Rewarding Learning

eGUIDE//Biology

Biochemistry, Genetics and Evolutionary Trends

Unit A2 2 5.1 Respiration

This e-book is designed to complement other support materials and enhance the understanding of this unit for students at GCE level. The topics covered are in accordance with those topics present in the current specification.

Contents

Respiration

5.1

Learning Outcomes from A2 2 5.1

Students should be able to:

- Demonstrate knowledge and understanding of the nature and function of ATP
- Demonstrate knowledge and understanding of glycolysis
- Demonstrate knowledge and understanding of aerobic respiration
- Demonstrate knowledge and understanding of anaerobic respiration
- Demonstrate knowledge and understanding of Krebs cycle
- Demonstrate knowledge and understanding of the electron transport chain
- Demonstrate knowledge and understanding of the comparison between aerobic and anaerobic respiration
- Demonstrate knowledge and understanding of the respiratory quotient (RQ)
- *Carry out practical work to include using the respirometer to calculate oxygen uptake, CO_2 production and RQ values, and the use of redox indicators (for example methylene blue) to demonstrate the role of hydrogen acceptors.*

What is Respiration?

Starter activity:
https://www.tes.com/teaching-resource/respiration-starter-activity-6047805

What do we mean by a cell 'doing work'? What sort of activities does the cell need energy for? Discuss some specific examples of cell activity where energy is required from your previous areas of study.

Respiration is the chemical breakdown of food (mainly glucose) to release the energy that cells need to 'do work'. It can take place in two main ways;

1. Aerobic respiration takes place in the presence of oxygen.
2. Anaerobic respiration takes place 'without oxygen'.

In summary, the OVERALL equation for aerobic respiration is;

glucose + oxygen → carbon dioxide + water + ENERGY

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + ENERGY

There are two types of anaerobic respiration

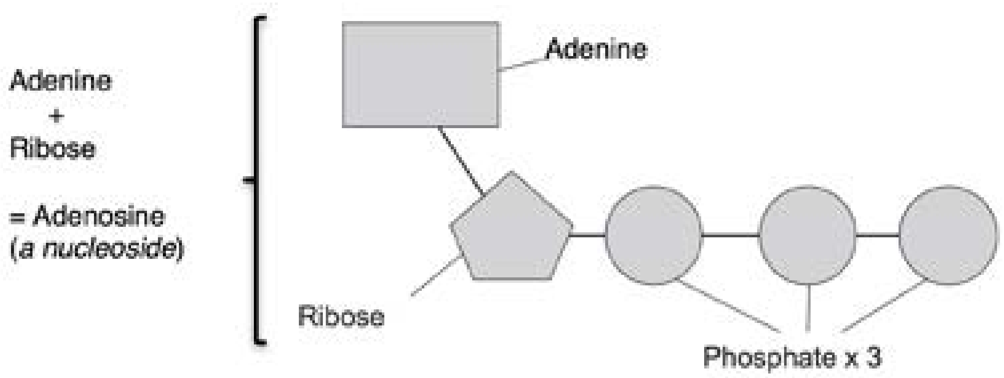
- In plants and yeast, anaerobic respiration is also known as alcoholic fermentation and produces ethanol, carbon dioxide and energy.
- In animals anaerobic respiration is also known as lactate fermentation and produces lactate (lactic acid) and energy.

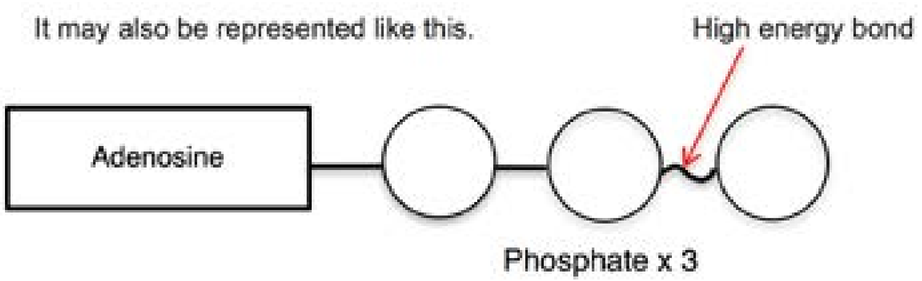
This will be considered in more detail later, but it is important to note that aerobic respiration is by far the more efficient process in energy production.

The structure and function of ATP

ATP or Adenosine Tri-Phosphate acts as the main energy 'currency' of the cell. It is found in all living organisms. It is not an energy storage molecule or fuel, but rather can be considered an *energy-coupling agent or shuttle*, i.e. it is produced by one set of reactions (for example, in cellular respiration) and the accessible energy is almost immediately used in another set of chemical reactions to enable cells to undertake 'work' such as driving metabolic reactions, transporting substances across membranes (active transport) or do mechanical work (for example, muscle contraction). In other words ATP couples the energy produced through respiration with energy use by the cell.

It consists of an adenine base, a ribose sugar and three phosphate molecules as shown below.





