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Cell Respiration

IB Biology - Revision Notes

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Adenosine Triphosphate (ATP)

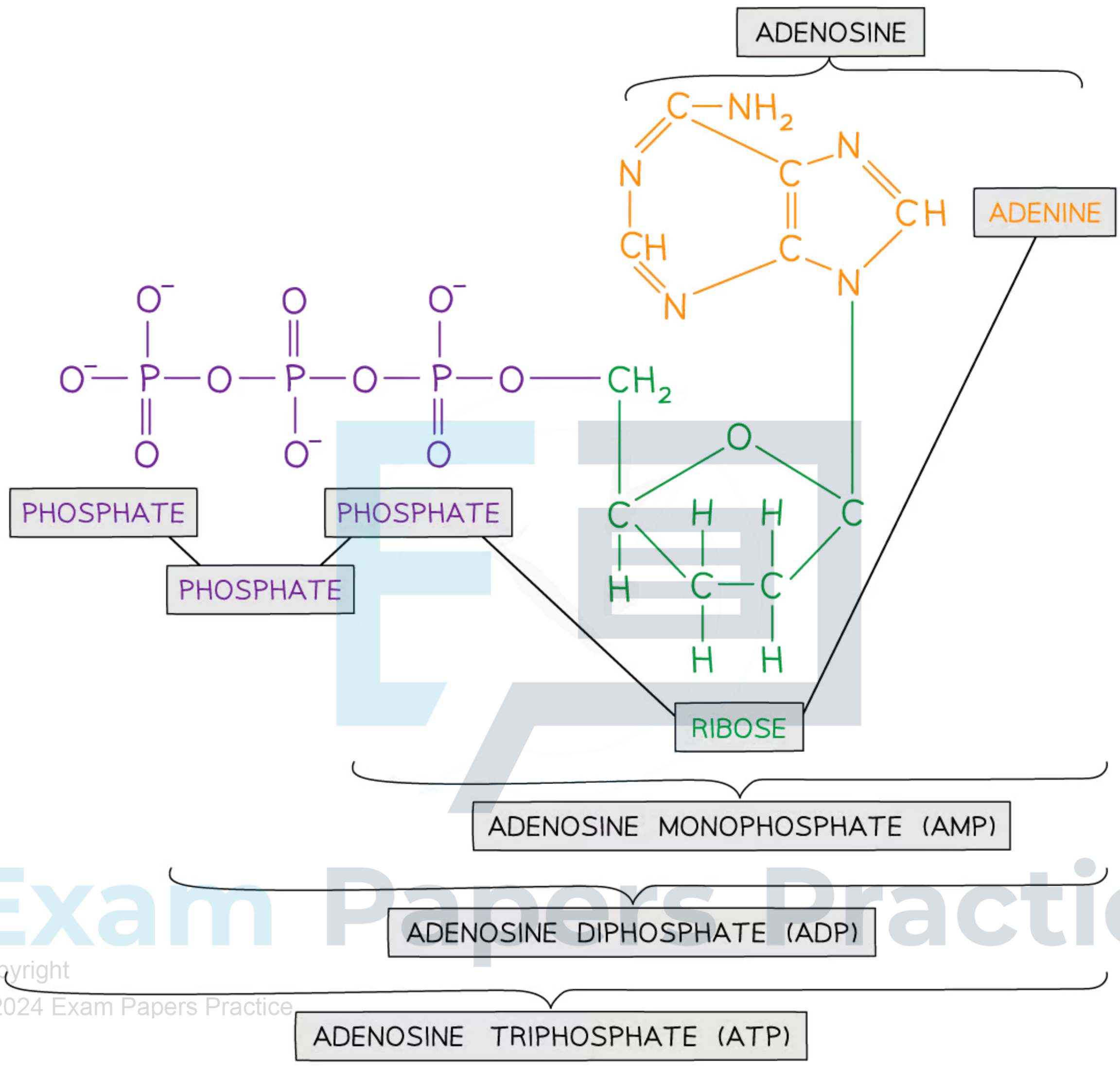
Adenosine Triphosphate (ATP)

