?
3. What does the QRS complex on an ECG show?
4. How do you calculate cardiac output?
5. Which part of the brain contains the ventilation centre?

5 Homeostasis, hormones and the kidney

Spec 7.16-7.22

A Level only

Negative and positive feedback Spec 7.16

Most control systems in the body contain the same components: a **receptor** detects a change in a factor, a coordination centre (for example the hypothalamus) processes the information, and an **effector** (a muscle or gland) brings about a response.

Negative feedback

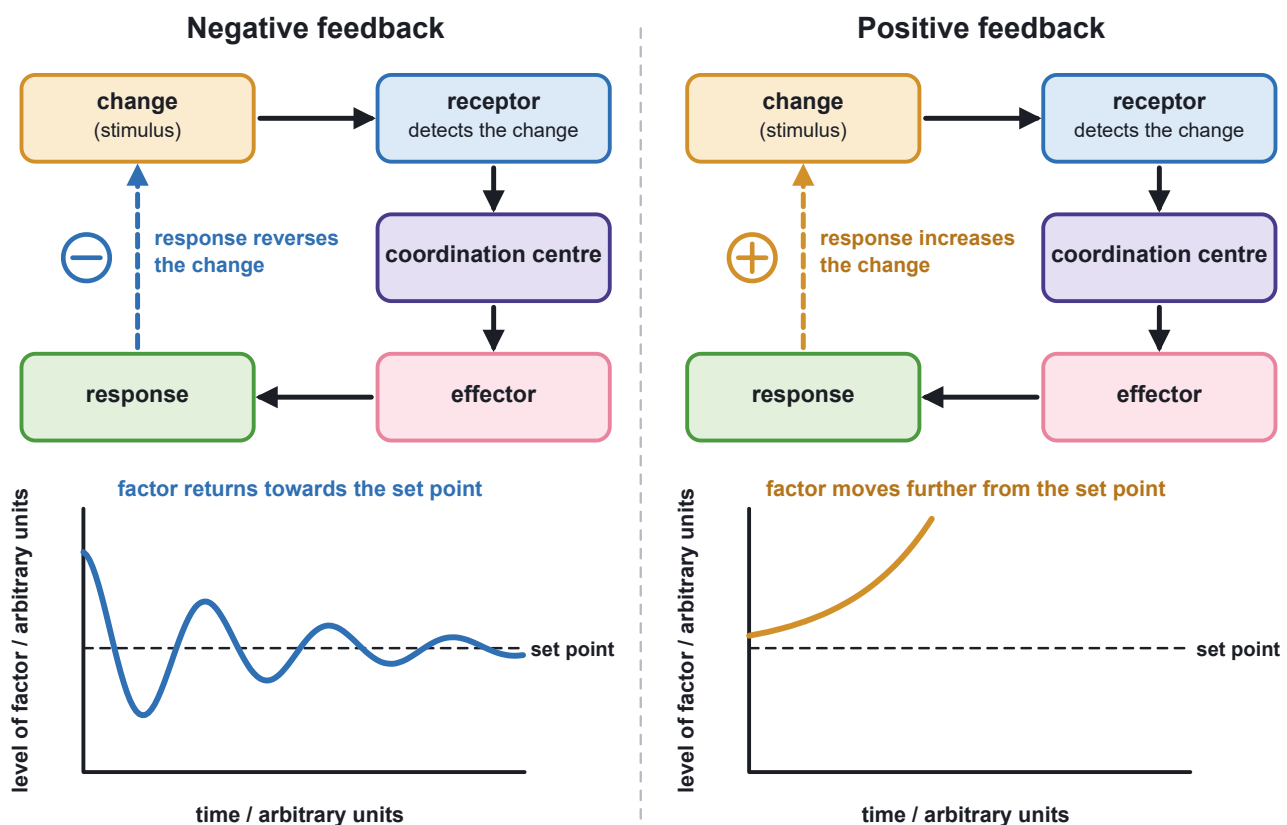
In **negative feedback**, the response reverses the original change. If the factor rises above the set point, the response makes it fall; if it falls below, the response makes it rise. The factor therefore fluctuates around the set point within narrow limits. Having receptors and effectors that work in opposite directions (for example vasoconstriction and vasodilation) gives control in both directions.

1. A factor changes from its set point (the stimulus).
2. Receptors detect the change and send information to the coordination centre.
3. The coordination centre sends signals (nerve impulses or hormones) to effectors.
4. Effectors produce a response that reverses the change.
5. The factor returns to its set point and the stimulus is removed, so the response is switched off.