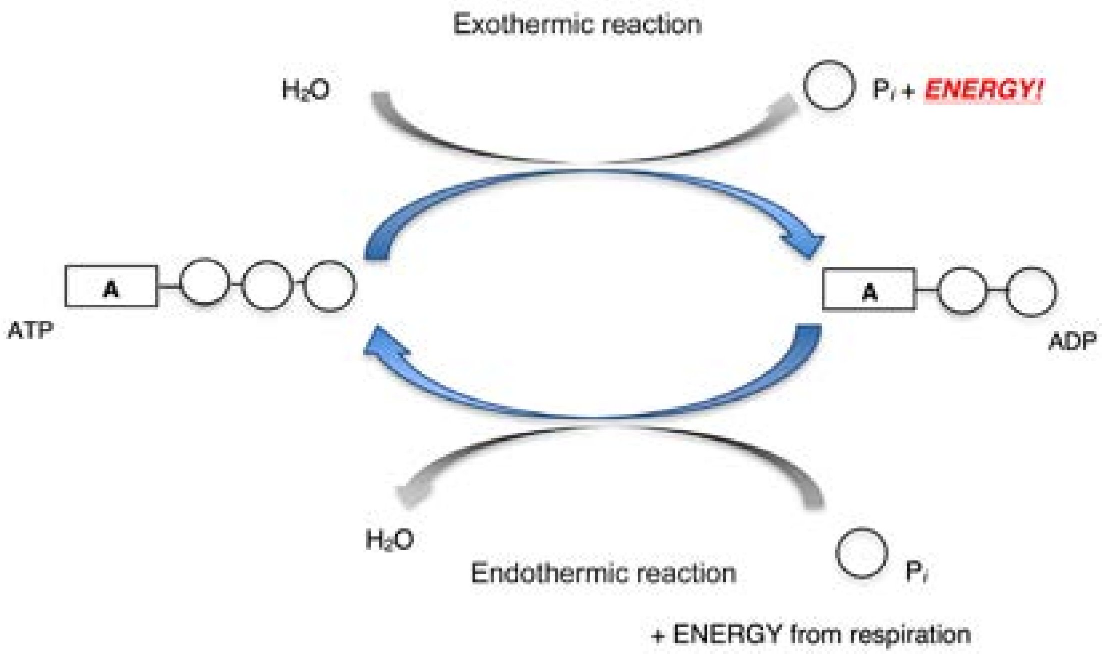
The base, adenine and sugar ribose together are known as adenosine, a nucleoside (nitrogenous base +sugar).

The terminal phosphate in ATP is held in place by a relatively unstable high-energy bond. When this is broken it releases energy required by the cell to 'do work'. This happens in the ATP cycle.

The ATP cycle

The ATP cycle explains how ATP is broken down to ADP, releasing energy (an endothermic reaction) needed by cells in a usable form – the energy 'currency'. This process requires the addition of H_2O to break the bond between the terminal phosphate and the rest of the molecule. This is an example of a hydrolysis reaction.

ATP is then regenerated as energy from cellular respiration and is used (an exothermic reaction) to form a new bond between an inorganic phosphate and the ADP. Water is released in the process. This is an example of a condensation reaction.



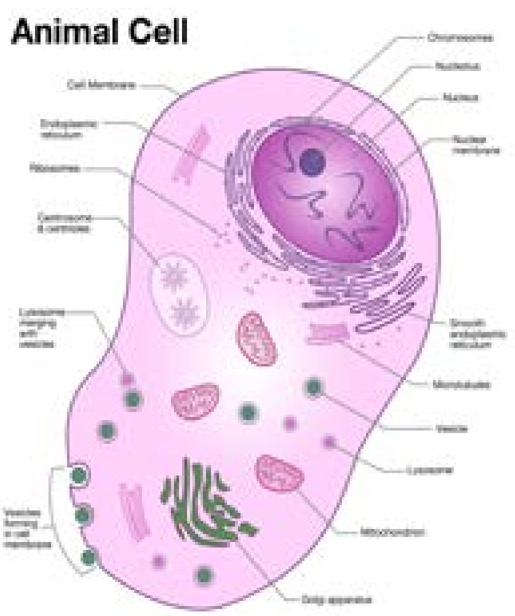
Watch What is the ATP cycle? by Jeremy LeCornu
https://www.youtube.com/watch?v=o7fpyP2IFrQ

Aerobic Respiration

Aerobic respiration takes place in a number of stages. Each stage takes place at a specific location within the cell.

1. **Glycolysis** – takes place in the cytoplasm of the cell
2. The **'Link Reaction'** – links the products of glycolysis in the cytoplasm with events in the mitochondria. This takes place in the mitochondrial matrix.
3. **Krebs Cycle** – in the matrix of mitochondria
4. The **Electron Transport Chain (ETC)** – on the cristae of mitochondria

Structure of animal cells and mitochondria.