- Living organisms require energy to perform and maintain life processes such as movement, nutrition and excretion
- This **energy is released by the process of cell respiration**
- Energy released during the reactions of respiration is transferred to the molecule **adenosine triphosphate** (ATP)
  - The energy is transferred in a series of small steps
  - Heat is lost at each step, which is used to regulate body temperature in endotherms
- ATP is a small and soluble molecule that provides a **short-term store** of chemical energy that cells can use to do work
  - Its solubility and size enables it to move easily in cells and living organisms by **facilitated diffusion**
- It is vital in linking energy requiring and energy yielding reactions
- ATP is described as a **universal energy currency**
  - Universal: It is used in all organisms
  - Currency: Like money, it can be used for different purposes (reactions) and is reused countless times
- The use of ATP as an 'energy-currency' is beneficial for many reasons:
  - The **hydrolysis of ATP** can be carried out **quickly and easily** wherever energy is required within the cell by the action of just one enzyme, ATPase
  - A **useful** (not too small, not too large) **quantity of energy is released** from the hydrolysis of one ATP molecule - this is beneficial as it reduces waste but also gives the cell control over what processes occur
  - ATP is **relatively stable** at cellular pH levels

Structure of ATP

- ATP is a phosphorylated nucleotide
- It is made up of:
  - Ribose sugar
  - Adenine base
  - Three phosphate groups

ATP Diagram



Structure of ATP contains ribose sugar, an adenine base and three phosphate groups

Features of ATP Table

Feature	Benefit
Releases a small but sufficient quantity of energy	This is enough energy to drive important metabolic reactions while keeping energy wastage low

Exists as a stable molecule	It doesn't break down unless a catalyst (ATPase) is present so energy won't be wasted
Can be recycled	The breakdown of ATP is a reversible reaction, ATP can be reformed from ADP and P_i. This means the same molecule can be reused elsewhere in the cell for different reactions
Hydrolysis is quick and easy	Allows cells to respond to a sudden increase in energy demand
Soluble and moves easily within cells	Can transport energy to different areas of the cell
Forms phosphorylated intermediates	This can make metabolites more reactive and lower the activation energy required for a reaction

Exam Tip

Be careful not to use the terms energy and ATP interchangeably. Energy is the capacity or power to do work while ATP is a molecule which carries energy to places in the cell that need it in order to do work.

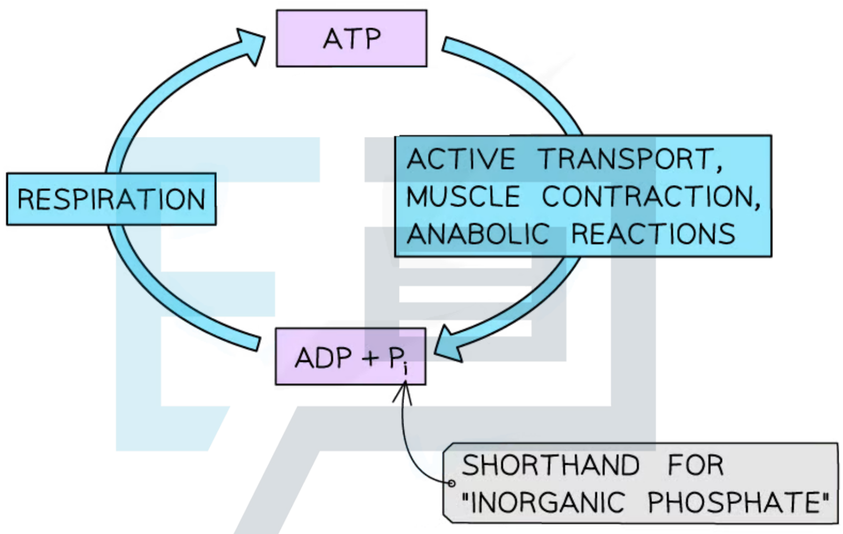
Life Processes Reliant On ATP

- Some of the life processes that are reliant on ATP as a source of energy include:
  - In **anabolic reactions** to synthesise larger molecules (macromolecules) from smaller ones
  - To move molecules across the cell membrane against their concentration gradient during **active transport**
  - Enabling **movement of the entire cell**
  - The **move cell components**, such as chromosomes, within the cell
- ATP is readily converted to **adenosine diphosphate** (ADP) and a **phosphate ion** (P_i), during which energy is released
  - Since ATP is a very **reactive molecule**, it is not stored in living organisms
- Molecules such as **glucose and fatty acids** are used as short-term stores of energy, while **glycogen**, **starch and triglycerides** act as long-term storage molecules of energy

