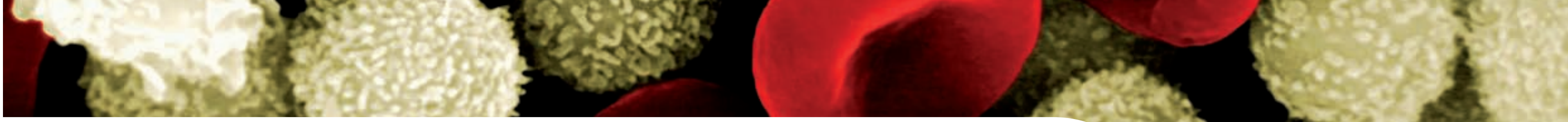


Chapter 4
Cells at work—cell metabolism

Unit
2A

Unit content

Cells, metabolism and regulation

Metabolic reactions make energy and matter available for use in cells. These reactions are controlled by enzymes which are affected by various factors. Cellular structures provide for metabolism.

Metabolism:

- anabolic and catabolic reactions and organelles involved e.g. mitochondria and ribosomes
- respiration (aerobic and anaerobic); inputs, outputs and organelles involved
- nutrients required and their uses including carbohydrates/simple sugars, proteins/amino acids, lipids/fatty acids and glycerols, vitamins and minerals
- enzyme function including reduction in activation energy, lock and key principle
- factors that affect enzyme activity including pH, temperature, cofactors, co-enzymes.

Figure 4.1 The energy made available in the cells enables our bodies to perform many functions including vigorous activity

Although cells differ greatly in size, shape and the particular function they perform, they all carry out chemical processes that keep the organism alive.

All the chemical reactions that take place in cells, and therefore in the organism of which the cells are a part, are referred to as **metabolism**. Metabolism is made up of two different types of chemical reaction: reactions in which large molecules are broken down to smaller ones are known as **catabolism**; reactions in which small molecules are built up into larger ones are referred to as **anabolism**. Catabolic reactions release energy whereas anabolic reactions require energy. Thus, metabolism is concerned with maintaining a balance between energy release and energy utilisation.

Enzymes and metabolism

Enzymes are proteins that allow chemical reactions to take place at normal body temperature. Without enzymes these reactions would be too slow to be of any use to the body. Most chemical reactions require energy to get started. For example, when striking a match the friction between the match head and the striking surface of the box releases enough energy to begin the process of combustion and the match catches alight. The heat energy from the match can then be used to start other chemical reactions such as burning a candle.

The energy needed to get a chemical reaction started is called **activation energy**. Enzymes reduce the activation energy needed to begin a reaction. Thus, when our cells 'burn' glucose in respiration the reaction can occur at body temperature instead of at the normally higher temperature of combustion. Not only do enzymes decrease the activation energy but they also allow the reactions to proceed at a rate that suits the body's requirements.

For more on enzymes and the lock and key model see http://www.hi.com.au/resource/rfacts.asp?kla=1&subtopicid=1320

The molecules on which an enzyme acts are called the **substrate**. Enzymes are specific. Each enzyme will combine with only one particular substrate and is therefore involved in only one specific reaction. This occurs because the enzyme and its substrate have characteristics that are complementary to one another; that is, the enzyme and substrate have a shape and structure that allow them to fit together. The situation has been likened to a lock and key: the key (enzyme) is shaped to fit the lock (substrate), and only the correct key will open the lock (Fig. 4.2). The part of the enzyme molecule that combines with the substrate is called the **active site**. When the enzyme and substrate are combined they are called an **enzyme-substrate complex**.

Figure 4.2 Enzyme action: the lock and key model

Factors affecting enzyme activity

A number of factors influence the activity of enzymes and the rates of chemical reactions in which they are involved.

- The higher the concentration of enzyme, the faster the rate of a chemical reaction. By regulating the type and amount of enzymes present, the body is able to control which reactions occur and the rate at which they proceed.
- Temperature influences enzyme activity. The rate of most chemical reactions increases as temperature increases. This is true of most enzyme reactions but

only within a limited temperature range. Because they are proteins, the structure of enzymes changes beyond about 45–50°C and the enzyme is inactivated. The temperature at which an enzyme works best is called the *optimum temperature*. For most enzymes in the human body this is between 30°C and 40°C.