© Science Photo Library

Animal Cell

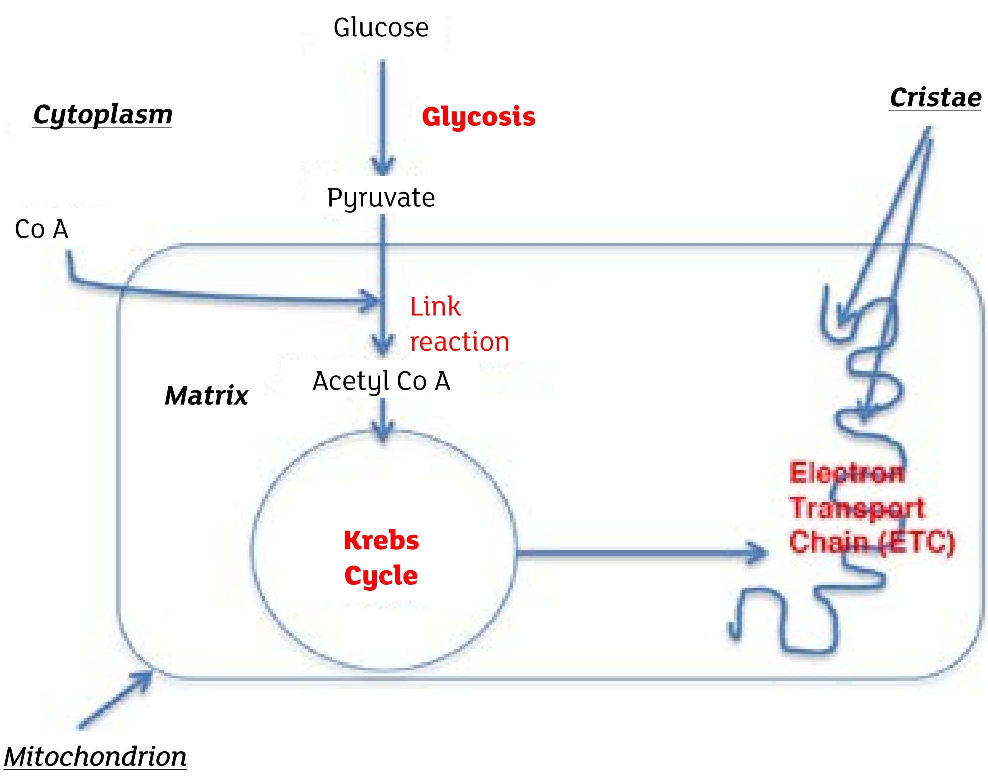

© Science Photo Library

Mitochondria

Label the following parts of the mitochondrion

a) Outer membrane
b) Inner membrane
c) Matrix
d) Cristae

Stages of aerobic respiration.



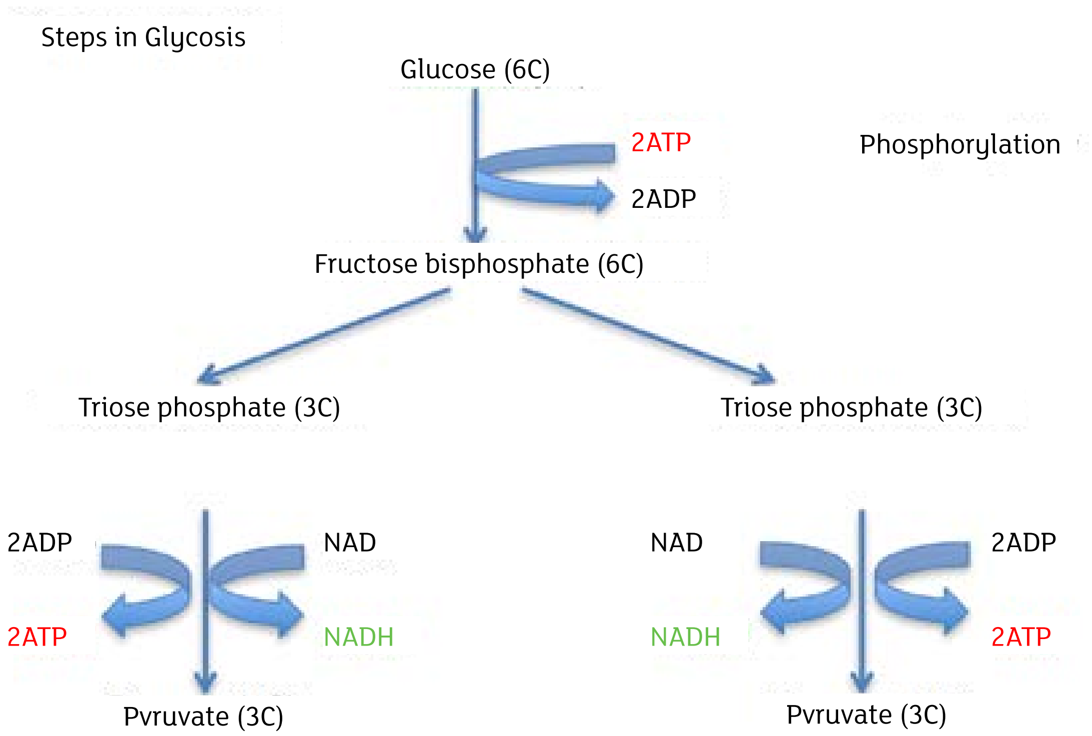
[Note: the diagram above does not show all the stages, intermediates and products in aerobic respiration but is simply a tool to help remember the order of the stages and where they take place. Further detail will be provided in the following sections]

1. Glycolysis.

Glycolysis literally means the splitting of sugar (for example glucose)
It takes place in the cytoplasm and does not need oxygen to take place.
Glycolysis is a process common to both aerobic and anaerobic respiration.

Note:

- Glucose is a relatively stable molecule and so it is initially converted into a less stable phosphorylated fructose bisphosphate (6C) molecule (which contains 2 phosphate groups)
- This process requires 2ATP to give up energy and phosphates to form 2ADP. This process is called phosphorylation
- The fructose bisphosphate is subsequently broken down to 2 triose phosphate (3C) molecules
- Each triose phosphate molecule is eventually converted into a molecule of pyruvate
- 4 molecules of ATP are produced during this process by substrate level phosphorylation i.e. the direct transfer of a phosphate group from a substrate to ADP to produce ATP
- 2 molecules of pyruvate are produced from the breakdown of a single glucose molecule.



NAD = Nicotinamide Adenine Dinucleotide, a coenzyme and hydrogen (H) carrier
When it accepts H it becomes reduced NAD or NADH

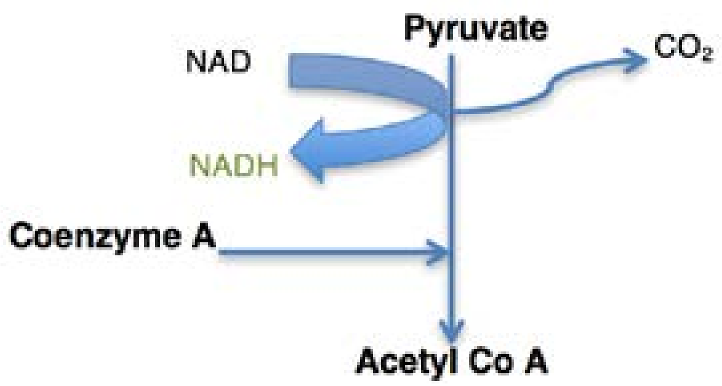
Important – from glycolysis (per molecule of glucose):

- TOTAL ATP = 2 used, 4 produced NET GAIN = 2ATP
- NADH (reduced NAD) = 2 produced. The reducing power carried in these molecules will lead to the further production of ATP via the ETC in aerobic respiration. It is important to remember this, as it also occurs at stage 4 in the Electron Transfer Chain.

