Extension 13: Biochemistry and Nutrition: Energy in Living Systems

Fig. 13.1 Energy is required to sit, walk, breathe and dream! This appendix looks at how energy is made available to the body from the 'fuel' (the food) we consume. Photograph © Getty Images/Hero Images

1. Prerequisites

The key ideas required to understand this section are:

Topic	Book page
Oxidation and reduction	102
Combustion	229
Functional group organic chemistry	341
Proteins and amino acids	356
Fatty acids	351-352
Carbohydrates	349

2. Types of energy

Let's start with what we know about energy. Energy is measured in units called joules. Energy is expended when something does work. Work and energy have the same units. Energy may be converted from one form to another, but the total amount of energy is kept constant in chemical reactions: this is the Law of Conservation of Energy.

We are particularly concerned with two forms of energy: chemical energy and heat. Chemical energy is an example of stored (or potential) energy. An example is a car battery, which releases its chemical energy as electricity. Many chemical reactions, such as the burning of a fuel, release their chemical energy as heat and light.

It is also possible to transfer chemical energy without releasing all of it as heat. This is done by chemical reaction. For example, reacting hydrogen gas with ethene (ethylene):

$$H_2 + CH_2{=}CH_2 \rightarrow CH_3CH_3$$

converts it to ethane. Ethene, hydrogen and ethane are all fuels, so it is clear that some of the chemical energy of the ethene and hydrogen are retained in the ethane. We have simply transferred some chemical energy from one form to another. This type of transfer occurs frequently within the body.

The total amount of chemical energy in a material is very difficult to measure or calculate, and it is customary to speak of energy differences. By agreement, the maximum amount of chemical energy that can be released by a fuel is taken as the heat energy produced when a known amount of the fuel is completely burned in oxygen (air). The heat released is simply the difference in energy between the reactants (fuel + O_2) and products (CO_2 + H_2O). Such an experiment is carried out in a **bomb calorimeter** and the heat outputs, measured in joules per 100 g of fuel, are found to vary dramatically with the fuel. Any carbon containing compound will burn in a bomb calorimeter. The uses of common foods as the 'fuel' in the calorimeter provides the familiar calorific tables ('calorific energy values') that are found in tables of books on dieting.

In the body, nearly all of the food that is absorbed in the digestive system is converted to energy, with about 60 per cent of it being converted to heat and about 40 per cent of it being available to do work in the body, including breathing, running, standing and cell replication. The fact that only 40 per cent of the calorific value of absorbed food is available for work is taken into account in the maximum daily calorific allowances of diet tables, but the stated calorific values of foods are those obtained by bomb calorimetry.

The disposal of the energy obtained from food is analogous to the income of a large corporation. If we define the efficiency of the corporation as simply profit, then the corporation might be judged as inefficient. But its marketing, personnel, transport and administrative costs are essential to the maintenance of the company. Similarly, the energy costs incurred by the healthy body are numerous and considerable, but they are all essential for the continued survival of the individual. Keeping the body warm and providing energy for cellular work are the two main uses of food that is absorbed by the body. The only 'wasted energy' is the calorific value of undigested (excreted) waste, which forms less than 10 per cent of the total calorific value of the average diet. In this sense, the body is highly efficient (>90 per cent) at using the energy from food.

3. Chamber experiments on human metabolism: direct calorimetry

About a hundred years ago, scientists started a series of experiments to measure the energy and gas consumption of human beings. This involved producing a thermally insulated chamber (shown schematically in Fig. 13.2) within which a human being would live. Known quantities of oxygen were fed in from an oxygen cylinder and the composition of the exhaled gases measured by standard analytical techniques. The temperature of the chamber was also measured. These experiments are known as **direct calorimetry**.