- Enzymes are very sensitive to the pH of the medium in which a reaction is taking place. Each enzyme has an optimum pH at which it will work most effectively.
- Many enzymes require the presence of certain ions or non-protein molecules before they will catalyse a reaction. Such substances are called **co-factors**. Co-factors change the shape of the active site so that the enzyme can combine with the substrate. Without a co-factor the enzyme molecule is intact but cannot function. Some co-factors are non-protein organic molecules. They are then called **co-enzymes**. Many vitamins function as co-enzymes.

Cellular respiration

Cellular respiration is one of the most important metabolic processes in any cell. It is the process by which organic molecules, taken in as food, are broken down in the cells to release energy for the cell's activities—activities such as movement of the cell, uptake of materials from the surroundings, or production and secretion of new chemical compounds.

The term 'respiration' is often used loosely to mean breathing, and so the chemical process of respiration is referred to as cellular respiration (or sometimes *tissue respiration* or *internal respiration*). The process goes on in every cell in the body, to supply each cell with the energy it needs.

Glucose formed from the breakdown of complex carbohydrates, amino acids formed from protein breakdown, and fatty acids and glycerol from lipids (Fig. 4.3 on pages 44 and 45) can all be broken down in cellular respiration to release energy. However, the main food material utilised is glucose and discussion here will therefore be confined to the respiration of glucose.

Respiration can be summarised as an equation:

$$\underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2} \longrightarrow \underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O} + \text{energy}$$

This summary makes respiration look like a simple reaction. However, the breakdown of glucose to carbon dioxide and water actually involves over 20 separate reactions, which occur in a series, one after the other. At each step an intermediate compound is formed, and each step is catalysed by a different enzyme. Small amounts of energy are released as the reactions proceed. In this way release of energy is controlled rather than happening all at once.

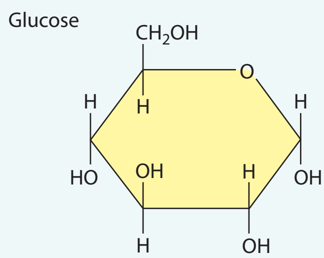
Energy from cellular respiration

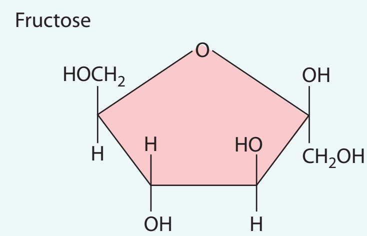
In the complete breakdown of glucose to carbon dioxide and water, about 60% of the available energy is released as heat. Cells cannot utilise heat energy, but it is important in keeping the body temperature constant. Heat is continually lost to the environment, so a continual supply of heat is necessary in order to maintain body temperature.

The remaining energy from cellular respiration is used to form a compound called **adenosine triphosphate**, or **ATP** (Fig. 4.4 on page 46). ATP is formed when an inorganic phosphate group is joined to a molecule of **adenosine diphosphate (ADP)**. The phosphate groups in ATP are joined by high-energy chemical bonds (Fig. 4.5). Some of the energy from cellular respiration is stored in the bond between the ADP molecule and the third phosphate group. This bond is more easily broken than the bond between the first and second phosphate groups.

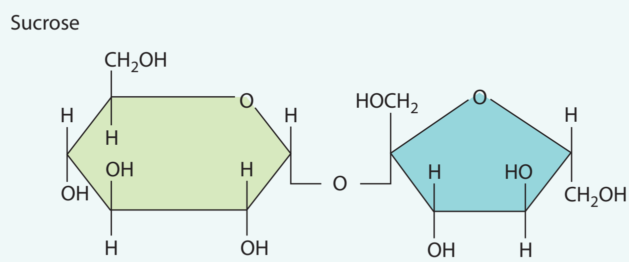
Carbohydates always contain carbon, hydrogen and oxygen. There are always twice as many hydrogen atoms as oxygen atoms.

Monosaccharides are simple sugars or single-unit sugars; examples are glucose, fructose and galactose.