The pathway of the pyruvate molecules depends on whether oxygen is available or not.
If oxygen is available (aerobic respiration) – the Link Reaction occurs;

- the pyruvate molecules enter the matrix of a mitochondrion,
- CO_2 and H are removed from each pyruvate to form a 2C (acetyl) molecule,
- each 2C molecule combines with Coenzyme A to form Acetyl Coenzyme A (Acetyl Co A),
- CO_2 is released as a gas and H is used to reduce NAD to NADH.

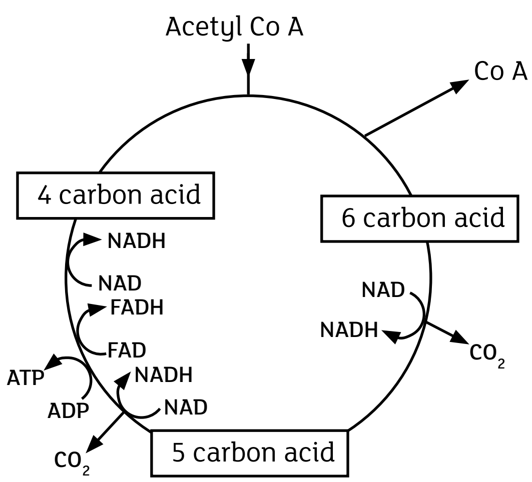
2. Link Reaction in mitochondria



For each glucose molecule -

Into the link reaction	Produced by link reaction
2 x Pyruvate	2 x CO_2
2 x NAD	2 x NADH
2 x Coenzyme A	2 x Acetyl Co A

3. Krebs Cycle



FAD = Flavine Adenine Dinucleotide

It is a coenzyme and hydrogen carrier like NAD.
When it accepts H from substrates in Krebs Cycle, it becomes reduced FAD or FADH.

Look at the diagram of Krebs Cycle above:
- As each acetyl Co A enters the cycle, the acetyl (2C) group reacts with a 4C acid to produce a 6C acid.
- Coenzyme A is released and is now free to react with another pyruvate molecule and go through the link reaction again.

- The 6C molecule is broken down by an oxidation process called oxidative decarboxylation with the result that CO_2 molecules are released, to form initially a 5C acid and ultimately regenerating the initial 4C molecule; ready to react with another acetyl Co A molecule to start the cycle again.
- A total of $2CO_2$ molecules are released per Acetyl CoA molecule through oxidative decarboxylation.

Note
1ATP is formed directly by substrate level phosphorylation, 3NADH are formed per cycle and 1FADH is formed per cycle.

As two pyruvate (3C) molecules are formed from each glucose (6C) molecule, then two cycles occur for each glucose entering aerobic respiration. So for each glucose molecule, the total yield from Kreb's Cycle is

2ATP
6NADH
2FADH
} → Electron Transfer Chain (ETC)

The energy carried in the NADH and FADH molecules will lead to the further production of ATP via the ETC in aerobic respiration (as mentioned in stage 3).

4 Electron Transport Chain (ETC).

http://revisionworld.com/a2-level-level-revision/biology/energy-life/respiration/glycolysis-and-krebs-cycle
Cells use the ETC to transfer H ions or electrons along a series of carriers to the final acceptor; oxygen. This is where oxygen plays its role in the respiration pathway; as the final H acceptor at the end of the ETC. The carriers are arranged in a stepwise fashion at progressively lower energy levels. As H ions or electrons are passed from one carrier to another, energy is released which can be coupled to the production of ATP from ADP and inorganic phosphate (Pi). The carriers are found in membrane-bound enzyme complexes embedded in the inner mitochondrial membrane (cristae).

The components of the Electron Transfer Chain are:
- NAD
- Flavoprotein
- Coenzyme Q
- Cytochromes