Interconversions Between ATP & ADP

- ATP is a very reactive molecule and is readily converted to **ADP** and **phosphate** when releasing its energy
  - ADP and phosphate can then be **re-converted to ATP** during respiration
- Organisms require a **constant supply of ATP** because much of the energy is lost to the surroundings as **heat**

ATP Cycle Diagram

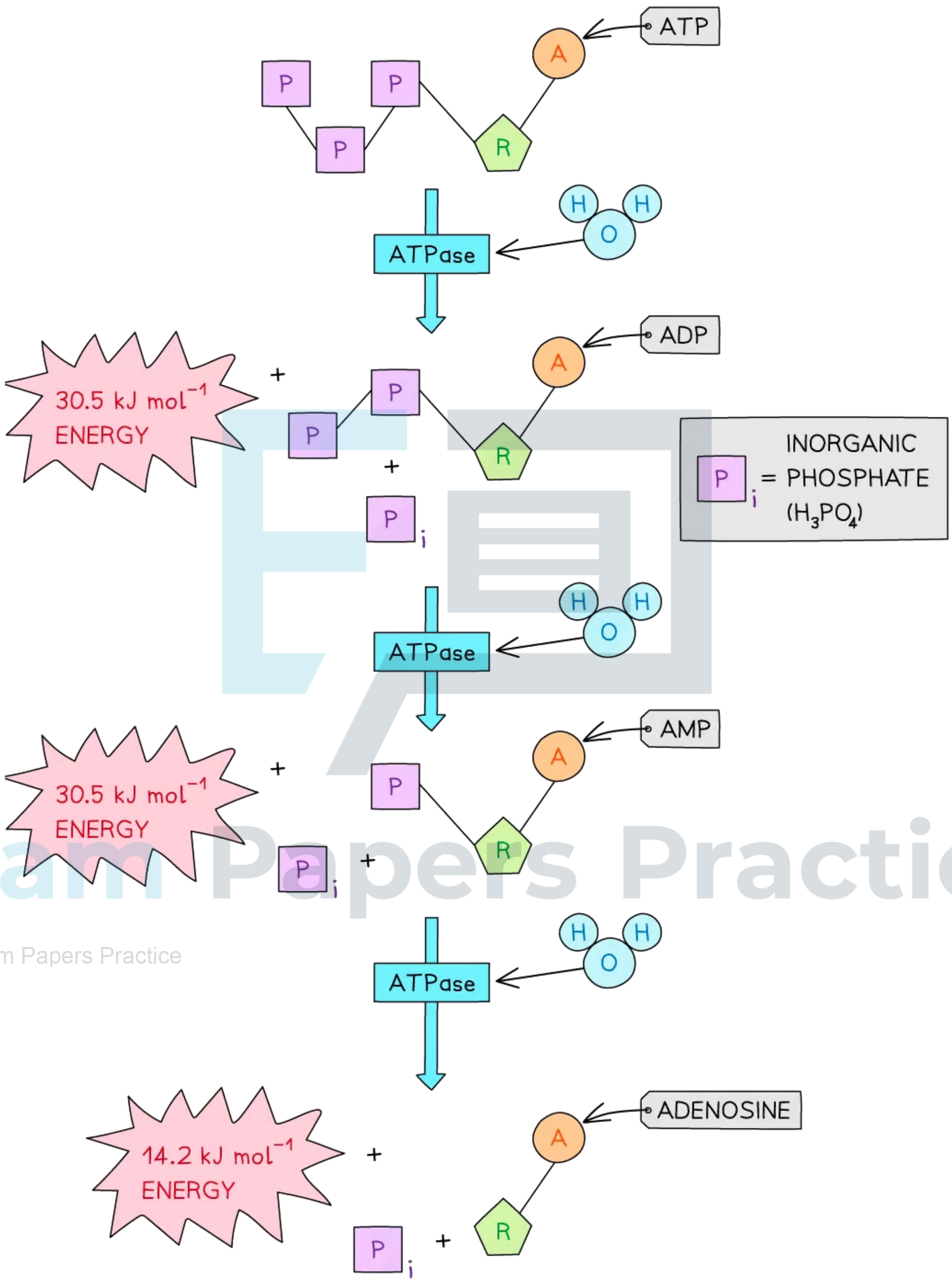


The constant cycling of ATP and ADP + P_i within a cell

Hydrolysis of ATP

- When ATP is hydrolysed (broken down), ADP and phosphate are produced
- As ADP forms, **free energy** is released that can be used for processes within a cell e.g. DNA synthesis
  - Removal of one phosphate group from ATP releases approximately 30.5 kJ mol $^{-1}$ of energy, forming ADP
  - Removal of a second phosphate group from ADP also releases approximately 30.5 kJ mol^{-1} of energy, forming AMP
  - Removal of the third and final phosphate group from AMP releases 14.2 kJ mol^{-1} of energy, forming adenosine