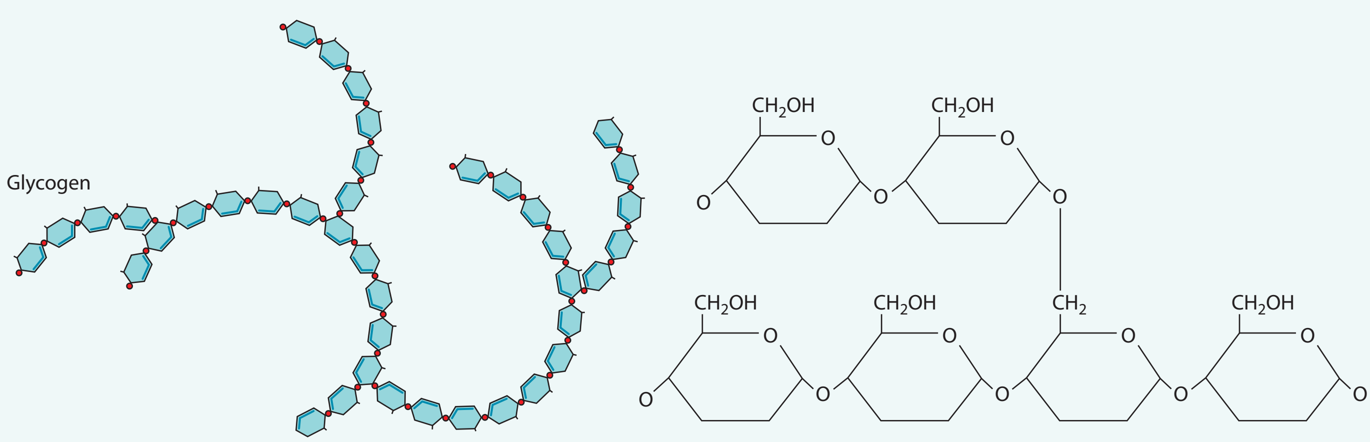




Disaccharides are two simple sugars joined together; examples are sucrose, maltose and lactose.



Polysaccharides are large numbers of simple sugars joined together; examples are glycogen, cellulose and starch.



Carbohydrates provide energy for body cells.

Figure 4.3 The structure of organic compounds

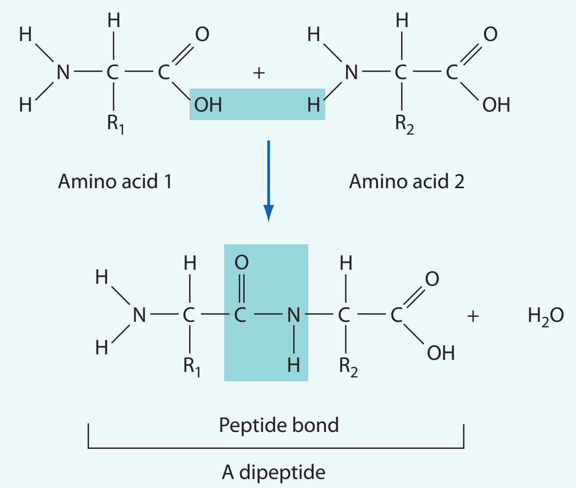
Proteins always contain carbon, hydrogen, oxygen and nitrogen and often sulfur and phosphorus. Made up of large numbers of smaller molecules called **amino acids**; there are about 20 different amino acids; examples of amino acids are glycine, alanine, valine and glutamic acid.

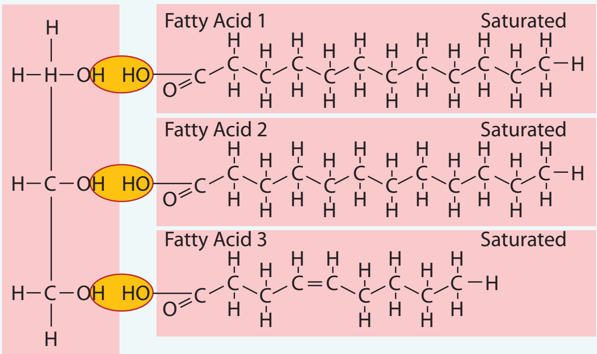
The bond that forms between amino acids is called a **peptide bond**; two amino acids joined by a peptide bond is a **dipeptide**.

Ten or more amino acids joined is a **polypeptide**.

Proteins consist of 100 or more amino acids. Each protein's chain of amino acids is folded in a unique way.