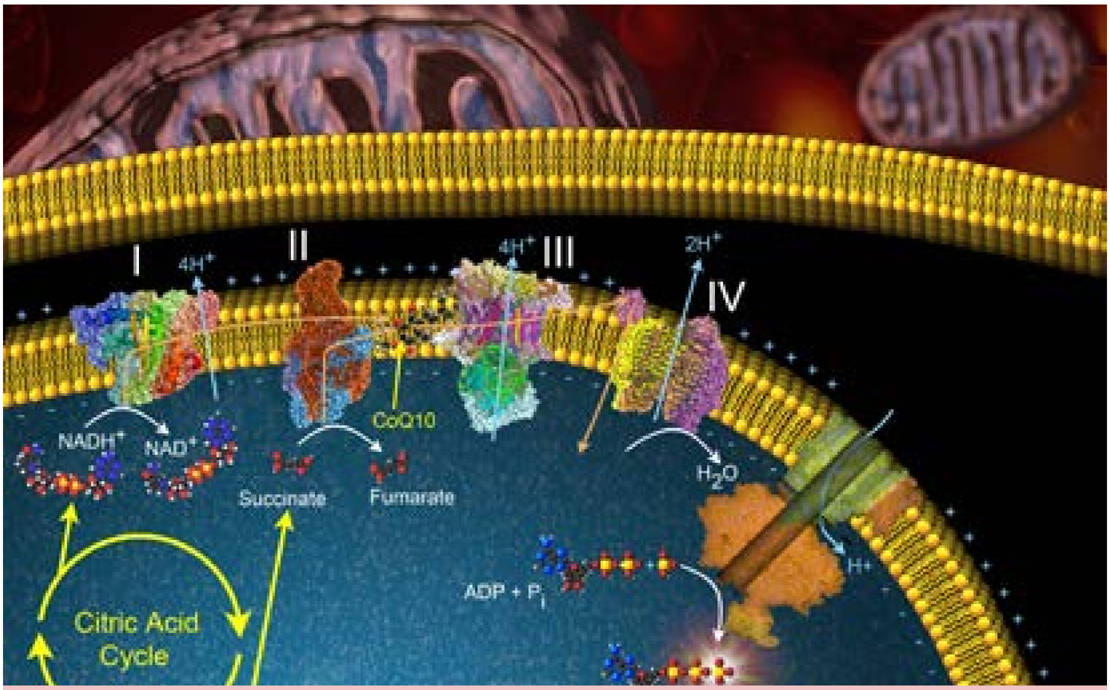


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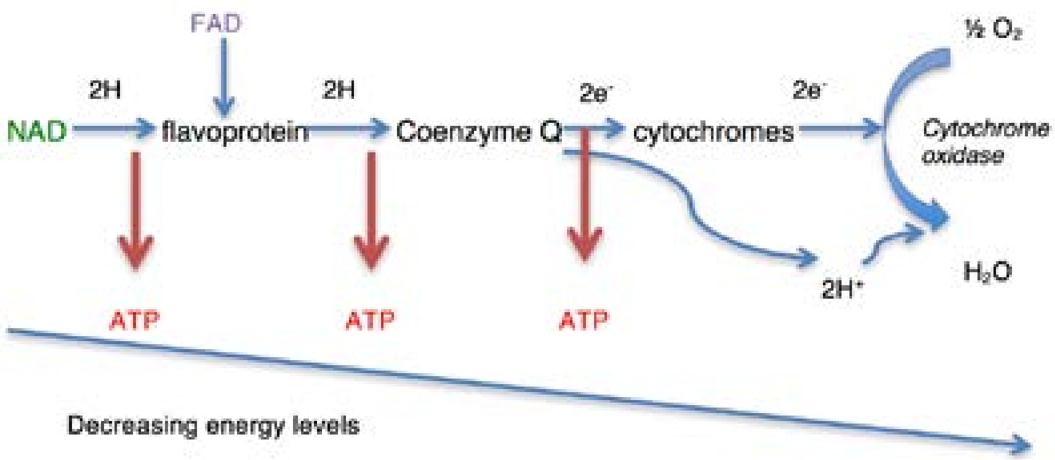
Illustration of the electron transport chain, a series of protein complexes located in the inner membrane of mitochondria.

NAD – Nicotinamide Adenine Dinucleotide, a coenzyme and H carrier. Reduced NAD or NADH is formed during glycolysis, the Link Reaction and Krebs Cycle. It passes 2H onto the next carrier in the ETC – Flavoprotein. In this process NADH is oxidised while flavoprotein is reduced.
Flavoprotein – reduced flavoprotein passes on 2H to co-enzyme Q.
Coenzyme Q – similar in structure to Vitamin K. Coenzyme Q can also carry 2H and forms a bridge between flavoprotein and the cytochromes.
Cytochromes – electron carriers transferring electrons from Coenzyme Q to oxygen. They are named cytochromes a, b and c according to the order of their discovery.

Carriers in the Electron Transport Chain

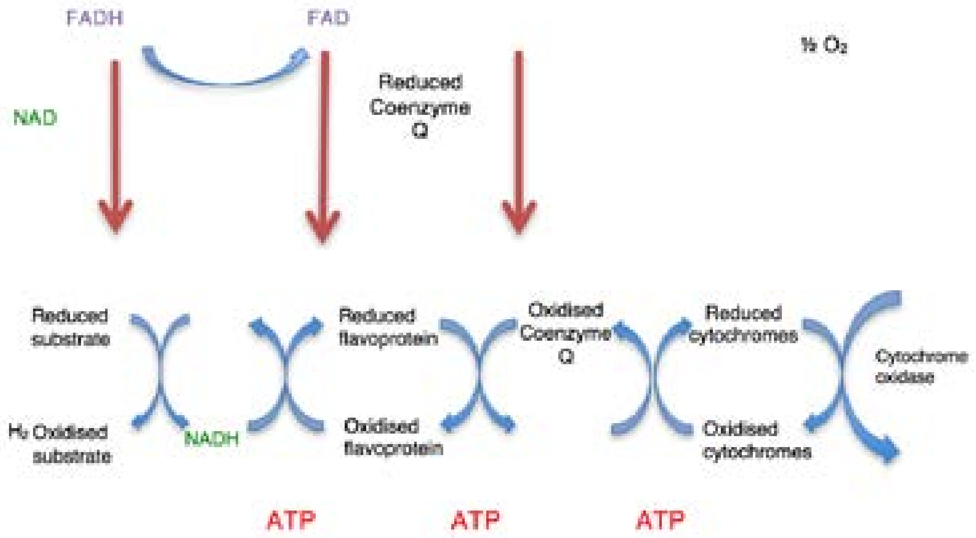


Note
The H atoms produced from the oxidation of substrates in glycolysis, the link reaction and Kreb's cycle can enter the ETC via NAD or FAD.

As can be seen from the diagram: each reduced NAD (NADH) produces 3 ATP molecules and each reduced FAD (FADH) produces 2 ATP molecules.

As the H ions or electrons are passed from one carrier to another, there is a series of oxidation and reduction or REDOX reactions. Remember: OILRIG. Oxidation Is Loss of electrons. Reduction Is Gain of electrons.

The enzyme cytochrome oxidase catalyses the last reaction in the chain – the reduction of oxygen to form water.



The process in which ATP is formed as a result of the transfer of electrons from NADH or FADH to O_2 by a series of electron carriers in the ETC is called oxidative phosphorylation. It is important to note that oxidised NAD and FAD are regenerated and so are available to be reduced again in the course of the aerobic respiration pathway, enabling aerobic respiration to continue.