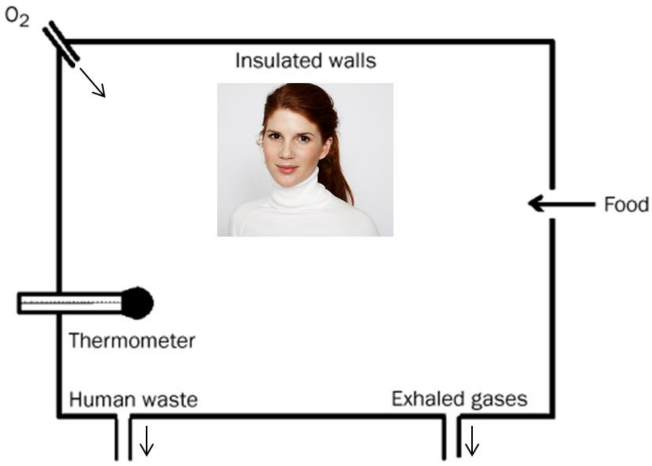

Fig. 13.2 Diagram of a chamber for direct calorimetry. Photograph © Getty Images/Andreas Kindler

Such experiments allowed measurements of the amount of energy used up by a fasting person (one who has not eaten for 24 hours) who is completely at rest. This energy consumption, usually expressed in units of joules per day, is given the name **basal metabolic rate** (BMR). This is 'the metabolic rate' referred to so often in diet books. The value of the BMR varies from person to person, but it is usually about 8 megajoules per day (8 MJ day^{-1} = 8 × 10^{6} J day^{-1}).

If a person walks or does heavy work like cycling or lifting, more energy is required. The total energy demands (including the BMR) of an individual are obtained by multiplying the BMR by factors to allow for exercise. If a person walks at 'normal speed' along a level surface, the factor is about 3 (see Example 1), meaning that a full day of such walking would consume three times the energy requirement of the BMR for that person. For strenuous physical activity, such as digging, the factor might be 6.

EXAMPLE 1

A woman with a BMR of 7 MJ day-1 walks for 2.4 hours and is completely at rest for the rest of the day. Estimate her total energy costs.

Answer

Split the calculation into the energy consumption during rest and during the 2.4 h of walking. During rest, for 21.6 h (90% or 0.9 of the day), the consumption will be 7 × 0.9 = 6.3 MJ. During the 2.4 h (10% or 0.1 of the day) of walking, the energy consumption is 3 × 7 × 0.1 = 2.1 MJ. The total energy requirement per day = 6.3 + 2.1 = 8.4 MJ. This represents an increase of (8.4 – 7) = 1.4 MJ day^{-1} over BMR.

4. Indirect calorimetry

Indirect calorimetry is the name given to the determination of energy consumption based on the amount of O_2 consumed, or on the amount of CO_2 produced. Both quantities are measured readily using modern instrumentation, and experiments show that indirect calorimetry gives the same results as the more expensive direct calorimetric measurements. Indirect calorimetry does not require a chamber. Perhaps surprisingly, the amount of heat produced from the consumption (not the inhalation!) of exactly one litre of oxygen does not vary much with the nature of the food. For fat or protein, the amount of heat is 19.3 kJ, close to that for carbohydrates (20.7 kJ). Diets are normally mixtures of all three classes of foods, and this brings the average value to about **20 kJ per**

dm³ of oxygen consumed irrespective of size, sex or diet. This is described in more detail in Unit 13 of the book.

EXERCISE 13A

List five factors which control the energy expenditure in human beings.

5. The estimation of energy requirements

For an individual who desires neither to gain nor to lose weight, the energy intake must balance the expenditure. Equations are available to allow calculations for average individuals at different ages. Many organizations, including the World Health Organisation, carry out such calculations, which are particularly important for Third-World countries.

6. Cell metabolism

Living organisms are unique in that they can extract energy from their environment and they are able to use it to grow and reproduce. Details of cell metabolism are given in books on biochemistry, but the purpose of this section is to provide an outline of the main processes so that the reader can 'navigate' more easily through biochemistry textbooks on this subject.

7. Metabolism

Metabolism is the collective term for all the chemical reactions undergone by an organism. Participating compounds are referred to as *metabolites*. The processes collectively described by the term metabolism fall into two categories:

(i) Those involving the building of complex molecules (biosynthesis), ion transport, muscle contraction, and the transcription of the genetic code. All these processes are collectively called **anabolism**.

(ii) Those involving the break-up of complex molecules to simpler ones (called **catabolism**). It is catabolism that will be our main concern. Catabolism involves three stages, each of which is discussed in greater detail below: (a) digestion; (b) the incomplete oxidation of small molecules; and (c) cellular respiration within the cytochrome of the cell.