Proteins are important structural materials in the body. All enzymes are proteins so they are involved in all the chemical reactions of the body.





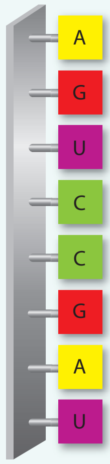
Lipids contain carbon, hydrogen and oxygen, but much less oxygen than carbohydrates. Examples of lipids are **fats**, stored in the body as energy reserves; **phospholipids**, important in cell membranes; **steroids**, including cholesterol and the sex hormones.

Each fat molecule consists of one molecule of glycerol and one, two or three **fatty acid** molecules. The type of fat stored in the body (and 98% of fat in foods) is **triglyceride**—glycerol plus three fatty acids.

Nucleic acids are very large molecules containing carbon, hydrogen, oxygen, nitrogen and phosphorus. They are made up of nucleotides, each of which contains a nitrogen base, a sugar and a phosphate. The two main kinds of nucleic acids are **ribonucleic acid**, **RNA**, and **deoxyribonucleic acid**, **DNA**.

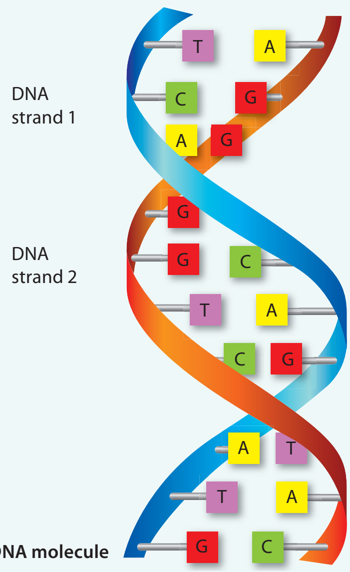
RNA consists of a single change of nucleotides that contain the sugar ribose.

RNA carries information from the DNA in the nuclear to parts of the cell where proteins are made.



(a) RNA molecule

DNA consists of two changes of nucleotides that contain the sugar deoxyribose.



(b) DNA molecule

DNA is the genetic material in the nucleus that stores inherited information.

Figure 4.3 The structure of organic compounds *continued*

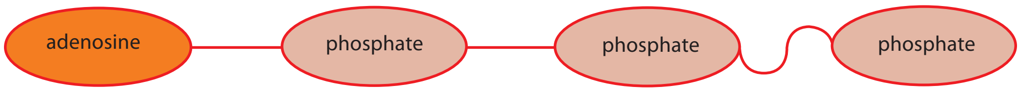


Figure 4.4 The ATP molecule consists of adenosine and a chain of three phosphate groups

Removal of the third phosphate group releases the energy in the bond (Fig. 4.5). ATP can thus be used to transfer the energy released in cellular respiration to processes in the cell that require energy.