For information on demonstrating the role of hydrogen acceptors using redox indicators such as methylene blue, see A2 Practical Support p9.

Summary table of ATP yield from aerobic respiration

	ATP produced	**NADH produced**	**FAD produced**
Glycolysis	2 (directly by substrate level phosphorylation)	2	
Link reaction		2	
Krebs cycle	2 (directly by substrate level phosphorylation)	6	2
ETC	34 (by oxidative phosphorylation via NADH and FADH)		
Total ATP (max)	38 ATP		

Q. Use the table above to show how a maximum of 38 ATP molecules is produced. Note that this is the maximum possible yield but more commonly in aerobic respiration the yield will be about 30 ATP depending on conditions.

Q. Why is the yield typically less than 38 ATP per molecule of glucose?

Q. What is the total number of CO_2 molecules produced from the aerobic respiration of 1 molecule of glucose? How does this relate to the chemical equation for respiration?

An overview of aerobic respiration is on the video "Cellular Respiration Glycolysis, Krebs cycle, Electron Transport 3D Animation YouTube 720p" at the following link.
https://www.youtube.com/watch?v=Fcu_8URp4Ac

"Cellular respiration for dummies" is a reminder the products of aerobic respiration and when/where they are formed.
https://www.youtube.com/watch?v=wrwUWhWWcz4

An overview of aerobic cellular respiration can be viewed on the following short video "What is aerobic respiration?" by Jeremy LeCornu at the following link
https://www.youtube.com/watch?v=vT-akaCy2Sc

The Youtube video "ATP & Respiration: Crash Course Biology #7"
https://www.youtube.com/watch?v=00jbG_cfGuQ
is also very useful and can be broken up into the stages of aerobic respiration as below.
4.19mins – 5.49mins Glycolysis
5.49mins – 6.46mins Anaerobic Respiration & Fermentation
7.10mins – 10.00mins Krebs cycle including NAD & FAD
11.07mins Electron Transport Chain

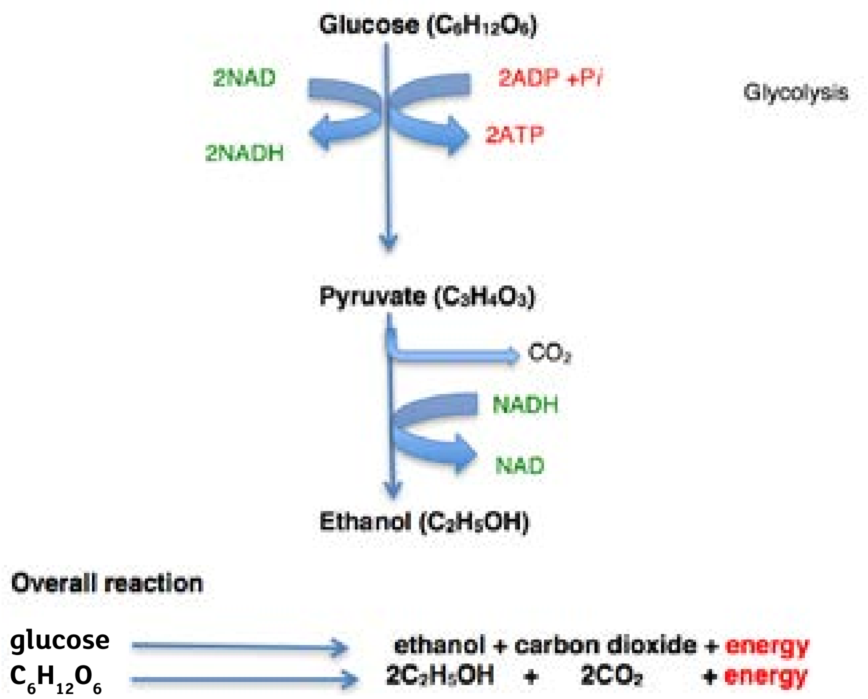
Useful resources:
Teachers can register free for the TES website

Welcome Trust Poster on Cellular Respiration.
https://www.tes.com/teaching-resource/poster-on-cellular-respiration-6154503
https://www.tes.com/teaching-resource/respiration-6095657
https://www.tes.com/teaching-resource/respiration-revision-summary-6301012

Anaerobic Respiration

If there is no oxygen available, anaerobic respiration takes place. Anaerobic respiration only takes place in the cytoplasm of cells.
Glycolysis is common to both aerobic and anaerobic respiration, but the fate of the pyruvate molecules produced depends on the presence or absence of oxygen and the type of organism. If there is no oxygen to act as the final acceptor in the ETC it stops working. As a result NAD and FAD cannot be regenerated through the ETC, so the biochemical pathway cannot continue. Instead pyruvate produced by glycolysis enters the following pathways in the cytoplasm in order to produce ATP.

Plants and Fungi – Alcohol fermentation



Note that NAD is regenerated in the reduction of pyruvate to ethanol and so can be reused in glycolysis.

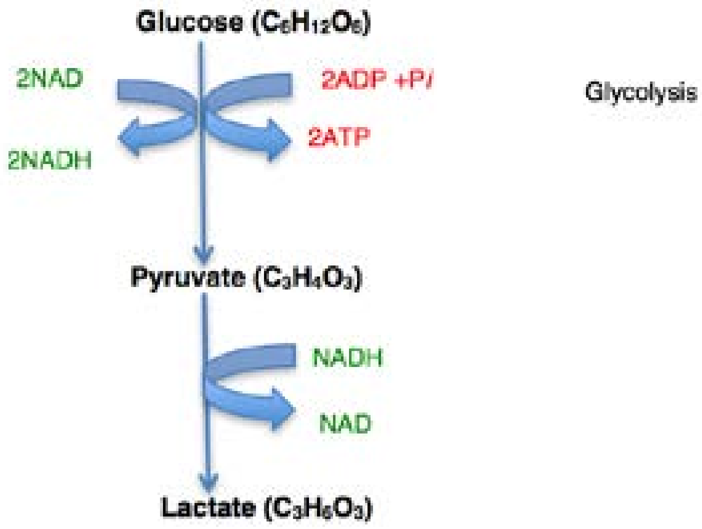
The number of molecules of ATP produced = 2 therefore this form of anaerobic respiration is much less efficient in energy production compared to aerobic respiration. Ethanol is the basis for alcoholic drinks and fuel. In bread making and baking the release of CO_2 causes dough to rise and gives alcoholic drinks, such as beer carbonation.

