Bio Factsheet

January 1998 Number 12

Respiration

Cellular respiration is the process by which the energy contained in organic molecules is made available for all of the active processes within a cell. The usual substrate (the organic substance from which energy is released) is glucose, although fats, amino acids and other substrates can be used if necessary. The energy which is released is stored - in the short term - in molecules of ATP. The process of respiration can occur with oxygen (aerobic) or without oxygen (anaerobic). For every glucose molecule which is broken down, aerobic respiration produces nineteen times as much ATP than anaerobic respiration.

Aerobic respiration can be divided into four stages:

1. Glycolysis (G)
2. The Link reaction (LR)
3. Kreb's cycle (K)
4. The electron transfer chain (ETC)

These take place in different parts of the cell (Table 1) and the detailed biochemistry of these reactions is shown overleaf.

Respiratory quotients

The respiratory quotient (RQ) is defined as the ratio of carbon dioxide produced to oxygen consumed per unit time by an organism:

$$RQ = \frac{\text{volume of } CO_2 \text{ produced}}{\text{volume of } O_2 \text{ consumed}} \text{ per unit time.}$$

Different substances give different RQ values

Substrate	RQ
Glucose	1
Amino Acids	0.9
Triglyceride (fat)	0.7

Anaerobic respiration

If oxygen is unavailable the Kreb's cycle and electron transfer chain cannot operate. This is because without oxygen there would be no way of disposing of the hydrogen at, for example, the end of the electron transfer chain. However, even in anaerobic conditions, glycolysis occurs so reduced NAD still forms. If glycolysis is to continue, the reduced NAD must be reoxidized, that is, the hydrogen must be removed and disposed of. Anaerobic organisms have developed two ways of doing this:

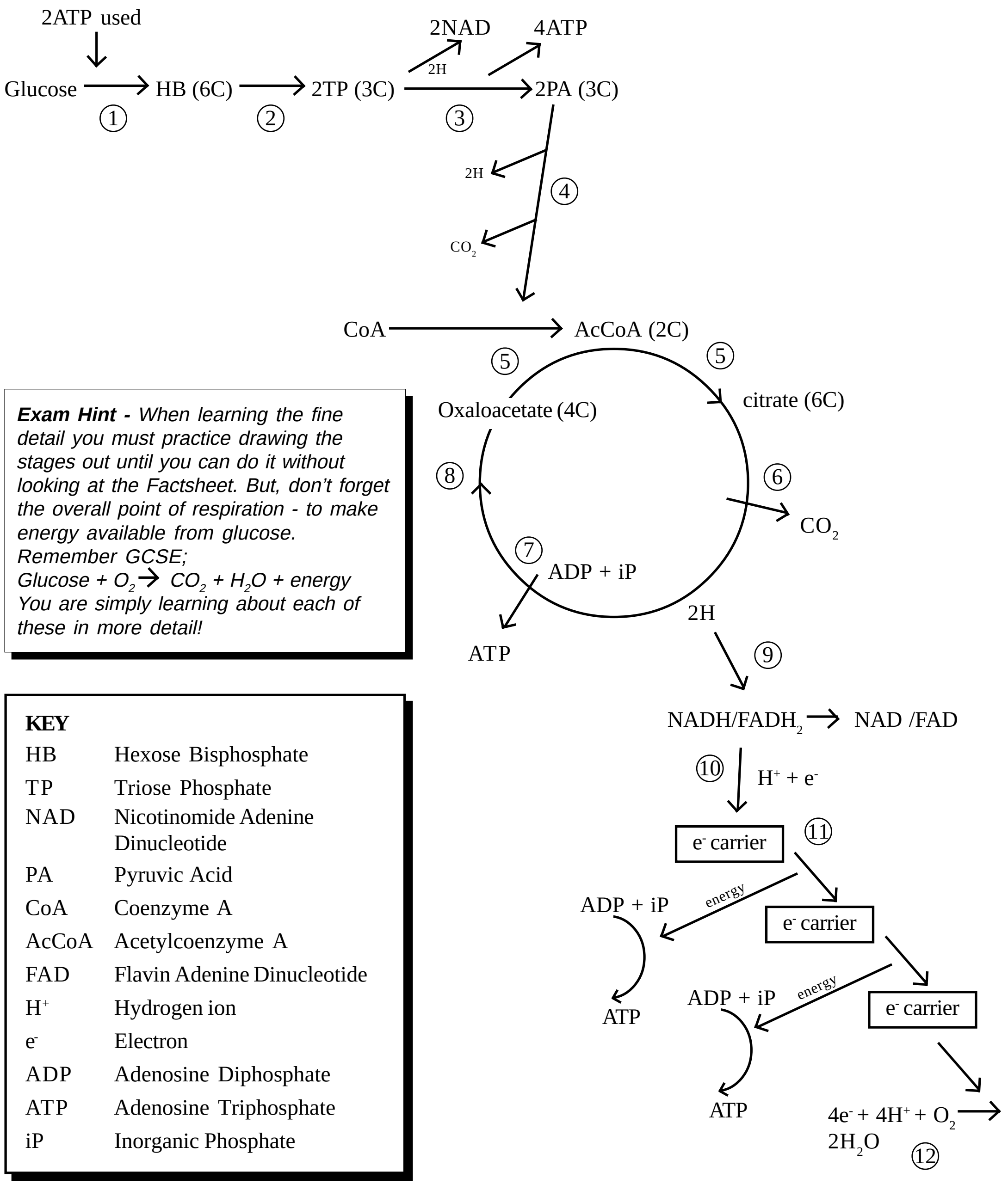
1. In yeast, pyruvate is decarboxylated to produce ethenal. Ethenal then accepts the hydrogen from NAD and forms ethanol. This releases the NAD to be reused in glycolysis. The conversion of pyruvic acid to ethanol with the release of carbon dioxide is called **alcoholic fermentation**.