Through biosynthesis, cells manufacture complex materials from simpler ones. Like all known 'systems' within the Universe, living things do not consume energy: they merely change its form. In doing so, cells convert energy from a less useful to a more useful form, from sunlight (the ultimate source of nutrients), to adenosine triphosphate (ATP):

$$\text{Solar energy} \longrightarrow \text{food} \longrightarrow \underset{\text{MAKING ATP}}{\text{CELLULAR RESPIRATION}} \xrightarrow{O_2} H_2O$$

ATP can be thought of as the 'energy currency' or 'energy bank' of the body (see Fig. 13.3). Just as money has to be spent in order to do build a new building or transport goods, so ATP is 'spent' by the body in building cells, making enzymes and transporting nutrients in the blood.

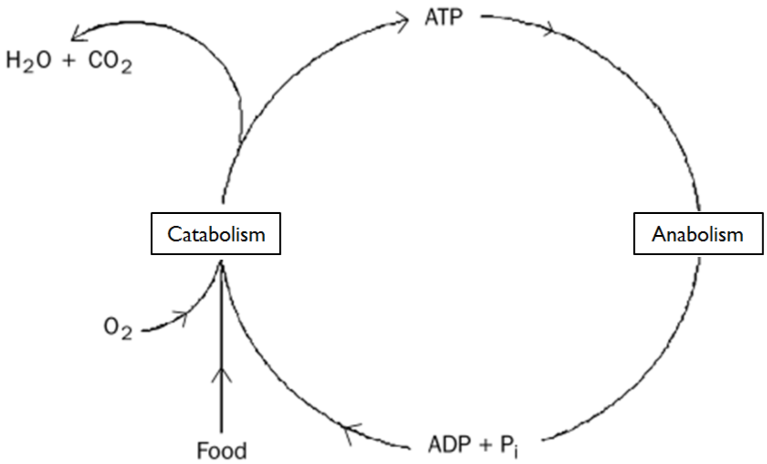

Fig. 13.3 ATP, catabolism and anabolism. Catabolism produces ATP by reacting ADP with phosphate (P_i). Anabolism consumes ATP.

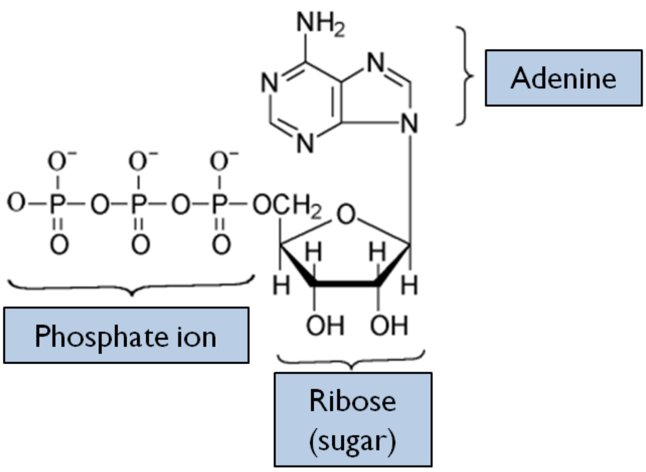

Fig 13.4 Adenosine triphosphate (ATP)

The structure of ATP is shown in Fig. 13.4. It is much more complicated than the molecules we have met so far, but by biochemical standards it is at best a medium-sized molecule! The details of the structure are not important to the energy cycles discussed below, but we can see that ATP consists of three parts: a phosphate ion with three P atoms; a sugar (ribose); and a nitrogen-containing molecule called adenine. ADP is similar, but contains only two P atoms.

8. Stage 1 of catabolism: the digestion of foods

Digestion occurs mainly in the intestinal tract and involves the breaking down of large molecules into smaller ones.

EXERCISE 13B

What are the ‘smaller’ molecules produced from the digestion of carbohydrates, fats (lipids) and proteins?

The amount of useful energy produced in the digestion stage is very small indeed. Most of the released energy appears as heat, which although valuable in maintaining the temperature of the organism, cannot be utilized by the cell for work. The process of digestion is, however, far from pointless: its purpose is to produce smaller molecules (substrates) which can either be stored in the body or used immediately to release useful (chemical energy) in catabolism.

