FOX AND CAMERON'S

Food Science, Nutrition & Health

7th Edition

MICHAEL E.J. LEAN

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Food Science, Nutrition & Health 7th edition

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Preface to the 7th edition

Fox and Cameron has rightly become the leading textbook in the field of Food Sciences and Nutrition, for use both in colleges and in schools, as well as a reference source for the food and catering companies. The style created by Fox and Cameron was both accessible and authoritative, and not without humour in places.

For this revised 7th edition, a great debt is still owed to B. A. Fox and A. G. Cameron (Brian Fox sadly died in 2002). I have tried to retain their human touch and the balance between presenting up-to-date scientific issues in the context of foods we all know and love (or loathe, in some cases).

I have been helped enormously by the hard work of Dr Wendy Wrieden, Centre for Public Health Nutrition Research, University of Dundee, UK, and we have both relied on help from our secretaries and academic colleagues in the process of revision.

Some of the book is left unchanged from the latest editions. This is in part a testimony to the huge amount of material marshalled by Fox and Cameron. However, all the chapters have been brought up-to-date to incorporate new evidence, new technologies and new emphasis. Reflecting the change in editorship and the changing demands of the food industry to meet the needs of consumers, this new edition includes a great deal more on the impact of foods on health – both through nutrition and through food-borne infections. Referencing is much reduced in this 7th edition. Rather than referring back to older publications, students and their teachers should be accessing the latest scientific regulatory and policy documents on the internet. The impact on the food industry of new, consumer-centred agencies such as the Food Standards Agency and the Joint Health Claims Initiative, are felt throughout this new edition, and students will need to monitor their websites for new information.

The times are certainly changing for the food industry. With continued globalization, and 90 per cent of all food regulations in UK now being derived from Europe, students and workers in the food industry need to keep on their toes. This book is designed to help.

Professor Mike E J Lean
2006

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Preface to the 6th edition

It is universally accepted that an adequate and well-balanced diet is essential for the enjoyment of good health but the scientific principles on which this belief is based are by no means widely understood. This book, which bridges the gap between science and practice in nutrition, is an attempt to make good this deficiency. It is largely concerned with what food *is*, how much of it we should eat and what happens to it – and to us – when we eat it. It provides a comprehensive and up-to-date survey of the body of knowledge which has come to be known as food science, and examines the nutritional significance of this knowledge. This is a more difficult task than might at first be supposed because of the many scientific disciplines involved, the complex nature of many apparently simple foodstuffs and the intricate biochemical reactions that occur when food is digested, absorbed and converted into the stuff of which we are made.

We have sought to make the book as self-contained as possible but a study of food science and nutrition, even at the fairly elementary level at which this book is pitched, is of necessity far-ranging and inevitably involves an assumption of some previous knowledge of basic science. Nevertheless, we hope that the text will be intelligible to all those who might wish to read it, and with this in mind, we have kept the use of structural formulae to a minimum. Unfortunately, it has not been possible to avoid using the combinations of initial letters which serve as abbreviations for frequently used groups of words with particular meanings; these have, in effect, become recognized as part of the specialized vocabulary of food science. To assist the reader in finding a way through this veritable thicket of alphabetic abbreviations a Glossary has been provided which we hope will prove helpful.

We have been encouraged by the consistent popularity of the book over a long period to conclude that it is fulfilling a need and meeting the objectives we set ourselves when it was first written. Consequently, we have not thought it necessary to make radical changes in preparing this sixth edition and it retains the basic structure of previous editions. The first three chapters describe in outline the nature and functions of food, and the changes it undergoes in the body when it is eaten, together with a preliminary exploration of the relationship between dietary factors and good health. A new chapter follows in which the relatively new terms known as dietary reference values, which are used to express dietary requirements, are introduced. These have taken the place of the terms used previously, such as recommended daily amount, and they are employed consistently throughout the remainder of the book. The main body of the text is given over to an account of the nature of nutrients and the foods which contain them and to a description of what happens to food when it is grown, stored, processed, preserved, cooked and eaten. A chapter dealing with the relationship between diet and health discusses the way in which dietary habits can be modified to promote good health and combat disease.

Subsequent chapters look at the related topics of food spoilage and preservation, food poisoning and food hygiene. The final chapter, which is concerned with the important topic of food contaminants and additives, seeks to present a balanced and comprehensive account of what has become a controversial subject. Although there may be risks involved in using some additives, considerable benefits may also be obtained and an attempt is made to balance these two aspects of the use of additives in food.