Hydrolysis of ATP Diagram

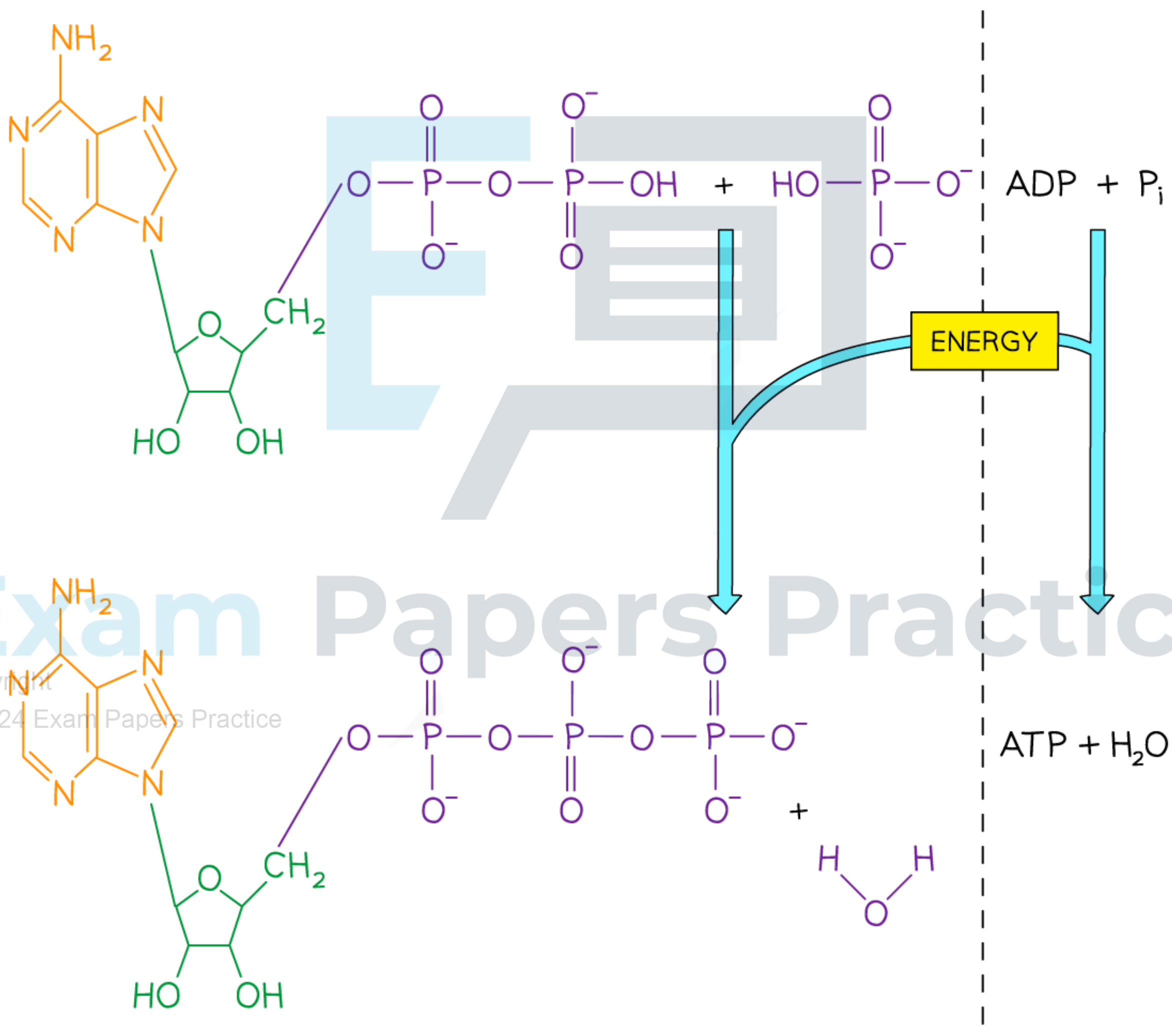


The hydrolysis of ATP

ATP synthesis

- On average humans use more than 50 kg of ATP in a day but only have a maximum of ~ 200g of ATP in their body at any given time
- Organisms **cannot build up large stores of ATP** and it rarely passes through the cell surface membrane
- This means the cells must make ATP as and when they need it
- ATP is formed when ADP is combined with an inorganic phosphate (Pi) group
  - This is an **energy-requiring reaction**
  - **Water is released** as a waste product (therefore ATP synthesis is a **condensation reaction**)

Synthesis of ATP Diagram



Energy-requiring synthesis of ATP from ADP and Phosphate

Exam Tip

Note that you are not required to know the exact quantity of energy in kilojoules that are involved with the interconversions between ATP and ADP, but you should appreciate that it is sufficient for performing tasks within the cell.

Cell Respiration

Cell Respiration

Cell respiration as a system for producing ATP

- Cell respiration is the **controlled release of energy from organic compounds to produce ATP**
- Respiration is a **series of chemical reactions** that happens in **every cell**
- Its purpose is to **release energy** in usable forms from chemical energy stored in food e.g. glucose
- Respiration is a catabolic process
- **Glucose** is the main respiratory fuel used in cells