2. In mammals, the pyruvate accepts the hydrogen from NAD and is reduced to lactate. The NAD is then available for further use in glycolysis. If oxygen later becomes available, the lactate is reoxidised.

Since anaerobic respiration only involves glycolysis, only the 2 ATP produced in glycolysis are formed.

Table 1. Summary box of cellular respiration

Stage	Site	Oxygen Needed?	What Happens?	Net ATP production per glucose molecule
Glycolysis	Cytoplasm	No	Glucose is converted to pyruvic acid. Hydrogen is removed and is passed to the electron carriers.	2
Link Reaction	Matrix of Mitochondria	Yes	Pyruvate enters mitochondrion, is decarboxylated, dehydrogenated and combines with coenzyme A to give acetyl coenzyme A. The hydrogen which is removed is passed to the electron carriers.	—
Kreb's Cycle	Matrix of Mitochondria	Yes	A cyclical series of reactions during which hydrogen is passed to the electron carriers, carbon dioxide is removed and the starting reagents are regenerated.	2
ETC.	Crista of Inner Membrane of Mitochondria	Yes	The hydrogen from glycolysis and Kreb's cycle is split to release electrons. These pass through carriers and generate ATP. The hydrogen reforms and is combined with oxygen to release water.	34



***Exam Hint** - When learning the fine detail you must practice drawing the stages out until you can do it without looking at the Factsheet. But, don't forget the overall point of respiration - to make energy available from glucose. Remember GCSE;*
Glucose + $O_2 \rightarrow CO_2 + H_2O$ + energy
You are simply learning about each of these in more detail!

KEY

HB	Hexose Bisphosphate
TP	Triose Phosphate
NAD	Nicotinomide Adenine Dinucleotide
PA	Pyruvic Acid
CoA	Coenzyme A
AcCoA	Acetylcoenzyme A
FAD	Flavin Adenine Dinucleotide
H^+	Hydrogen ion
e^-	Electron
ADP	Adenosine Diphosphate
ATP	Adenosine Triphosphate
iP	Inorganic Phosphate

Glycolysis - occurs in the cell cytoplasm in both aerobic and anaerobic conditions.

1. Glucose is phosphorylated, i.e. ATP is used to add a phosphate group to glucose. This makes the glucose more reactive, allowing it to be broken down. A six carbon (6C) phosphorylated sugar is produced called hexose bisphosphate.
2. The hexose bisphosphate is converted into two molecules of a 3C sugar phosphate called Triose Phosphate (TP)
3. Hydrogen is removed from each of the TP molecules, i.e. the TP molecules are oxidised. The hydrogen is passed to NAD, a coenzyme which, by definition, is said to be reduced. Remember - any substance that gains oxygen or loses hydrogen or electrons is said to be oxidised. Any substance that loses oxygen or gains hydrogen or electrons is said to be reduced. The enzymes which remove hydrogen from substances are called dehydrogenases. The hydrogen atoms picked up by NAD are used to generate four molecules of ATP. The removal of hydrogen from TP produces pyruvic acid (PA).

The Link Reaction - occurs only if oxygen is available.

4. PA enters the mitochondrion
5. Carbon dioxide and hydrogen are removed from the PA by decarboxylase and dehydrogenase enzymes respectively. The PA is combined with coenzyme A (CoA) to form a 2C compound called acetylcoenzyme A (AcCoA).

Kreb's Cycle - only occurs if oxygen is available.