Positive feedback

In **positive feedback**, the response increases the change away from the set point. It is not used to maintain a steady state. It is useful when a rapid, complete change is needed, for example the stimulation of uterine contractions by oxytocin during birth, and the opening of voltage-gated sodium channels in an action potential. If it is not stopped it can be harmful.

Common mistake: 'Negative' does not mean the effect is bad or that the response decreases the factor. Negative feedback reverses whichever change occurred. Positive feedback amplifies it.



Negative feedback reverses a change; **positive** feedback amplifies it.

Homeostasis and thermoregulation Spec 7.17

Homeostasis is the maintenance of a stable internal environment (for example body temperature, blood glucose concentration, blood water potential and pH) within narrow limits, by negative feedback. It is a state of **dynamic equilibrium**: conditions continually change slightly and are continually corrected, so they fluctuate around a set point.

It is important because enzymes work best at a particular temperature and pH, and cells need a stable water potential and a constant supply of glucose and oxygen for respiration. During exercise, muscle respiration increases heat production, CO₂ concentration and the demand for glucose and oxygen, so conditions must be corrected to prevent damage.

Thermoregulation and the hypothalamus

The **hypothalamus** contains thermoreceptors that detect the temperature of the blood flowing through it (core temperature). Thermoreceptors in the skin also send information to the hypothalamus. The hypothalamus acts as the coordination centre and sends impulses to the effectors.

Responses to a change in core temperature		
Response	If core temperature rises (e.g. exercise)	If core temperature falls
Skin arterioles	Vasodilation: more blood flows near the surface, so more heat is lost by radiation	Vasoconstriction: less blood flows near the surface, so less heat is lost
Sweat glands	Sweat secreted: evaporation of water takes heat from the skin	Little or no sweat
Skeletal muscles	No shivering	Shivering: rapid involuntary contractions release heat from respiration
Hair erector muscles	Relax: hairs lie flat (little effect in humans)	Contract: hairs stand up, trapping an insulating layer of air
Metabolic rate	Reduced	Increased (e.g. by hormones such as adrenaline and thyroxine)
Behaviour	Seek shade, remove clothing	Seek warmth, add clothing

Exam tip: In exercise, say that heat released by respiration in muscle raises core temperature, the hypothalamus detects it, and effectors such as sweat glands and skin arterioles lower it again (negative feedback).

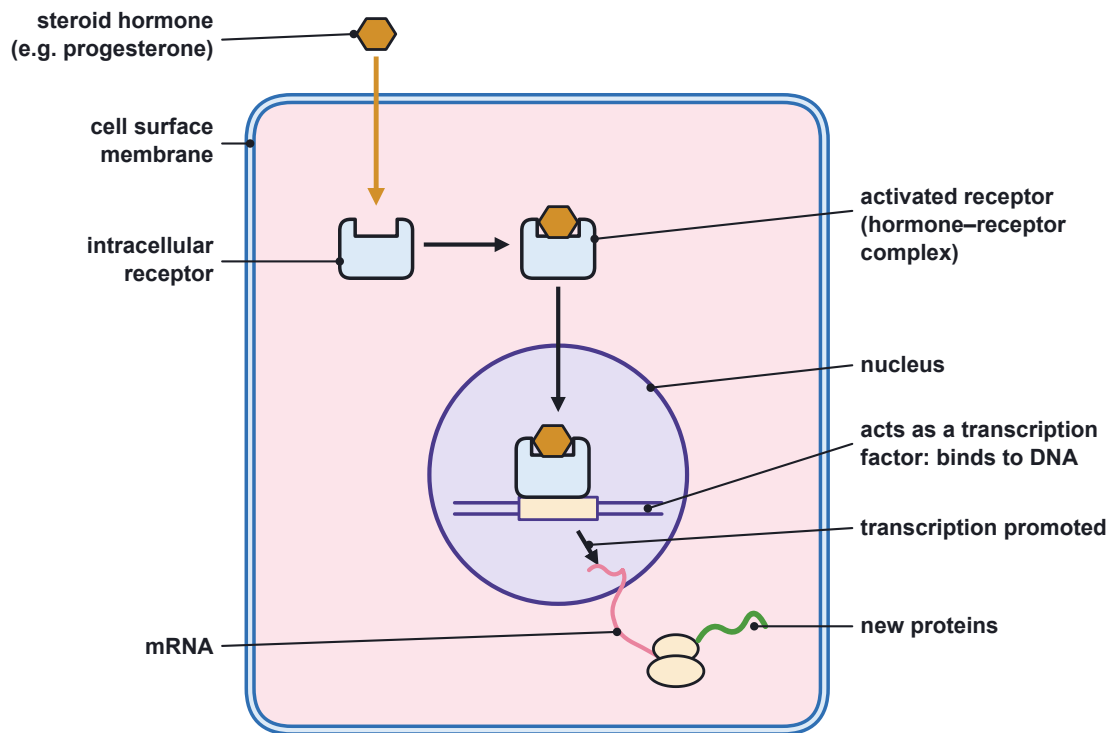
Hormones and transcription factors Spec 7.22

Transcription factors are proteins that bind to specific base sequences on DNA, near a gene. Some (activators) help RNA polymerase bind and so switch the gene on; others (repressors) block transcription and switch the gene off. Whether a gene is expressed, and how much protein is made, depends on which transcription factors are active in a cell.