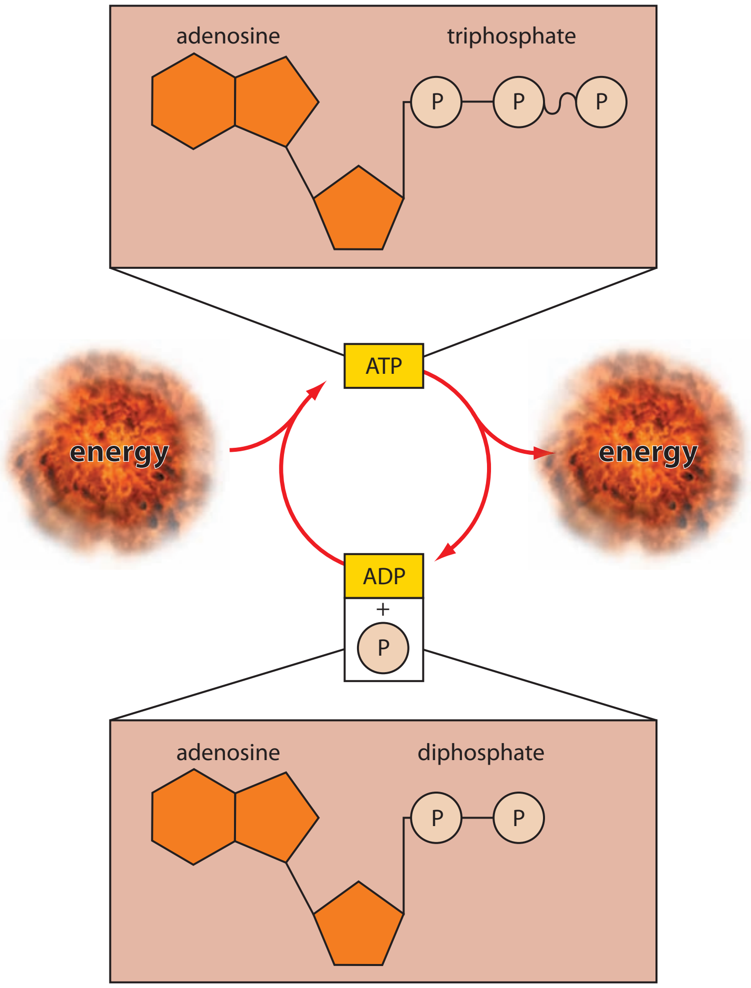


Figure 4.5 ATP stores energy. The energy is released when ATP breaks down to ADP

The ADP formed when the energy is released can be reused to store some more of the energy from cellular respiration. Thus, ATP acts as a go-between—a way of transferring energy from cellular respiration to cell processes that utilise energy.

Anaerobic respiration

The first phase in the breakdown of glucose is called **glycolysis**. A glucose molecule is broken down, in a series of 10 steps, to two molecules of pyruvic acid. No oxygen is required for this initial breakdown of glucose and if no oxygen is available the pyruvic acid produced in glycolysis is then converted to lactic acid. The production of lactic acid from glucose is called **anaerobic respiration**, which means respiration without oxygen. Glycolysis of one molecule of oxygen releases enough energy to convert two molecules of ADP to ATP. Anaerobic respiration allows cells to produce some energy in the absence of oxygen. The enzymes required for anaerobic respiration are available in the cytoplasm of the cell so glycolysis, and the conversion of pyruvic acid to lactic acid, occur in the cytoplasm.

Anaerobic respiration is very important during vigorous physical activity, when the respiratory and circulatory systems are unable to supply muscle cells with enough oxygen to meet all the energy demands of the contracting muscles. In such circumstances, anaerobic respiration supplies the extra energy. This results in the accumulation of lactic acid in the muscles, and it is the lactic acid that causes muscle pain and fatigue.

Lactic acid from anaerobic respiration is taken by the blood to the liver, where it can be recombined with oxygen to form glucose and eventually glycogen. As this process requires oxygen, physiologists say that, when cells are respiring anaerobically, the body is incurring an **oxygen debt**. After vigorous exercise one continues to breathe heavily for some time because the oxygen debt must be 'repaid' by converting lactic acid to glucose. The extra oxygen required after exercise may also be called **recovery oxygen**.

Aerobic respiration

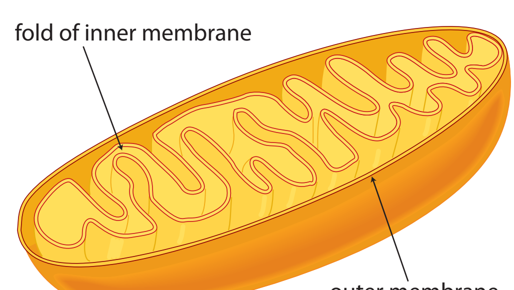
Complete breakdown of glucose to carbon dioxide and water requires oxygen. The pyruvic acid produced from glycolysis is completely broken down to carbon dioxide and water. This is known as **aerobic respiration**—respiration requiring oxygen.

Aerobic respiration occurs in the mitochondria of the cell. **Mitochondria** are organelles constructed with a double membrane—an outer membrane that forms the shape of the organelle, and an inner membrane that is folded inwards (Fig. 4.6). The enzymes for the reactions of aerobic respiration are attached to the internal membrane so folding produces a large surface area on which the reactions of aerobic respiration can take place.