Peat bogs tend to be saturated by water and therefore plants that live in peat bogs face oxygen deprivation and have to revert to anaerobic respiration. Many have evolved biochemical pathways that avoid the build up of toxic ethanol and instead accumulate harmless malate.

Saprophytes, responsible for breaking down dead and decaying plant and animal matter, also face anaerobic conditions in water saturated bogs and cannot complete the decomposition process. As a result large quantities of partially composed organic matter builds up which is compressed to form peat.

Obligate anaerobes are organisms that can only exist in the absence of oxygen. If oxygen is present they will die. An example is *Clostridium sp*. found in mud and peat bogs. Facultative anaerobes grow better with oxygen but can survive in its absence, for example, *Staphylococcus sp., E. coli*

Animals – Lactate (lactic Acid) production



Overall reaction

glucose → lactate + energy

$C_6H_{12}O_6 \rightarrow 2C_3H_6O_3 + \text{energy}$

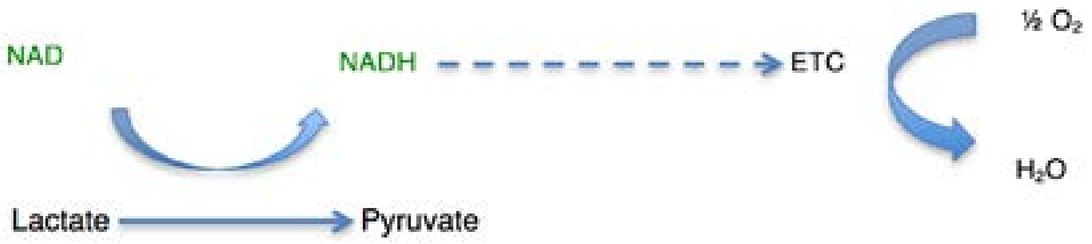
Note that NAD is regenerated in the reduction of pyruvate to lactate and so can be reused in glycolysis.

The number of molecules of ATP produced = 2 therefore this form of anaerobic respiration is also much less efficient in energy production compared to aerobic respiration. Lactate builds up in muscle cells during exercise as the cells fail to keep up with demand for oxygen. This can result in muscle fatigue and soreness or cramps. Lactate is toxic.

'Anaerobic Respiration – 100m Sprinter.'
https://prezi.com/9w1jwux6baum/anaerobic-respiration-100m-sprinter/
Oxygen is needed in order is convert the lactate back to pyruvate, doing this by acting as the final H acceptor in the ETC. The lactate can also be converted via pyruvate to glucose/glycogen by the liver and used again for respiration.

The amount of extra oxygen required to oxidise the lactate built up during vigorous exercise is called the 'oxygen debt'. This is why panting continues after exercise – to ensure sufficient oxygen reaches the cells to pay back the 'oxygen debt'.

Conversion of lactate to pyruvate needs NAD and O_2



The worksheet '*Respiration in Athletics*' examines lactate production in the muscles of athletes.
https://www.tes.com/teaching-resource/respiration-in-athletics-worksheet-6164579
'What is fermentation (anaerobic respiration)?' by Jeremy LeCornu
https://www.youtube.com/watch?v=1dpwr1of6VI&feature=iv&src_vid=o7fpyP2IFrQ&annotation_id=annotation_1128886755

Q. Complete the following comparison table between aerobic and anaerobic respiration

	Aerobic respiration	**Anaerobic respiration**
Location of reactions		
Reactants		
Products		
Stages		
ATPs per glucose molecule		
Combustion (complete or incomplete)		

How proteins and lipids provide energy in respiration

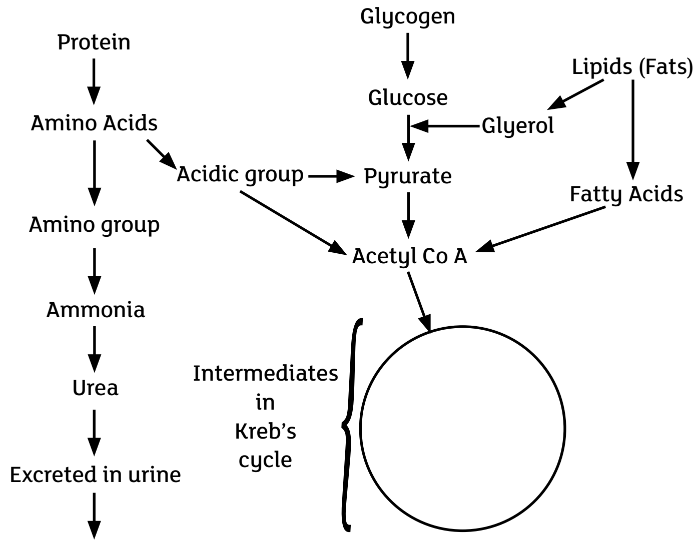
Fats (Lipids)

Lipids are initially broken down into their component fatty acids and glycerol.
Fatty acids are broken down into 2C fragments and enter the Kreb's cycle through acetyl Co A. Glycerol is converted to an intermediate in glycolysis and enters this pathway to be converted to pyruvate before entering the Kreb's cycle.