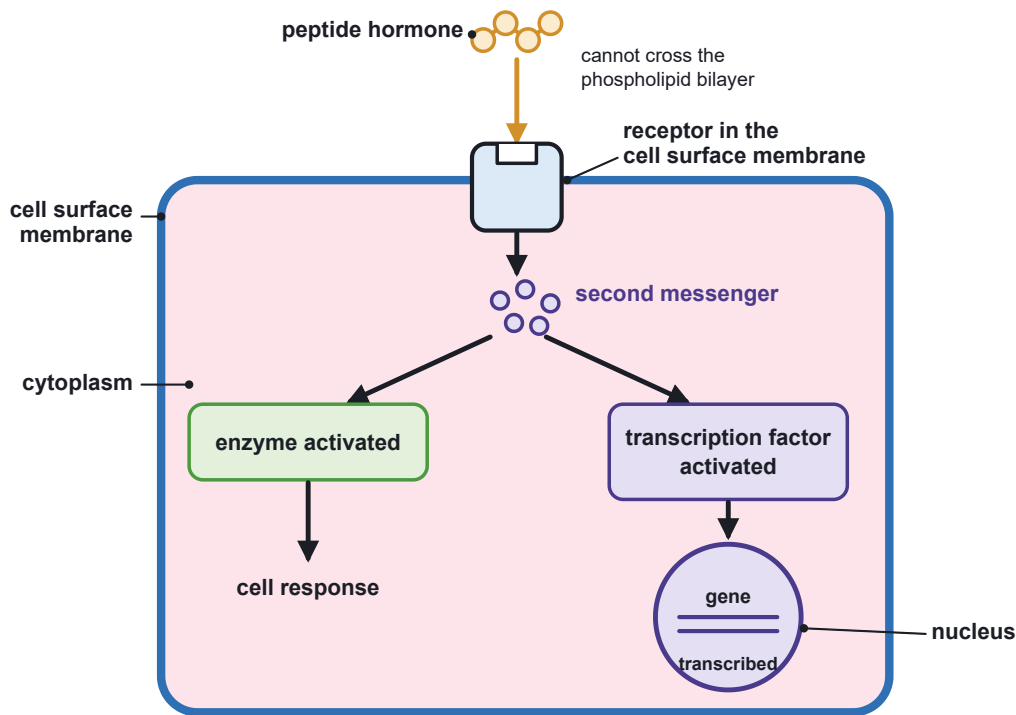
Two ways in which hormones affect gene expression

Feature	Steroid hormones (e.g. oestrogen)	Peptide hormones (e.g. insulin, glucagon)
Solubility	Lipid-soluble	Water-soluble
Entry to the cell	Pass through the phospholipid bilayer by diffusion	Cannot pass through the membrane
Receptor	Inside the cell (cytoplasm or nucleus): acts intracellularly	On the cell surface membrane: acts extracellularly
How gene expression changes	The hormone-receptor complex acts as a transcription factor: it binds to DNA, switching a gene on (or off), so mRNA and a protein are made	Binding activates a second messenger (e.g. cyclic AMP) inside the cell, which triggers a cascade that activates or inactivates transcription factors and enzymes
Speed of response	Slower: protein must be made	Often quicker, because enzymes already present are altered

Exam tip: Peptide hormones act without entering the cell because they cannot cross the phospholipid bilayer. Steroid hormones can, so their receptor is inside the cell.



Steroid hormones enter the cell and act as **transcription factors**.



Peptide hormones cannot cross the membrane, so they work through a **second messenger**.