(a)

Figure 4.6 **(a)** Electron micrograph showing a section through a mitochondrion; **(b)** Three-dimensional view of a mitochondrion

(b)



To complete the breakdown of glucose, the two pyruvic acid molecules produced in glycolysis must enter a mitochondrion, where enzymes are available to allow two more series of reactions to occur. The first of these, known as the **citric acid cycle** (or Krebs cycle), results in the formation of two more ATP molecules from the two pyruvic acid molecules. The second series of reactions, known as the electron transport system, can produce up to 34 molecules of ATP from the products of one molecule of glucose. Thus, aerobic respiration of one molecule of glucose has the potential to generate 38 molecules of ATP—two from glycolysis, two from the citric acid cycle and up to 34 from the electron transport mechanism. This can be represented as:

$$C_6H_{12}O_6 + O_2 \xrightarrow[38\ ADP\ +\ 38\ P\ \rightarrow\ 38\ ATP]{} 6CO_2 + 6H_2O$$

A summary of the processes of anaerobic and aerobic respiration is given in Figure 4.7.

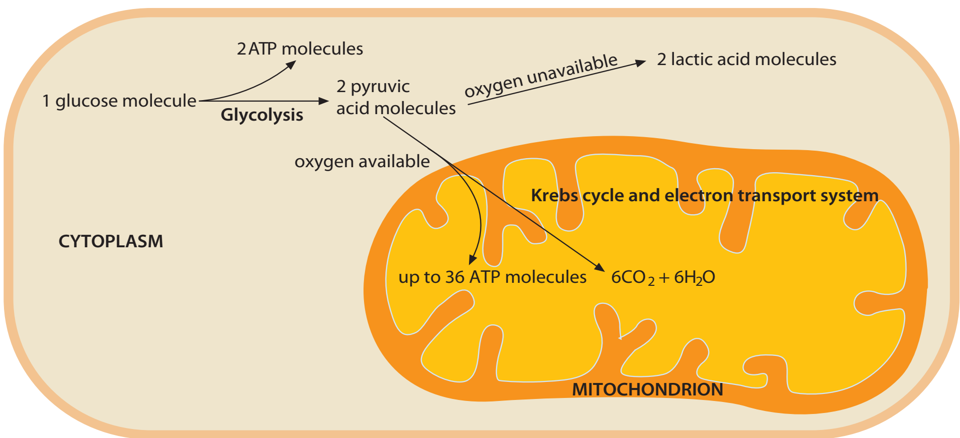


Figure 4.7 A summary of the processes of anaerobic and aerobic respiration in a cell

A yield of 38 ATP molecules from the energy contained in one molecule of glucose is the theoretical maximum. The actual ATP yield is often lower than this. Since the reactions of aerobic respiration take place in the mitochondria, and because aerobic respiration releases about 95% of the energy needed to keep a cell alive, the mitochondria are often known as the powerhouses of the cell.

Energy use by the cell

Cells need the energy that is temporarily stored in the ATP molecule for a variety of processes. These are summarised in Figure 4.8.

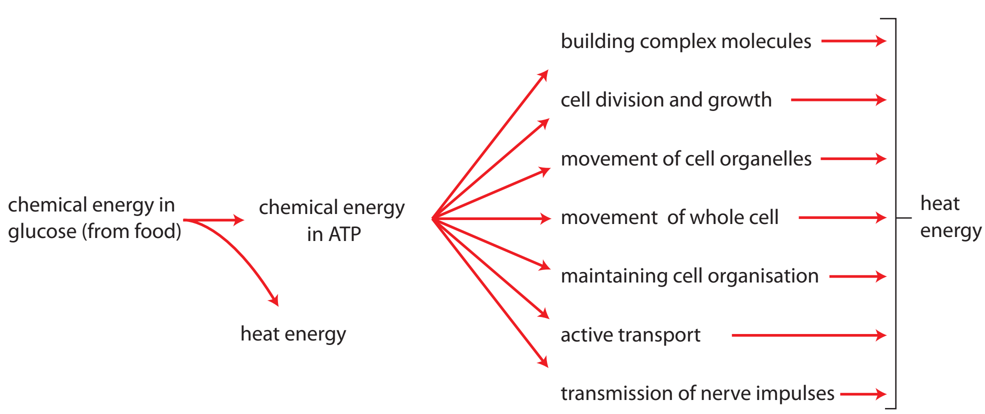


Figure 4.8 Uses of energy in the cell

From each of the chemical reactions involved in cellular processes, a certain amount of heat is produced. Only about 40% of the energy released in respiration is incorporated into ATP; the other 60% is lost as heat. Therefore, energy must be continually consumed in the form of food to replace that lost as heat and that utilised for other purposes.