  - **Lipids** and **proteins** can also be used but they must undergo several changes before they can enter the respiratory pathway
  - Glucose can **enter glycolysis directly** which makes it easier to oxidise than lipids and proteins
  - Since proteins are primarily structural molecules, they will only be used as a respiratory fuel in conditions where glucose and lipids are not available
- **Organic** food substances contain **a lot of chemical energy**
- This **energy cannot be released in one, uncontrolled step** in cells, which would cause cell damage and tissue death
- Enzymes **control the release of energy** through a series of chemical reactions called a **pathway**
- This ends in the production of **ATP** (adenosine triphosphate)
  - To make ATP, a **phosphate group** is linked to adenosine diphosphate (**ADP**)
  - This process **requires energy** which comes from the breakdown of organic molecules
- The energy that is released is used for
  - Fuelling anabolic processes
  - Muscle contraction
  - Fuelling **active transport**
  - Moving molecules around the cell
  - **Generating heat** to maintain body temperature in warm-blooded animals

Exam Tip

Respiration is **often confused with gas exchange**, but remember that respiration is a **chemical process** while gas exchange involves the exchange of carbon dioxide and oxygen at the alveoli or cells

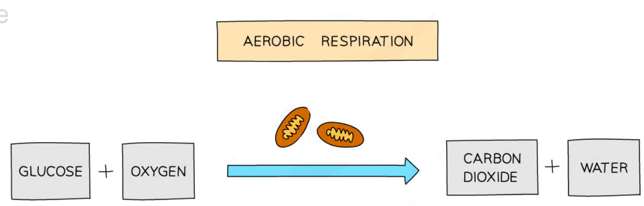
Comparing Anaerobic & Aerobic Cell Respiration