Structure of the mammalian kidney Spec 7.18

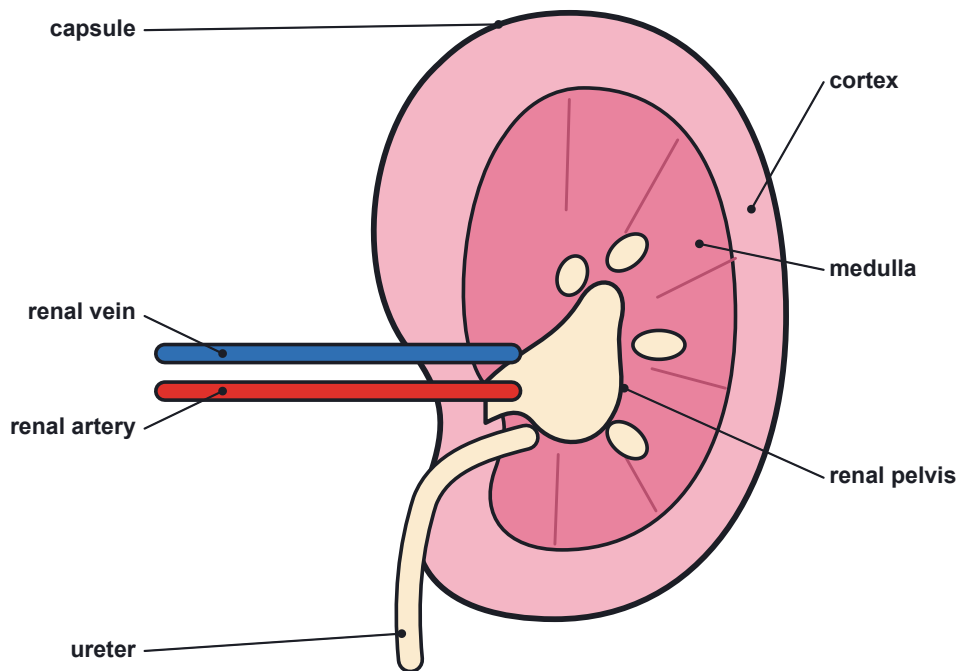
Gross structure

- Renal artery brings oxygenated blood with urea; renal vein carries blood away.
- Fibrous capsule around the outside.
- Cortex: outer region, containing the glomeruli, Bowman's capsules and convoluted tubules.
- Medulla: inner region, containing the loops of Henle and collecting ducts.
- Renal pelvis: the funnel-shaped cavity that collects urine and drains into the ureter, which leads to the bladder.

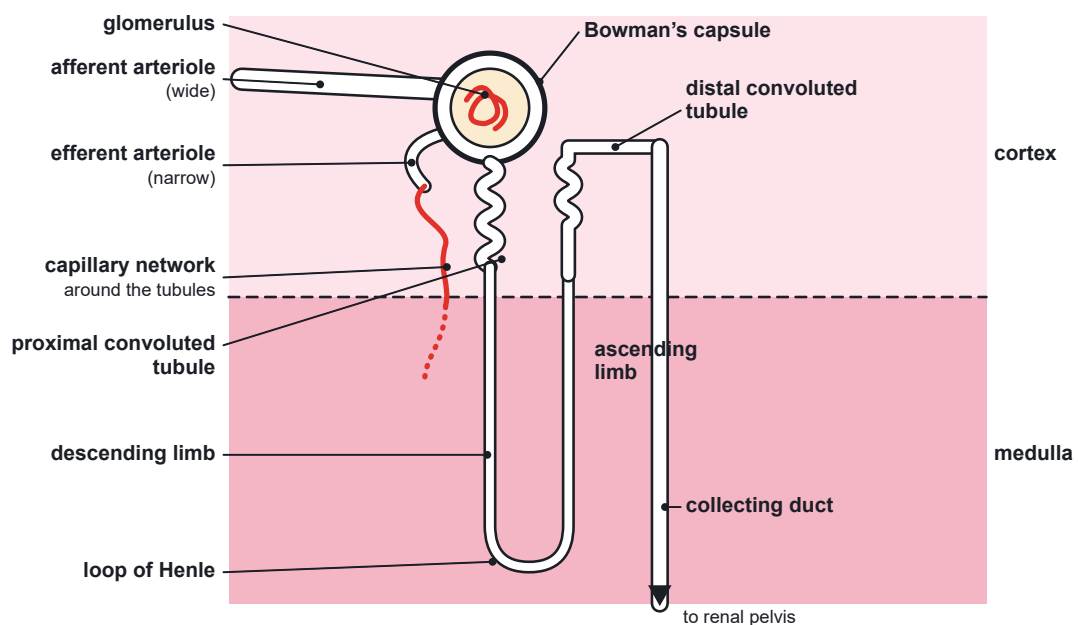
Microscopic structure: the nephron

Parts of a nephron		
Part	Position	Structure and role
Glomerulus	Cortex (inside Bowman's capsule)	Knot of capillaries; the afferent arteriole is wider than the efferent arteriole, which creates high pressure
Bowman's capsule	Cortex	Cup-shaped; the inner layer has podocytes; collects the filtrate
Proximal convoluted tubule	Cortex	Cuboidal epithelium with microvilli and many mitochondria; reabsorbs most of the filtrate
Loop of Henle	Medulla (descends and ascends)	Creates a high solute concentration (low water potential) in the medulla
Distal convoluted tubule	Cortex	Adjusts the ion content of the filtrate
Collecting duct	Cortex to medulla to pelvis	Collects urine from many nephrons; water reabsorbed under the control of ADH