As a consequence of digestion, starch and other carbohydrates are generally broken down into glucose. The glucose so produced is used as shown in Fig. 13.5, with excess glycogen ultimately stored as fat.

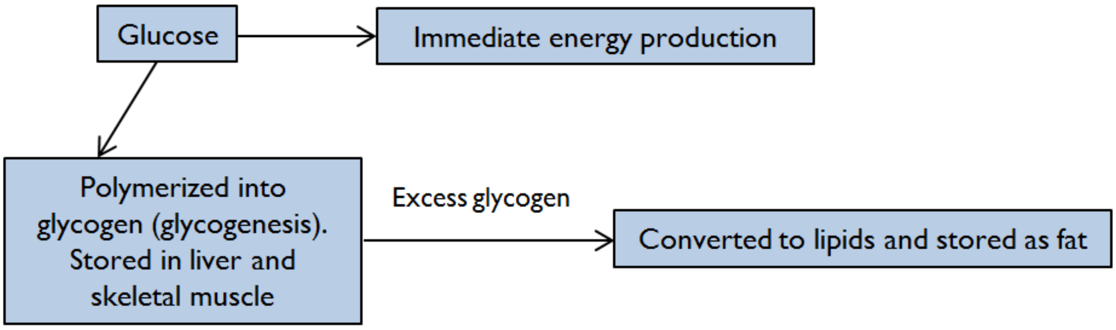

Fig. 13.5 The metabolic fate of glucose

Although amino acids, obtained by the digestion of proteins, can be used to produce energy when fats or carbohydrates are in short supply, the normal fate of amino acids is to be used by the body in the building of cells and in the manufacture of enzymes etc.

Fats (lipids) are digested by the body into fatty acids, some of which are laid in 'long term stores' below the skin.

9. Stage 2 of catabolism: the production of smaller molecules (pyruvate and acetyle-Co-A) which enter the citric acid cycle, producing carbon dioxide and water

The oxidation of glucose is often said to be 'the core of catabolism' because virtually all organisms rely on glucose as their main source of energy. Fig. 13.6 shows the main features of glucose catabolism and its links with fatty acids (obtained from the digestion of fats) and amino acids (obtained from the digestion of proteins).

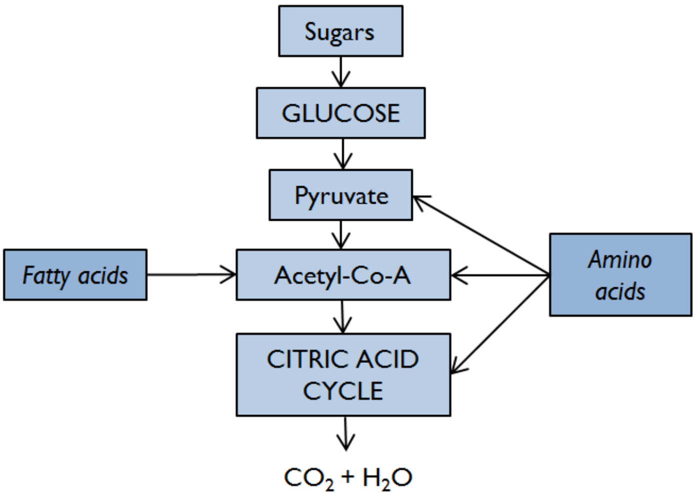

Fig. 13.6 The main pathways of glucose catabolism. Amino acids (after removal of nitrogen) can enter at any one of three points in the cycle.

The citric acid cycle produces carbon dioxide and water, but in addition the cycle carries out two very important conversions. Nicotinamide adenine dinucleotide (symbolised NAD^+) is converted to its reduced form, symbolised NADH. Flavin adenine dinucleotide (FAD), is converted into its reduced form, $FADH_2$. (The structures of these molecules need not bother us here, but they are similar to ATP in that they are assembled from nitrogen-containing molecules, phosphate ions and sugars molecules).