We have not attempted to provide references to the original sources of the information given in this book; such references would have greatly increased the length and cost of the book and would, perhaps, have been used by relatively few readers. A short reading list is given at the end of many chapters which will assist readers requiring more detailed information. Details of a number of books on food science and nutrition which are of more general interest are given in a General Reading List at the end of the book.

Great care has been taken to ensure that the information contained in this book is as accurate and up-to-date as possible but it is almost inevitable that

errors and ambiguities will occur in a book which attempts to summarize a large and expanding field of knowledge. We should be grateful if any such inaccuracies, for which we alone are responsible, can be brought to our notice.

We trust that the book will continue to be of interest and value to all who are concerned with food science and nutrition. It is principally intended for students of Food Science and Technology, Catering and Nutrition and for A-level and BTEC students in schools and colleges. We know that it has also been found to be of interest by many members of the general public who are concerned about the relationship between dietary habits and good health, and who wisely take an interest in 'healthy eating'. We hope that all who read the book will enjoy doing so and that the information it contains will assist them in the pursuit of good health and the avoidance of those life-threatening diseases which are now known to have a nutritional component.

Brian A Fox
Allan G Cameron
1994

Acronyms/terms used

AFD	accelerated freeze-drying
ADI	acceptable daily intake
ACP	acid calcium phosphate
ASP	acid sodium pyrophosphate
ADP	adenosine diphosphate
AMP	adenosine monophosphate
ATP	adenosine triphosphate
ADH	antidiuretic hormone
BV	biological value
BSE	bovine spongiform encephalopathy
COMA	Committee on Medical Aspects of Food Policy
CAS	controlled-atmosphere storage
CHD	coronary heart disease
DEFRA	Department for Environment, Food and Rural Affairs
DRV	dietary reference value
DHA	docosahexanoic acid
ECG	electrocardiogram
EFAs	essential fatty acids
EAR	estimated average requirement
GMOs	genetically modified organisms
GDL	Glucono-delta-lactone
HDL	high-density lipoprotein
HTST	high-temperature short-time
JHCI	Joint Health Claims Initiative
LDL	low-density lipoprotein cholesterol
LRNI	lower reference nutrient intake
MRL	maximum residue level
MAP	modified-atmosphere packaging
MAS	modified-atmosphere storage
MSG	monosodium glutamate
MUFA	monounsaturated fatty acid
NHDC	neohesperidine dihydrochalcone
NPU	net protein utilization
PSD	Pesticides Safety Directorate
PKU	phenylketonuria
PUFA	polyunsaturated fatty acid
POMC	pro-opio-melanocortin
PEM	protein-energy malnutrition
PLP	pyridoxal-5-phosphate
RDA	recommended daily amount
RDI	recommended daily intakes
RNI	reference nutrient intake
SI	safe intake
SRSV	small round structured virus
SIADH	syndrome of inappropriate antidiuretic hormone
TVP	textured vegetable protein
TDT	thermal death time
TDF	total dietary fiber
UHT	ultra-high temperature
VLCDs	very low calorie diets
VLDL	very low density lipoproteins
WHO	World Health Organization

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1

Food and its functions

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The basic function of food is to keep us alive and healthy, to grow and to reproduce. In this book we shall consider how food does this, although we shall also need to think about many other related matters. Indeed, we cannot answer such a fundamental 'How' question without first finding out the answer to some simpler 'What' questions, such as what is food, what happens to it when it is stored, processed, preserved, cooked, eaten and digested. The answers to such questions can only be found out by experiment, and many different sciences play a part in helping to provide the answers. In recent years the study of food has been accepted as a distinct discipline of its own and given the name food science.

Food science exists partly to pursue academic knowledge (the insatiable curiosity of mankind finds in food a universal theme of shared interest). As Samuel Johnson phrased it, 'I look upon it that he who does not mind his belly will hardly mind anything else' (Boswell, *The Life of Samuel Johnson*, Vol. 3, Ch. 9). Its interest lies also in the fact that our knowledge of the subject is growing, leading to an unfolding of new perspectives about what is significant, while new techniques are being developed leading to new methods in food processing and of analysing nutrients, additives and possible contaminants in food. Food science also promotes the fulfilment of a basic human need for a diet that will sustain life and health. To be effective, food science must be applied, in the manufacture and preparation of food and this is the province of *food technology*.