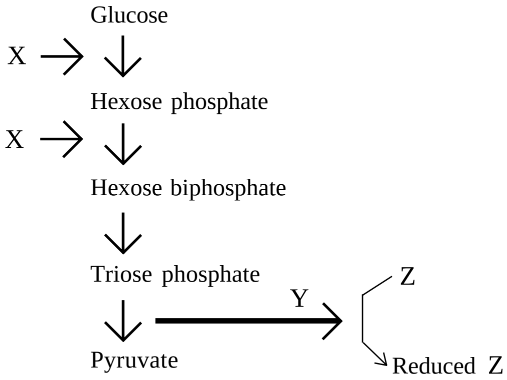
5. AcCoA (2C) is combined with oxaloacetate (4C) to form citrate (6C). Citrate enters the Kreb's cycle. This involves a series of decarboxylation and dehydrogenation reactions.
6. The carbon dioxide is released. The hydrogen which is removed is passed to coenzymes such as NAD and FAD (i.e. the coenzymes are reduced).
7. 2ATP molecules are generated directly in the Kreb's cycle.
8. Eventually the 4C compound (oxaloacetate) is regenerated. This then combines with more AcCoA and the whole cycle begins again.

The electron transfer chain - only occurs if oxygen is available.

9. The reduced coenzymes NAD and FAD are reoxidized, i.e. hydrogen is removed from them by dehydrogenase enzymes located on the cristi of the inner membrane of the mitochondrion.
10. Each hydrogen atom is split into a hydrogen ion (H^+) and an electron (e^-).
11. The electrons then pass through a series of electron carriers. Just as in the electron transfer chain in the light-dependent stage of photosynthesis (see Factsheet 2), the electron carriers are at successively lower energy levels. As the electron passes down from one electron carrier to another, some of their energy is released. This energy is used to convert ADP into ATP, i.e. to phosphorylate ADP. Since the removal of hydrogen or electrons from substance is defined as oxidation, the overall reactions of the ETC are known as oxidative phosphorylation.
12. Finally, each electron is reunited with a hydrogen ion (H^+) and the hydrogen which forms immediately combines with oxygen to form water.

Practice questions

1. The diagram shows some of the stages in glycolysis:



(a) Identify substances:
(i) X (1 mark)
(ii) Y (1 mark)

(b) Explain why anaerobic breakdown of glucose is much less efficient than aerobic breakdown. (4 marks)

2. Differentiate between oxidative photophosphorylation and oxidative phosphorylation. (2 marks)

3. Carefully read the following account of aerobic respiration and then fill in the blanks.

In the first stage of respiration which occurs in the .... of the cell, glucose is .... to pyruvic acid. Glycolysis yields .... and reduced coenzyme. The pyruvic acid then combines with coenzyme A to form .... which enters the Kreb's cycle which occurs in the .... of the .... During these reactions hydrogen atoms are removed from a series of intermediate compounds by enzymes called .... The hydrogen atoms are passed to carriers such as .... In the third stage of aerobic respiration, the carriers are alternately reduced and................... as they gain and lose electrons. Energy is released and used to phosphorylate ADP forming...................... The hydrogen atoms finally combine with .... to form ....

(12 marks)

4. The diagram shows some of the stages of anaerobic respiration in a muscle.

$$\text{Glucose} \xrightarrow[\text{ProcessX}]{\nearrow 2H} \text{Pyruvate} \rightarrow \text{Y} \rightarrow \text{ethanol}$$

(a) Identify process X (1 mark)

(b) Where in the cell does this process occur? (1 mark)

(c) Identify substance Y (1 mark)

(d) What is the role of substance Y in this process? (1 mark)

Answers

Marking points are indicated by semicolons.

1. (a) (i) ATP;
(ii) hydrogen/hydrogen ions;

(b) Without oxygen, ETC and Kreb's cannot continue;
Because no hydrogen acceptor;
Only ATP production is from glycolysis;
Net production in anaerobic is 2ATP, but from aerobic is 38 ATP per molecule of glucose;

2. Oxidative photophosphorylation occurs in LDS of photosynthesis; in chloroplast;
Oxidative phosphorylation occurs in ETC of respiration; in mitochondria;

3. cytoplasm;
oxidised;
ATP;
Acetylcoenzyme A;
matrix;
mitochondria;
dehydrogenases;
NAD/FAD;
oxidised;
ATP;
oxygen;
water;

4. (a) glycolysis;

(b) cytoplasm;

(c) ethanal;

(d) Accept hydrogen from NAD/reoxidise NAD;

Acknowledgements;
Curriculum Press, Unit 305B, The Big Peg,
120 Vyse Street, Birmingham. B18 6NF

ISSN 1351-5136