10. Step 3 of catabolism: cellular respiration

Most of the ATP used by the body is produced by cellular respiration. In cellular respiration, molecular oxygen (O_2) is converted to water by NADH and $FADH_2$. This conversion is an example of a reduction. The overall reactions are:

$$2NADH + 2H^+ + O_2 \rightarrow 2NAD^+ + 2H_2O \qquad (1)$$
$$2FADH_2 + O_2 \rightarrow 2FAD + 2H_2O \qquad (2)$$

Reactions (1) and (2) do not occur in one step, but through a sequence of steps known as the respiratory, electron transport or cytochrome chain. At three points in the chain, ATP is produced from ADP (adenosine *di*phosphate):

$$\text{ADP} + \text{phosphate ion} \rightarrow \text{ATP} \qquad (3)$$

The interlinking between the citric acid cycle, powered by nutrients, and cellular respiration, which uses oxygen gas, now becomes clear. Without the citric acid cycle, there would be no NADH or $FADH_2$, and so the cells would be starved of ATP.

11. Where is 'fuel' stored within the body?

The stores of 'fuel' and energy within the body are shown in Table 13.1.

Table 13.1 Stores of 'fuel' and energy in the average body

Energy sources	MJ
Glycogen in liver	1.9
Glycogen in muscle	4.3
Glucose in body fluids	0.26
Fat in muscle	6.1
Subcutaneous fat	296
Total energy	309.6

Further reading

The Chemistry of Life by Steven Rose, Penguin (1999).

Revision questions

1. A man with a BMR of 8 MJ day^{-1} carries out heavy manual work for eight hours in a day. Estimate the total daily energy consumption, assuming that he is resting completely for the remaining time. (Factor = 6.)

2. Use Table 13.1 to estimate the total time a person could survive without food based on a daily energy consumption of 10 MJ.

3. Explain biochemically why the absence of oxygen gas or the absence of energy providing nutrients are both fatal to the human organism.

4. Consult a book on biochemistry and find out the structure of:

(i) the pyruvate ion
(ii) acetyl-Co-A

5. Consult an encyclopaedia and write short notes on the importance of the following in the human diet:

(i) calcium, iodine and iron
(ii) vitamins

Answers

Exercises

Exercise 13A

The factors include:

a) Body size: BMR increases with body mass.
b) Body composition: lean bodies have a higher metabolic rate (i.e. higher BMR) than fat bodies. BMR is often expressed per kg of lean tissue.
c) Age: BMR decreases rapidly with age since adults are not growing.
d) Sex of person: the BMR of males is slightly higher than that of females.

e) Diet: BMR increases with increasing protein consumption and with the total calorific value of the diet (although not in proportion to the added intake!).
f) Climate: the cooling effect of the wind and low temperatures, or lack of clothing, increases BMR.
g) Genetic differences: variations in BMR related to genetic differences for same age, sex and weight are up to ±10%.
h) Hormonal state: studies suggest that BMR decreases in early pregnancy but increases in late pregnancy. But this is a small effect.
i) Psychological state: only acute anxiety has a significant effect on BMR.
j) Pharmacological effects of drugs: even caffeine increases BMR by small but measurable amounts.
k) Disease: infections, burns, tumours and fevers increase BMR.

Exercise 13B
Proteins are converted into the different amino acids of which they are composed; carbohydrates (polysaccharides, such as starch, in plants and glycogen in animals) are degraded to sugars, such as glucose; and fats (lipids) are broken down into fatty acids and glycerol.

Revision questions

1. The man is assumed to be resting when he is not carrying out manual work. For the 16 hours his energy consumption is (16/24) 8 = 5.3 MJ. For the 8 h of work, his consumption is (8/24) 6 8 = 16 MJ. Total consumption is 16 + 5.3 = 21.3 MJ day^{-1}.

2. Total energy store in a person is about 310 MJ, which would last about 31 days.

3. A summary of the biochemistry is as follows. The nutrients from food are consumed in the citric acid cycle, producing NADH and FADH2. NADH and FADH2 are converted to NAD and FAD in cellular respiration, in which ATP is made, and O2 consumed. Therefore, lack of O2 stops ATP being produced, and the cells and body are starved of ATP, causing breathing to cease. This is a relatively rapid effect. Lack of nutrients is not such an immediate problem, because the body has stores of fat from which nutrients can be drawn for many days. But eventually, even these stocks would be consumed, and without them the citric acid cycle would not be functioning, so that even in the presence of oxygen, no NADH and FADH2 would be available for cellular respiration.

As a footnote, cyanide ions stop cellular respiration by combining irreversibly with molecules within the electron transport chain.