Determining the dietary needs of individuals, or of populations is the realm of *nutritional science*.

The problems involved in determining what foods in what combinations best meet the dietary needs of different countries, or individuals, of the compositional merits of various new foods, of how to store and preserve food with minimum nutritional loss are the provinces of food science. However, in order to use this information it must be applied – food must be grown, stored, processed, preserved and transported on a large scale – and this is the province of *agriculture and food technology*.

It becomes clear that promoting health through diet requires input from human nutritional science, food science and food technology.

In the following pages we shall study the relation between food science, nutrition and health, but first it is important to understand just what we mean by the term food.

FOOD AND FOODS

The definition of what is, and what is not, a food is surprisingly taxing, not least because of the need to provide control and regulation over the things, which, for different purposes, people swallow.

Not everything people eat is food. Children, pregnant women and sometimes others sometimes eat non-food materials such as coal. This behaviour is known as 'pica'. Few people would class coal as food,

on the grounds that it is not absorbed and does not contribute in any way to biochemical or physiological function in the body. But where does that leave chewing gum? Chewing gum is produced by 'food companies' with the intention that it should be taken by mouth, recognizing that it will occasionally be swallowed. Although inert, and non-absorbable, chewing gum deserves (and receives) the same regulation as other less ambiguous foods.

According to the Food and Agriculture Organization, 'Food means any substance, whether processed, semi-processed or raw, which is intended for human consumption, and includes drink, chewing gum and any substance which has been used in the manufacture, preparation or treatment of 'food' but does not include cosmetics or tobacco or substances used only as drugs' (ftp://ftp.fao.org/codex/manual/Manual12ce.pdf, p. 41).

It is important to recognize that a food is almost always a complex substance, rather than a pure compound of single, uniform composition. Food is characterized by more than just its chemical composition. There are exceptions of course. Table sugar is indisputably 'a food', although it is a pure industrial preparation of $(CH_2O)_6$. However, for most foods there is a characteristic physical form, containing a variety of nutrients with a range of properties. Some grow that way, others are created by food technology and manufacturers. Some are consumed as grown or produced, others form ingredients of still more complex foods, dishes or meals. In the twenty-first century, we probably have to extend our concept of what constitutes a food, at least as perceived by consumers, to include its packaging and the imagery and descriptive or promotional text included, just as we would include the skin of a banana, or the outer leaves of an onion, as part of 'the food'. We make judgements about food quality from all these components, and packaging, natural or man-made, can influence food composition even if it is not consumed.

Foods contain nutrients – components that contribute to, and in some cases uniquely provide for, biochemical and physiological functions in the body. Foods may also include non-absorbed components which may influence bowel health and function. Some phenolic compounds, such as tannins and classes of non-starch polysaccharides (e.g. cellulose) probably fall into this category. Food may also include contaminants from unusual soil types, or from industrial pollution. Heavy metals, radioactive isotopes, and microbial contamination all have potential negative health effects.

A final and even more tricky consideration is that foods contain a variety of compounds which can be absorbed and which have important biological effects. A good example is caffeine. It is present in several common foods (tea, coffee, chocolate). It is also sold, and prescribed, as a drug. In doses similar to the amount in a cup of coffee it stimulates brain, heart and lung function, with several beneficial (and some potentially harmful) consequences. So, it is perfectly possible for foods to have potent 'pharmacological' actions. Caffeine, depending on how it is packaged, may be subject to either food law or drug law. Fish oils are also currently marketed as drugs while obviously being available as part of fish. The distinction between a 'food product' and a 'drug/medicinal product' is a fine one with scope for interpretation. The European Union (EU) has proposed a definition for a medicinal product as 'Any substance or combination of substances presented for treating or preventing disease in human beings. Any substance or combination of substances which may be administered to human beings with a view to making a medical diagnosis or to restoring, correcting or modifying physiological functions in human beings is likewise considered a medicinal product' (European Parliament, 2001).