Proteins

Dietary proteins are broken down in respiration to their component amino acids. Excess amino acids cannot be stored by the body and therefore are either metabolised or excreted. If excess dietary amino acids are to be used in respiration the first stage is the removal of the amino group – deamination. The amino group combines with CO_2 and ultimately forms urea, which is excreted in urine. The acidic component of amino acids (organic acids) can be converted into pyruvate, acetyl Co A or a number of the intermediates in Krebs Cycle.

These reactions are summarised in the diagram below.



How protein and fats link to the biochemical respiratory pathway.

Body proteins are only broken down during illness or extreme starvation, when dietary energy supplies are inadequate for the body's requirements. In these cases proteins in the liver are used in preference to those from other organs such as the brain.

Khan Academy 'The Basics of Metabolism'.
https://www.youtube.com/watch?v=wQ1QGZ6gJ8w

Respiratory Quotient (RQ)

The RQ is the ratio of carbon dioxide produced to oxygen consumed by a respiring organism. The RQ value shows the type of substrate(s) being used in respiration, and detect if anaerobic respiration is taking place.

From experimentation we know that the approximate RQ values for:

Carbohydrates = 1.0
Protein = 0.9
Fats = 0.7

In order to calculate the RQ for a respiratory substrate, the equation for its breakdown by respiration needs to be known.

For example, the equation for the aerobic respiration of carbohydrate is

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy}$$

The RQ is calculated as

$$RQ = \frac{6CO_2}{6O_2}$$ Answer = 1.0

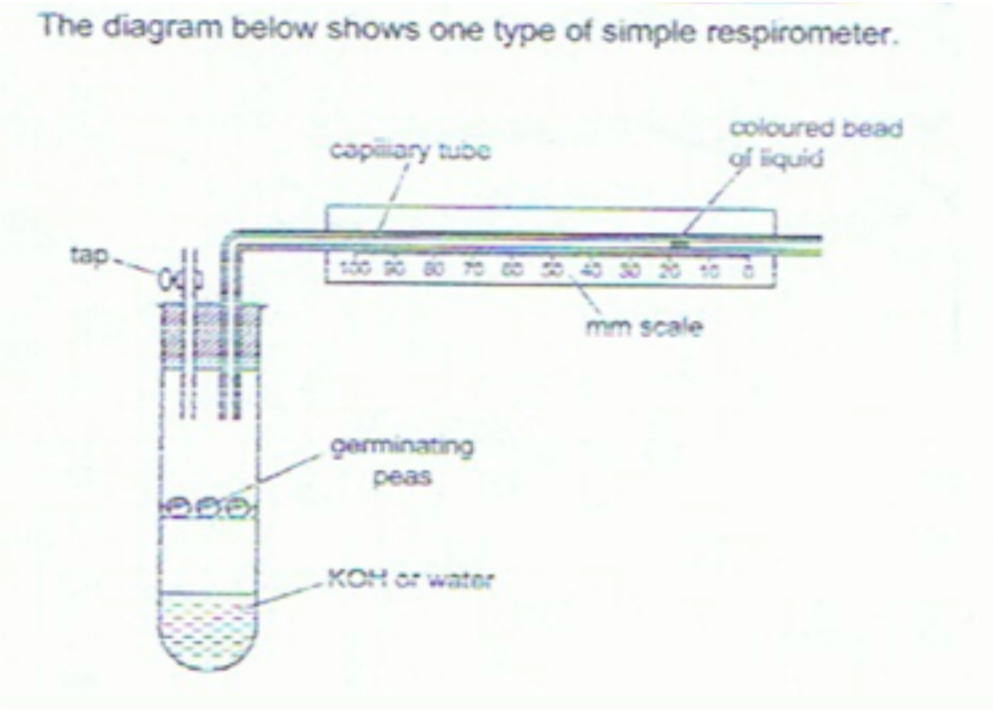
Q. Carry out the same calculation for the anaerobic breakdown of glucose
Q. Calculate the RQ value for the lipid tristearin

$$2\ C_{57}H_{110}O_6 + 163\ O_2 \rightarrow 110\ H_2O + 114\ CO_2$$

Some further examples of calculation of RQ values:
http://www.tutorvista.com/content/biology/biology-iv/respiration/respiratory-quotient.php#

Measuring RQ?

Apparatus called a respirometer, is used.



For a description of how to use a respirometer,
See A2 Practical Support p8/9
or
http://www.nuffieldfoundation.org/practical-biology/measuring-respiratory-quotient

Useful resources:

A useful link to an overview of respiration can be found here:
http://www.biology-innovation.co.uk/pages/human-biology/respiration/

The following resources are useful for revision activities at any time. Just pick a range of flash cards appropriate to the learning outcomes covered.
Quizlet 70 terms on respiration by jalbe860
https://quizlet.com/jalbe860/folders/cellular-respiration

Quizlet flash cards on respiration
https://quizlet.com/628160/cellular-respiration-flash-cards/

Quizlet flash cards on respiration and photosynthesis
https://quizlet.com/9692601/cellular-respiration-photosynthesis-quiz-flash-cards/

Resources from TES website
https://www.tes.com/teaching-resource/respiration-flipped-classroom-resources-6443527
https://www.tes.com/teaching-resource/respiration-revision-notes-6357252
https://www.tes.com/teaching-resource/comparision-of-aerobic-and-anerobic-respiration-6037212
https://www.tes.com/teaching-resource/respiration-summary-6058522
https://www.tes.com/teaching-resource/key-summary-points-on-human-cellular-respiration-6078195
https://www.tes.com/teaching-resource/aqa-a2-biology-respiration-revision-summary-6429171
https://www.tes.com/teaching-resource/respiration-some-important-points-11038431

CCEA past examination questions on 'respiration'
(all from Assessment Unit 2 2)

May/June 2015	Question 6
May/June 2014	Question 8
May/June 2013	Question 3
May/June 2012	Question 8
May/June 2011	Question 3
May/June 2010	Question 2