Blood flows from the renal artery to the afferent arteriole, glomerulus and efferent arteriole, then through a capillary network around the tubules (where substances are reabsorbed), and leaves in the renal vein.



Structure of the kidney in section.



A nephron, with the cortex / medulla boundary marked.

Urea production and ultrafiltration Spec 7.19

Making urea in the liver

1. Amino acids not needed for protein synthesis cannot be stored. In the liver, the amino group is removed from each excess amino acid (deamination), forming ammonia and a keto acid.
2. The keto acid can be respired or converted to carbohydrate or fat.
3. Ammonia is toxic and very soluble, so it is combined with carbon dioxide in the ornithine cycle (details are not required) to make urea, using ATP.

4. Urea is soluble and much less toxic. It is carried in the blood plasma to the kidneys.

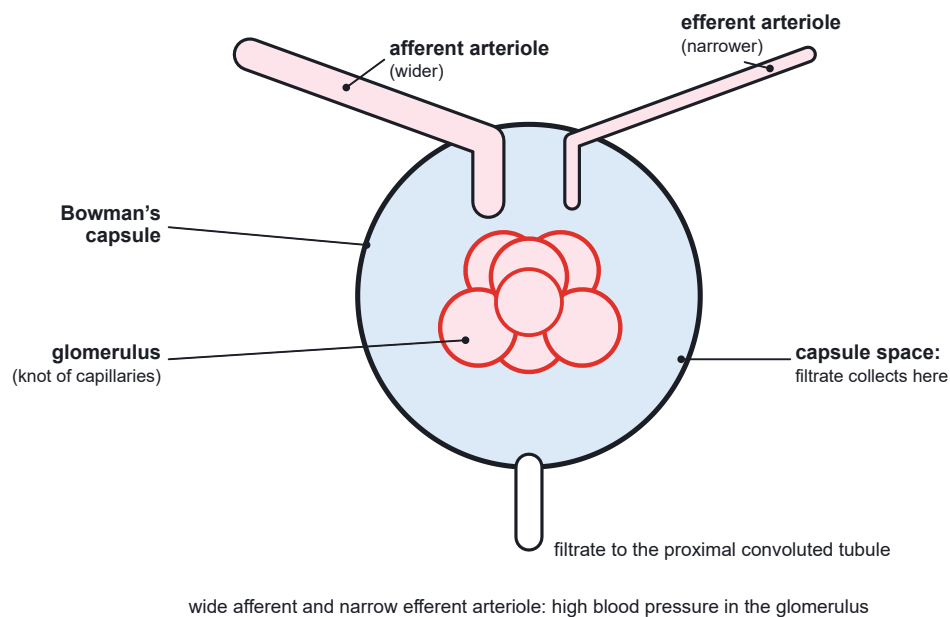
Ultrafiltration

Ultrafiltration is filtration at the molecular level. Blood in the glomerulus is at high hydrostatic pressure, because the afferent arteriole is wider than the efferent arteriole. This forces water and small solutes out of the capillaries into the Bowman's capsule, through three layers:

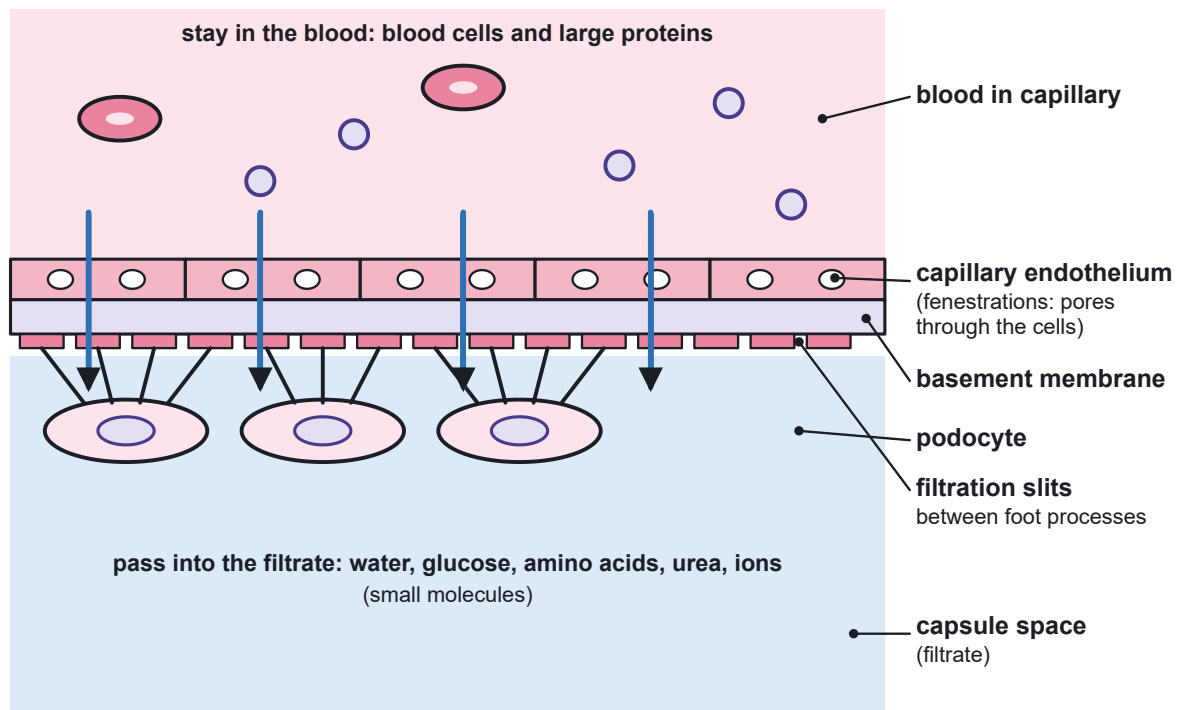
- the fenestrated capillary endothelium, whose cells have many small pores (fenestrations) through them;
- the basement membrane, a mesh of collagen and glycoproteins that acts as the filter and stops large proteins;
- the podocytes of the Bowman's capsule, which have filtration slits between their feet-like extensions.

The **glomerular filtrate** contains water, glucose, amino acids, urea and inorganic ions. It does not contain blood cells or large plasma proteins, which are too large to pass through. The pressure is opposed by the water potential of the blood (which is lowered by the plasma proteins) and the pressure of fluid in the capsule. The volume filtered is about 125 cm³ per minute in humans.

Exam tip: State all three layers and the reason for the high pressure (wide afferent, narrow efferent arteriole). 'Ultrafiltration' needs a high pressure, not just a membrane.



The wide afferent and narrow efferent arteriole keep the **pressure high** in the glomerulus.



Three layers filter the blood: **endothelium, basement membrane and podocytes**.

Selective reabsorption and the loop of Henle Spec 7.20

The proximal convoluted tubule

The cells lining the proximal tubule have microvilli (a large surface area) and many mitochondria (to supply ATP for active transport). They carry out **selective reabsorption**:

- Sodium ions are actively transported out of the cell into the blood side by sodium-potassium pumps, lowering the sodium concentration in the cell.
- Sodium ions then move into the cell from the filtrate down their concentration gradient through co-transporter proteins, carrying glucose or amino acids with them (co-transport). Glucose and amino acids then pass into the blood by facilitated diffusion.
- All of the glucose and amino acids are normally reabsorbed, as well as much of the sodium and chloride ions.
- Water follows by osmosis, because the water potential of the cells and blood is now lower. Most of the filtrate (about 80%) is reabsorbed here, and some urea diffuses out.