Differences between anaerobic and aerobic respiration in humans

- Respiration involves the transfer of **chemical potential energy** from nutrient molecules (such as carbohydrates, fats and proteins) into a usable energy form (through the synthesis of ATP) that can be used for work within an organism
- It is a vital process that takes place in the cells of all living organisms
- There are two forms of respiration depending on the oxygen availability of the cell:
  - **Aerobic** respiration
  - **Anaerobic** respiration
- **Aerobic** respiration is the process of breaking down a **respiratory substrate** in order to produce ATP **using oxygen**
  - The substrate is completely oxidised, thereby releasing a large amount of energy
- **Anaerobic** respiration takes place **in the absence of oxygen** and also breaks down a respiratory substrate but produces **less ATP** for the cell
- The main **respiratory substrate** involved in respiration is **glucose**

Aerobic respiration

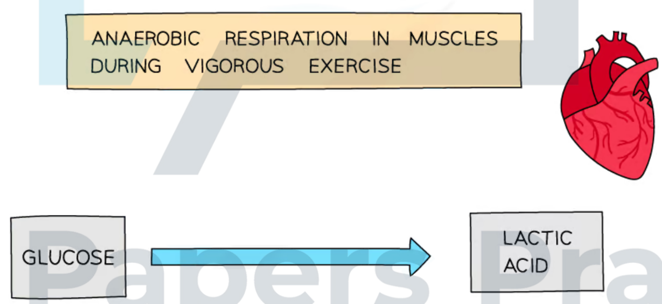
- Aerobic cell respiration requires oxygen and gives a **large yield of ATP from glucose**
- The presence of oxygen allows **glucose to be broken down fully** into carbon dioxide and water
- This yields far more energy (approx. 36 ATP molecules) than anaerobic respiration (2 ATP molecules) per molecule of glucose
- CO_2 is a **waste product** and has to be excreted
  - Except in plants where it is used for photosynthesis
- Water is a **by-product** and contributes to the organism's water needs
  - Some animals that live in deserts **drink very little** but survive on this water
- Most of the reactions of aerobic respiration, in eukaryotes, take place in the **mitochondria**



Aerobic respiration releases energy during the reaction between glucose and oxygen

Anaerobic respiration

- In cells, there is a much **lower energy yield** from respiration in **anaerobic conditions** than in aerobic conditions
- The reactions of anaerobic respiration will occur in the **cytoplasm** of cells and does not involve the mitochondria
- There can be different ways in which oxygen becomes unavailable
  - When **oxygen supply can't keep up with demand** in heavily respiring cells
    - But a short supply of ATP is still required e.g. **vigorous exercise** requiring a lot of muscle contraction
  - In conditions where oxygen **cannot reach the organisms** e.g. in waterlogged soil
- In anaerobic respiration, **glucose is only partially oxidised** meaning only **a small part of its chemical energy is released** and transferred to ATP
  - The only ATP-producing reaction that continues is the first stage of respiration (around 2 ATP molecules per molecule of glucose)
- As there is no oxygen, **none of the remaining reactions** (of aerobic respiration) can take place
  - This means that around **36 ATP molecules are not produced anaerobically** that would otherwise have been produced in the presence of oxygen
  - 2 ATP molecules are better than zero ATP molecules, so anaerobic respiration can give **a short discharge of energy** when oxygen runs out
- Different types of organisms produce **different products** when respiring anaerobically
  - **Plants and yeasts** produce **ethanol** and **CO_2**
  - **Animals** produce **lactate**



Anaerobic respiration in humans (and other animal cells) will partially oxidise glucose to form lactic acid

Comparison of Aerobic & Anaerobic Respiration in Humans Table

	Aerobic respiration	Anaerobic respiration
Oxidation of glucose	Complete	Incomplete
Oxygen required	Yes	No

Relative ATP yield	High (~36 molecules)	Low (2 molecules)
Products	CO_2 and H_2O	Lactate
Location of reactions	Cytoplasm and mitochondria	Cytoplasm

Exam Tip

You should be able to write simple word equations for both types of respiration, with glucose as the substrate. Remember that ATP is produced during both aerobic and anaerobic respiration