As mentioned previously, ATP may be used to transfer energy from cellular respiration to reactions involving the build-up of large molecules. Such reactions require energy to form the chemical bonds that hold the parts of the molecule together. For example, when lactic acid is recombined with oxygen in the liver to form glucose, or when glucose molecules are joined to form glycogen, the energy required comes from the breakdown of ATP to ADP. Similarly, energy for the build-up of proteins, lipids and other molecules is transferred from cellular respiration by ATP (Fig. 4.9).

For another look at respiration go to http://www.bbc.co.uk/schools/gcsebitesize/biology/humansasorganisms/3respirationrev1.shtml

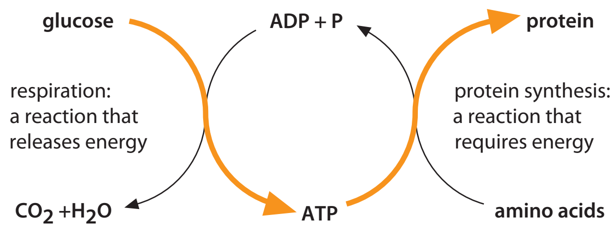


Figure 4.9 ATP transfers energy from reactions that release energy to reactions that require energy

Synthesis

Synthesis is the combining of small molecules to make larger molecules (it means the same as anabolism). In the example of energy transfer by ATP, shown in Figure 4.9, protein is synthesised from amino acids. In a similar way, glycogen molecules can be synthesised by joining glucose units together and glucose can be synthesised from lactic acid and oxygen. Synthesis requires both matter and energy—matter in the form of small molecules to be joined, and energy to form the chemical bonds that hold the smaller units together.

Nutrients and their uses

A **nutrient** is any substance in our food that is used for growth, repair or maintaining the body; that is, any substance required for metabolism. There are six groups of nutrients—water, carbohydrates, lipids, proteins, minerals and vitamins.

- **Water** is important in metabolism because it is the fluid in which other substances are dissolved. Chemical reactions in the cell occur in water and water molecules actually take part in some reactions.
- **Carbohydrates** are the main source of energy for cells. Complex carbohydrates are broken down to simple sugars, particularly glucose, which can then be broken down in cellular respiration to release energy.
- **Lipids** are also an important energy source. They are broken down to fatty acids and glycerol. Glycerol can then enter the glycolysis pathway and is broken down to release energy in a similar way to glucose.
- **Proteins** are broken down into amino acids. As we have seen, amino acid molecules can be assembled into new proteins. With regard to metabolism, the

most important proteins made are enzymes. Enzymes control metabolism by controlling the chemical reactions that occur in the body. Proteins can also be used as a source of energy but only if the supply of carbohydrates and lipids is inadequate.

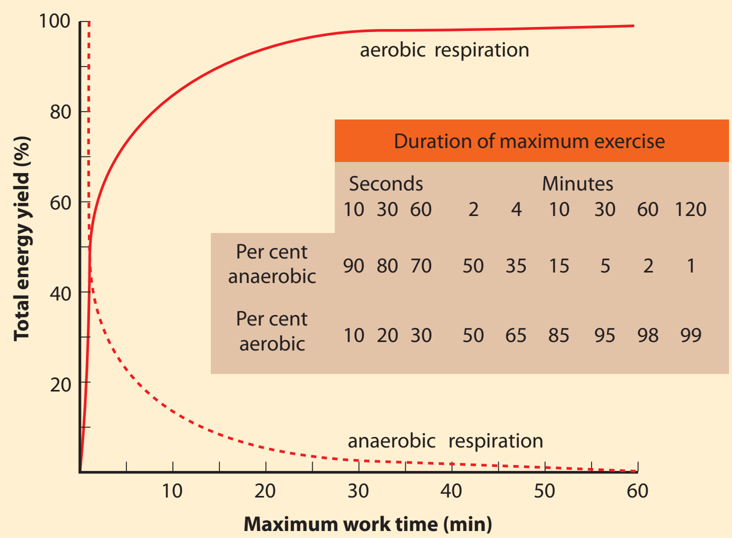
- **Minerals** are important for metabolism because they may be a part of enzymes, may function as co-factors for enzymes or may be a part of substances like ATP that are involved in metabolism.
- **Vitamins** act as co-enzymes for many of the chemical reactions of metabolism.