The loop of Henle as a countercurrent multiplier

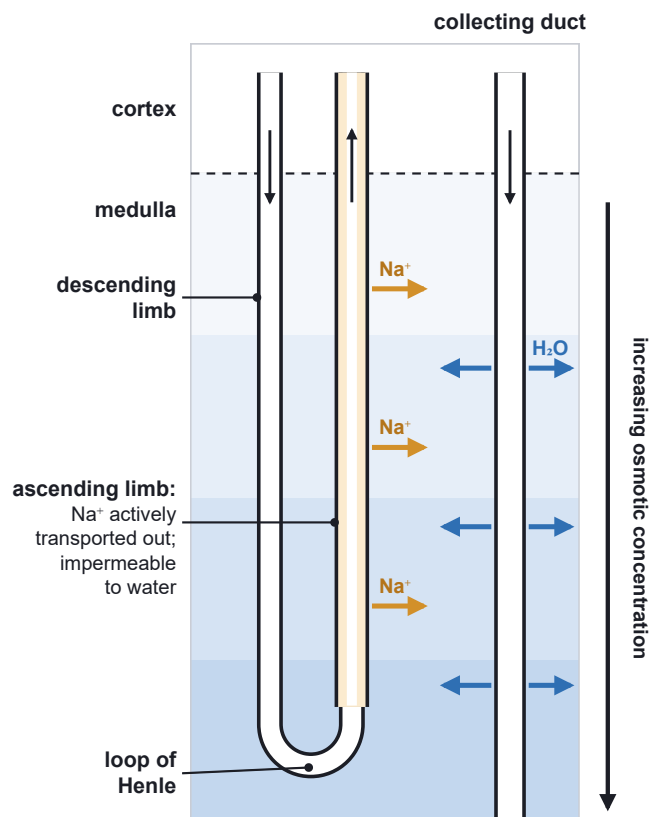
The loop creates a high concentration of solutes (a low water potential) in the tissue fluid of the medulla, which increases the reabsorption of water from the filtrate in the collecting duct. It does this by using a **countercurrent multiplier** mechanism: the fluid flows in opposite directions in the two limbs, and a small difference at each level is multiplied into a large gradient along the whole loop.

1. In the ascending limb, which is impermeable to water, sodium and chloride ions are actively pumped out into the medulla. This lowers the water potential of the medulla tissue fluid.
2. In the descending limb, which is permeable to water but not to ions, water leaves the filtrate by osmosis into the medulla. The filtrate becomes more concentrated as it descends, so it is most concentrated at the bottom of the loop.
3. As the filtrate rises in the ascending limb, ions move out (they diffuse out from the lower part and are actively pumped out in the upper part), so the filtrate becomes more dilute again.

4. The concentration gradient in the medulla is kept steep, with the lowest water potential deepest in the medulla.
5. Blood capillaries (the vasa recta) carry away the reabsorbed water.

The filtrate then flows through the distal tubule and the collecting duct, which pass back down through the medulla. If the collecting duct is permeable to water, water moves out by osmosis down the water potential gradient, producing concentrated urine. Animals with long loops of Henle (such as desert mammals) have a steeper gradient and can produce a more concentrated urine.

Common mistake: The descending limb is permeable to water, while the ascending limb is not. Do not say that water is reabsorbed from the ascending limb.



The loop of Henle builds up a **high solute concentration in the medulla**, so water can be reabsorbed.

ADH and the control of plasma concentration Spec 7.21

The concentration of the blood plasma (its water potential) and the blood volume must be kept within narrow limits. This is **osmoregulation**, and it is controlled by negative feedback involving the hypothalamus, the pituitary gland and the hormone **ADH** (antidiuretic hormone).

If the blood plasma becomes too concentrated (for example after sweating, or little water)

1. Osmoreceptors in the hypothalamus detect the low water potential of the blood: they lose water by osmosis and shrink.
2. The hypothalamus stimulates neurosecretory cells that make ADH. ADH passes down their axons to the posterior pituitary gland and is released into the blood.
3. ADH travels in the blood to the kidney and binds to receptors on the cell surface membranes of the collecting duct (and distal convoluted tubule) cells.
4. This activates a second messenger system that causes vesicles containing aquaporins (water channels) to fuse with the cell surface membrane. The walls therefore become more permeable to