Cell Respiration: Skills

The Rate of Cell Respiration

Variables affecting the rate of cell respiration

- The rate of cell respiration may vary depending on the following:
  - How **metabolically active** the cell is
    - e.g. muscle cells will have a higher rate of cell respiration than adipose cells because of their higher energy needs
  - **Size** of the organism
    - e.g. smaller organisms will have a higher surface area : volume ratio than larger organisms, so they will have a higher rate of respiration to compensate for higher heat loss
  - The **oxygen supply**
    - When oxygen availability is low, cells will respire anaerobically
  - Supply of **respiratory substrates**
    - e.g. glucose availability is of particular importance, since it is the main respiratory substrate
    - The lower the supply of these substrates, the lower the rate of respiration will be
  - **Temperature**
    - The rate of respiration will **increase up to the optimum temperature** of the enzymes catalysing the reactions, whereafter the rate will drop as the enzymes denature
  - **pH**
    - Carbon dioxide released during respiration will **decrease the pH** of cells and tissues, which may also denature enzymes involved with respiration

Determining the rate of respiration

- Respirometers are used to measure and investigate the **rate of oxygen consumption** during respiration in organisms
- The experiments usually **require live organisms** such as seeds or invertebrates
  - **Use of animals should be minimised** when seeds can provide excellent data
- There are **many different designs of respirometers**, though they all have certain features in common
  - A **sealed container** containing **live organisms** and **air**
  - An alkaline solution (e.g. potassium hydroxide) to absorb CO_2
  - A **capillary tube** connected to the container and set **against a graduated scale** (a **manometer**)
- The organisms **respire aerobically** and **absorb oxygen** from the air
- The CO_2 they release is **absorbed by the alkali**
- This **reduces the air pressure** inside the sealed chamber

- The manometer fluid (shown in red below) **moves towards the organisms** because of the pressure drop inside the chamber
- The respirometer must be kept in **very temperature-controlled conditions** because slight fluctuations in temperature can affect the air pressure
  - A **thermostatically controlled water bath** is the best way to maintain a constant temperature
- **Repeat readings** should be carried out for each set of experimental conditions, in order to **identify** and **eliminate anomalies**
  - **Repeat** readings give a **reliable** mean