For some new products, it can be a close decision whether to market it through food outlets as a 'food product' with permitted health claims to be made, or whether to have it registered and sold on prescription or over the counter in pharmacies as a drug, which permits medical claims. The technology required is identical, although greater controls over content variability may be required for a drug. The main difference lies in the differences between what constitutes a medical claim (drug) and a health claim (food product). Again, there is a grey area for interpretation, and the ultimate practical distinction between a food or a drug lies in the enormous amount of highly expensive research required by drug licensing authorities. For a drug, advertising is restricted, and the market much more limited, but vastly greater prices can be charged and drug patents ensure no direct competition for several years. There is currently great interest in protecting consumers against food companies which make

health claims, or even medical claims for their products, often based on no direct evidence at all. The counterargument runs that since antiquity certain foods have been attributed with magical qualities in folklore, and to strip these beliefs from food marketing is to deny a rich and evolving food culture. The leading agency in the UK and Europe is the Joint Health Claims Initiative, a partnership between the food industry, consumer organization and enforcement authorities, which was established to develop a Code of Practice for health claims on foods. The legal and regulatory issues on foods are too complex to be addressed in detail in this book, but a clear and helpful introduction can be found at http://www.jhci.co.uk.

TYPES OF NUTRIENT

The two basic functions of nutrients are to provide materials for growth and repair of tissues – that is, to provide and maintain the basic structure of our bodies – and to supply the body with the energy required to perform external activities as well as carrying on its own internal activities. The fact that the body is able to sustain life is dependent upon its ability to maintain its own internal processes. This means that although we may eat all sorts of different foods and our bodies may engage in all sorts of external activities, and even suffer injury or illness, the internal processes of the body should absorb and neutralize the effects of these events and carry on with a constant rhythm. This is only possible because the components of our bodies are engaged in a ceaseless process of breakdown and renewal (a theme to which we will return).

If the body's internal processes are to be maintained constant despite its ceaseless and varying activity, and in the face of external pressures, there needs to be systems in place to regulate very precisely all the processes needed for life. Thus, nutrients have a third function, namely that of controlling body processes, a function that will be considered in the next chapter.

Although habits and patterns of eating may vary from person to person, and diets may be selected from hundreds of different foods, everyone needs the same types of nutrients and in roughly the same proportions. The relation between nutrients, their functions in the body and important foods that supply them is shown in Fig. 1.1.

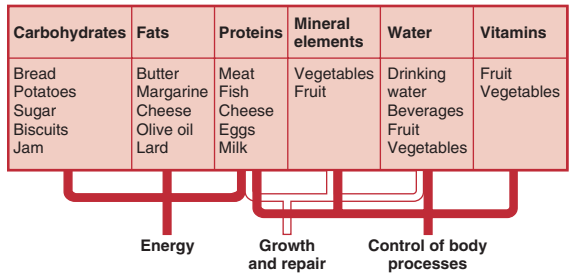

Figure 1.1 *The nutrients: diagram showing their functions and representative foods in which they are found*

Nutrients are often grouped according to their chemical composition. For example, although different oils and fats, such as olive oil and palm oil, do not have identical compositions, they are chemically similar and mostly use the same biochemical pathways for digestion, absorption, transport and metabolism. In the same way, different proteins (and carbohydrates) are constructed and metabolized according to the same general chemical patterns. The three 'macronutrients' (fat, carbohydrate and protein) are therefore conveniently grouped together. Vitamins are not classified according to chemical type; at the time of their discovery in food their chemical nature, which in most cases is complex, was unknown. They were grouped together because it was known that small quantities of them were essential to health and they do not fall into the macronutrient classes. At first they were identified in terms of their effect on growth and health and distinguished by letters as vitamins A, B, C and so on. Their chemical composition is now known, and it has become apparent that they are not chemically related to each other. They all have different functions but it is still convenient to consider them together.

FOOD AS A SOURCE OF ENERGY

Energy is required for sustaining all forms of life on Earth. The prime source of the earth's energy is the sun, without which there could be no life on this planet. The sun continually radiates energy, a tiny fraction of which is intercepted by the Earth and stored in various ways; plants and coal, for

example, act as energy storehouses. Living plants convert the sun's energy into chemical energy and some plants of past ages have been converted, over many millions of years, into coal.