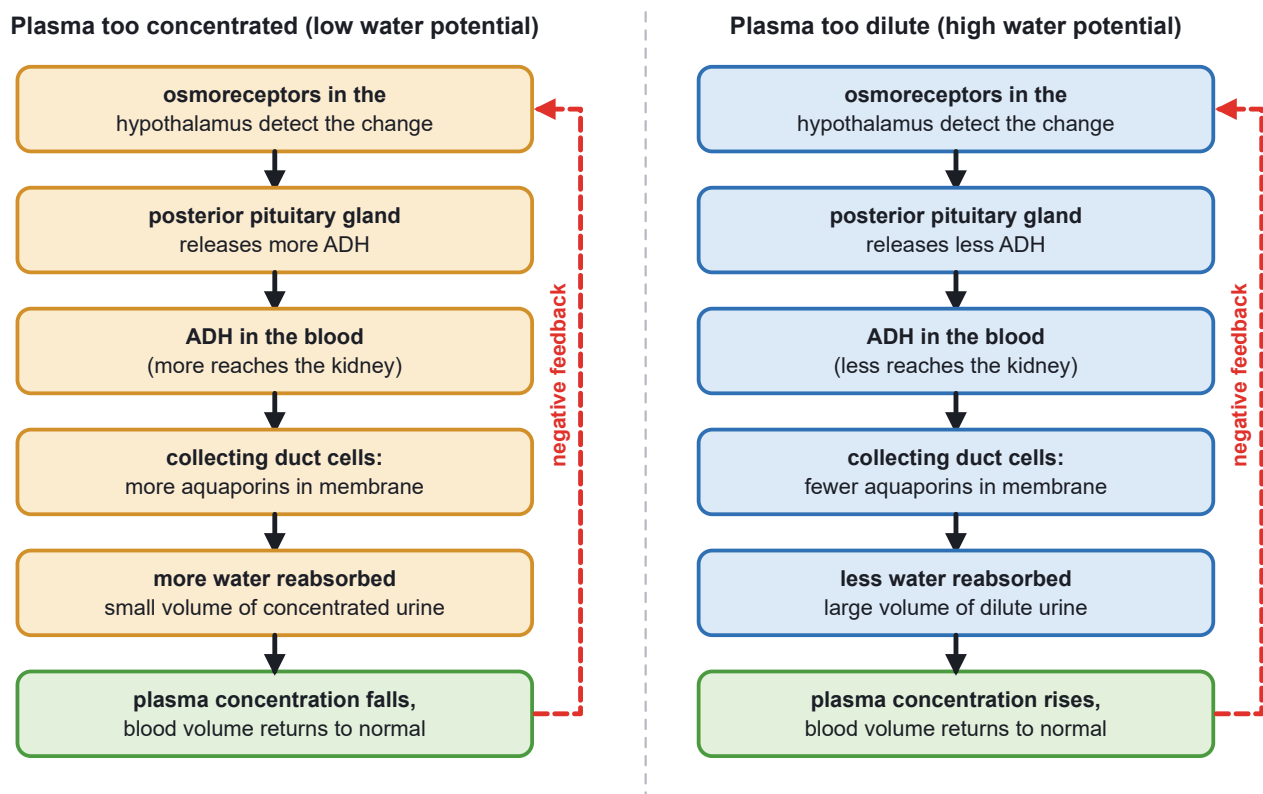
water.

5. More water leaves the collecting duct by osmosis into the concentrated medulla and returns to the blood. A small volume of concentrated urine is produced.
6. Plasma water potential and blood volume rise back to normal, so osmoreceptors are no longer stimulated and less ADH is released: negative feedback.

If the blood plasma is too dilute

The osmoreceptors are not stimulated, so less ADH is released. Fewer aquaporins are in the membrane of the collecting duct, so it is less permeable to water. Less water is reabsorbed and a large volume of dilute urine is produced. This lowers the blood volume and raises the concentration of the plasma.

Exam tip: Describe the whole loop: stimulus, receptor, hormone, target cells, response, then the effect that reverses the change. Mention the pituitary gland and aquaporins.



ADH adjusts **water reabsorption** in the collecting duct by negative feedback.

Quick check

1. What is negative feedback?
2. Which part of the brain contains the thermoreceptors that detect core temperature?
3. What forces fluid out of the glomerulus?
4. Which limb of the loop of Henle is impermeable to water?
5. What is the effect of ADH on the collecting duct?

Quick check answers

Stages of respiration

1. In the cytoplasm.
2. Two (four are made, two are used).
3. Acetyl CoA, carbon dioxide and reduced NAD.
4. It is the final electron acceptor, combining with electrons and protons to form water.
5. Reduced NAD would not be oxidised, so NAD would not be regenerated for glycolysis.

Respiratory quotient and respiration practicals

1. $RQ = \text{volume of CO}_2 \text{ produced} \div \text{volume of O}_2 \text{ consumed}$.
2. About 1.0.
3. It accepts hydrogen from dehydrogenase enzymes, so it is reduced and loses its blue colour.
4. It absorbs carbon dioxide, so that the movement of fluid shows the volume of oxygen consumed.

Muscles and movement

1. A tendon joins muscle to bone; a ligament joins bone to bone.
2. Two muscles that have opposite effects at a joint: when one contracts the other relaxes.
3. The A band.
4. Troponin.
5. They use anaerobic respiration, so lactate builds up.

The heart, ventilation and exercise

1. The heart muscle can contract and relax on its own, without nerve impulses.
2. In the wall of the right atrium.
3. Depolarisation of the ventricles.
4. $\text{Stroke volume} \times \text{heart rate}$.
5. The medulla oblongata.

Homeostasis, hormones and the kidney

1. A change is detected and the response reverses it, returning the factor towards its set point.
2. The hypothalamus.
3. High hydrostatic pressure, caused by the afferent arteriole being wider than the efferent arteriole.
4. The ascending limb.
5. It makes the walls more permeable to water by inserting aquaporins, so more water is reabsorbed.