Working scientifically

Activity 4.1 Aerobic and anaerobic respiration during exercise

During exercise part of the energy required by the muscles comes from anaerobic respiration and part comes from aerobic respiration. The proportion of energy from each of the types of respiration depends on the nature of the exercise.

The graph and table in Figure 4.10 show the relationship between the duration of maximum effort and the proportions of energy derived from each of the two types of respiration.



	Duration of maximum exercise								
	Seconds					Minutes			
	10	30	60	2	4	10	30	60	120
Per cent anaerobic	90	80	70	50	35	15	5	2	1
Per cent aerobic	10	20	30	50	65	85	95	98	99

Figure 4.10 The relationship between maximum effort time and the proportion of energy provided by aerobic and anaerobic respiration

Use the graph and table to help you answer the following questions.

1. The world record for the 100 m sprint is less than 10 seconds. In a 100-m race, what proportion of a sprinter's energy would come from anaerobic respiration?
2. In a marathon race, what proportion of a runner's energy would come from anaerobic respiration?
3. At what duration of maximum effort would half of an athlete's energy come from aerobic and half from anaerobic respiration? Can you suggest some sports in which maximum effort would come in bursts of that duration?
4. Name some sports or activities in which most of the energy would come from *anaerobic* respiration.

5. Name some sports or activities in which most of the energy would come from *aerobic* respiration.
6. Some observers noted that a sprinter who had just run 400 m in 50 seconds was breathing much more heavily than a runner who had just completed a marathon in 2.5 hours. Suggest why this would be so.

REVIEW QUESTIONS

1. Explain what is meant by the terms 'metabolism', 'catabolism' and 'anabolism'.
2. **(a)** Why are enzymes necessary in living organisms?
   (b) What is meant by the statement that enzymes are specific?
   (c) List the factors that affect enzyme activity.
3. What is the difference between breathing and cellular respiration?
4. **(a)** Write a chemical equation that summarises cellular respiration.
   (b) Is the summary an accurate picture of what happens in cellular respiration? Explain.
   (c) Why is it necessary for cells to respire?
5. **(a)** Explain the role of ATP and ADP in cellular respiration.
   (b) What part do ATP and ADP play in the synthesis of organic molecules?
   (c) Using a diagram, summarise the energy relationship between ATP and ADP.
6. What is the difference between aerobic and anaerobic respiration in terms of:
   (a) the quantity of energy released?
   (b) the reactions involved?
   (c) the location of the chemical reactions within the cell?
7. Explain what is meant by 'oxygen debt' or 'recovery oxygen'. How is an oxygen debt 'repaid'?
8. List the processes for which cells need energy. Indicate whether each process is common to all cells or whether the process would occur only in particular cells.
9. What is synthesis? Why do reactions involving synthesis require matter and energy?
10. Draw up a table showing the six types of nutrient and the role of each in cellullar metabolism.

APPLY YOUR KNOWLEDGE

1. The law of conservation of energy states that energy can be neither created nor destroyed. If this is so, why do we need to continually take energy into the body in the form of food?
2. What compounds are synthesised from:
   (a) glucose?
   (b) amino acids?
   (c) fatty acids and glycerol?
3. Which of the following would yield the greatest amount of ATP if completely broken down in cellular respiration—a gram of carbohydrate, lipid or protein? (Use references if necessary.)

4. For each of the following processes state whether the chemical reactions are anabolic or catabolic reactions:
   (a) protein synthesis
   (b) aerobic respiration
   (c) anaerobic respiration
   (d) formation of glucose from lactic acid
   (e) formation of glycogen.
5. Adolf Hitler and a number of high-ranking Nazi leaders committed suicide by taking cyanide. Find out what effect cyanide has on cells. Why is cyanide a lethal poison?
6. Vitamin C is essential for the production of the hormone collagen in the body. A deficiency of vitamin C leads to scurvy, a disease that causes loss of teeth and easy bruising, especially around the joints. What role would vitamin C play in the production of collagen?
7. Figure 4.11 is a model showing how an enzyme is involved in a chemical reaction. Which letter corresponds to the enzyme, substrate, active site, enzyme–substrate complex and product?

Figure 4.11 A model for enzyme action