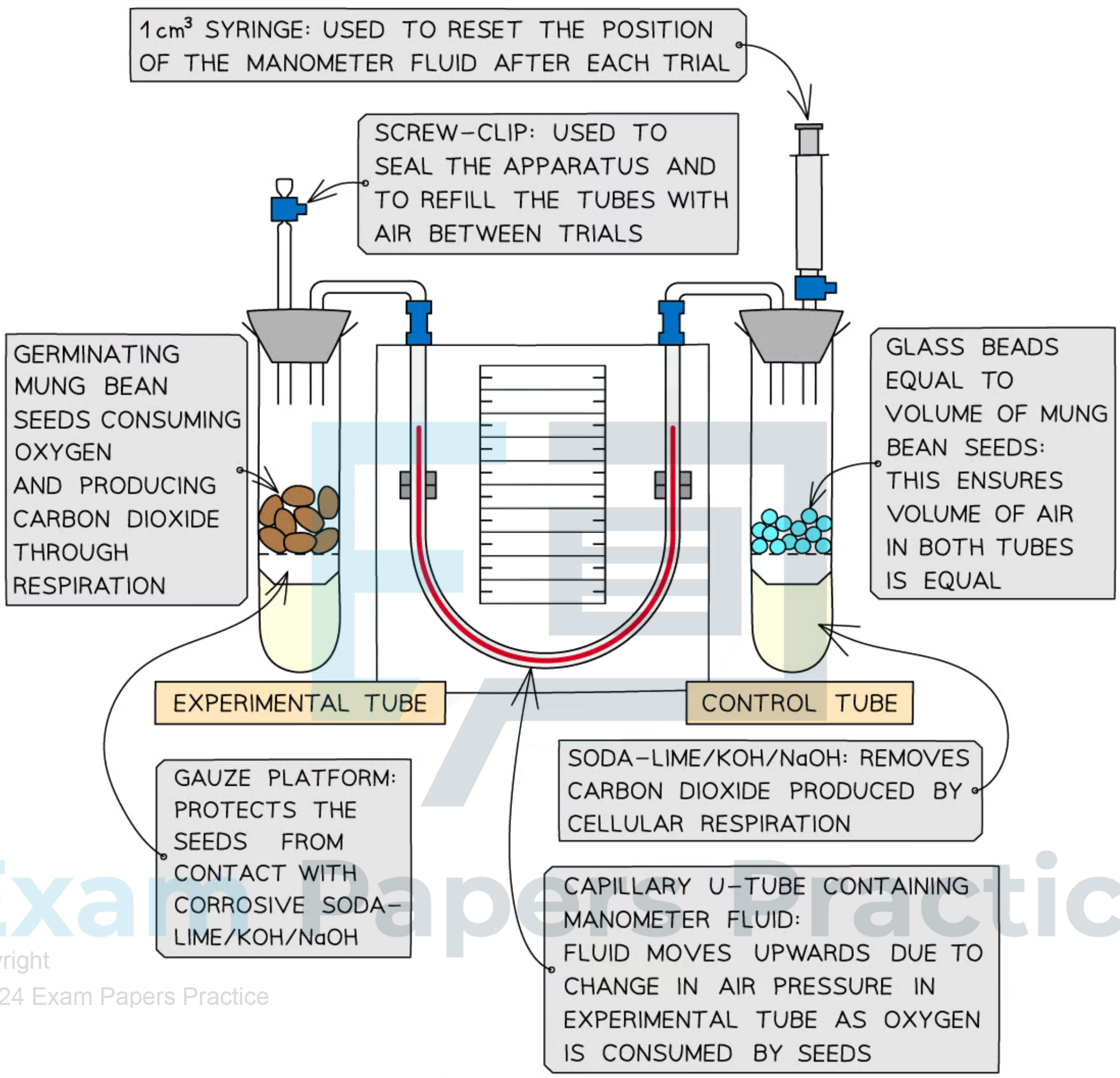
Analysis

  - Respirometers can be used in experiments **to investigate how different factors affect the rate of respiration** of organisms over time
    - E.g. temperature – using a series of water baths

Use of technology to measure rate of respiration

- **Technological devices** can automate and make the measurement of respiration rate easier
  - Not to be confused with **breathing rate**
- **Oxygen sensors** and **CO_2 monitors** can measure oxygen and CO_2 concentration in real-time
  - Without the need to expose the subject to hazards such as strong alkalis
- **Dataloggers** can record data over a period of time for analysis later

Respirometer Diagram



The typical set-up of a respirometer

The equation for calculating a change in gas volume

- The volume of oxygen consumed ($mm^3 min^{-1}$) during respiration can be worked out using the radius of the lumen of the capillary tube *r* (mm) and the distance moved by the manometer fluid *h* (mm) in a minute using the formula:

$$\pi r^2 h$$

- The volume of oxygen consumed can then be used to determine the average rate of respiration per unit time

Worked example

A respirometer was set up with germinating mung beans in the experimental tube. After a period of equilibration, the liquid in the capillary was measured to move by 2.3 cm in 25 minutes. The capillary tube had an internal diameter of 0.30 mm. Calculate the average rate of respiration of the mung beans, measured as the rate oxygen uptake, in $mm^3\ min^{-1}$ Use the value of pi (π) = 3.141.

Answer:

Step 1: Calculate the cross-sectional area of the capillary tube

Diameter = 0.30mm, so radius = $0.30 \div 2 = 0.15$ mm

Cross sectional area = $\pi r^2 = 3.141 \times 0.15^2 = 0.0707\ mm^2$

Step 2: Calculate the volume of oxygen that had been taken up

The liquid moved 2.3 cm, which is 23mm

Volume of liquid moved in 25 minutes =

$\pi r^2 h$, where h = 23 mm

$= 0.0707 \times 23 = 1.625\ mm^3$

Step 3: Calculate the average rate of oxygen consumption per minute

Rate per minute = $1.625 \div 25$

= $\mathbf{0.065\ mm^3\ min^{-1}}$

Exam Tip

There are several ways you can manage variables and increase the reliability of results in respirometer experiments:

- Use a controlled water bath to keep the **temperature** constant
- Have a control tube with an equal volume of inert material to the volume of the organisms to compensate for changes in atmospheric **pressure**
- Repeat the experiment multiple times for reliability and calculate a **mean**