Plants, by the process of *photosynthesis*, convert carbon dioxide and water into carbohydrate. Photosynthesis, which is discussed in detail in Chapter 8 (p. 88), can only take place in daylight because solar energy is needed for the process. A complex series of chemical changes occurs which can be represented by the following equation:

$$x\mathrm{CO_2} + y\mathrm{H_2O} \xrightarrow{\text{daylight}} \underset{\text{Carbohydrate}}{\mathrm{C_{12}(H_2O)}_y} + x\mathrm{O_2}$$

The formation of carbohydrate is, therefore, the method used by plants to trap and store a part of the sun's energy. Sugar-beet, which synthesizes carbohydrate in the form of the sugar sucrose, may be taken as an example:

$$12\mathrm{CO_2} + 11\mathrm{H_2O} \xrightarrow{\text{daylight}} \underset{\text{Sucrose}}{\mathrm{C_{12}(H_2O)_{11}}} + 12\mathrm{O_2}$$

When sucrose is formed from carbon dioxide and water, energy is absorbed and stored as chemical bonds within the sucrose molecule. It can be stored indefinitely in this form.

Animals, unlike plants, cannot store the sun's energy directly and so must gain it second-hand by using plants as food. Carnivorous animals and man take this process a stage further and also use other animals as food. In this way, chemical compounds which have been photosynthesized and stored in plants are eaten by man and animals and the stored energy made available. For example, the energy that is stored within the sucrose molecule when it is synthesized by sugar-beet is liberated when sucrose reverts to carbon dioxide and water. This breakdown of sucrose into simpler units is brought about in the body by digestion and oxidation, but the overall reaction is simply the reverse of that represented above, namely:

$$\underset{\text{Sucrose}}{\mathrm{C_{12}(H_2O)_{11}}} + 12\mathrm{O_2} \rightarrow 12\mathrm{CO_2} + 11\mathrm{H_2O}$$

When sucrose is converted into carbon dioxide and water in this way, the energy stored during synthesis is made available for use by the body, by converting it into short-term storage as ATP, a high-energy phosphate compound, which can release this energy for individual steps in biochemical metabolism. Sucrose may be converted into carbon dioxide and water by burning it in air. The chemical reaction is the same as that represented by the equation above, with exactly the same quantity of heat being liberated as when the oxidation occurs in the body. The difference in the two reactions concerns the speed at which they occur and their efficiency. Oxidation in the body takes place much more slowly than combustion in air as it takes place in a series of steps, thus ensuring a slow, controlled and gradual release of energy to body tissues. The efficiency of combustion within the body is less than that in air because only about two-thirds of the energy of the sucrose becomes available as biological energy, with one-third being 'lost' as heat which helps to maintain body temperature.

Both fat and proteins also contribute in similar oxidations (see Chapter 8).

$$\underset{\text{Fat}}{(\text{—}\mathrm{CH_2}\text{—})_{2n}} + (\mathrm{O_2})_{3n} \rightarrow {}_{3n}\mathrm{CO_2} + {}_{n}\mathrm{H_2O}$$

The oxidation of proteins depends on which amino acids are included. The nitrogen is removed and thus most are oxidized like carbohydrate while some are oxidized like fat.

The body is sometimes likened to a slow-combustion stove and macronutrients are described as fuel. It is clear that oxidation in the body is a most important process for it enables the energy stored in carbohydrates, fats and proteins to be liberated and made available for use by the body in a closely regulated way.

The energy value of food

Energy is usually measured in units called *calories*. A calorie is the amount of heat required to raise the temperature of 1 g of water by 1°C. As this is rather a small unit, energy derived from food may be expressed in units which are 1000-times larger and known as *kilocalories* (kcal). A kilocalorie is the amount of heat required to raise the temperature of 1 kg of water by 1°C. The common abbreviations for kilocalorie is kcal but Calorie, or Cal (with a capital C) is also used to indicate kilocalories in foods.

Another internationally recognized unit of energy is the *joule* (J), but like the calorie this is an

inconveniently small unit with which to express the energy value of food so that the *kilojoule* (kJ), which is 1000-times larger than the joule, is usually used. Sometimes an even larger unit, the *megajoule* (MJ), is used. A megajoule is 1000-times larger than a kilojoule.

The relationship between these units may be expressed as follows:

$$1\,\text{kcal} = 4.19 \times 10^{3}\,\text{J} = 4.19\,\text{kJ} = 4.19 \times 10^{-3}\,\text{MJ}$$

An average adult usually needs about 1800–2500 kcal/day, which is about 8–10 MJ/day.

In the remainder of this chapter both types of unit are given to illustrate their relation to each other. Elsewhere, however, kilojoules (and megajoules) are used.

In order to compare the energy of different foods it is simplest to determine the amount of energy produced, calculated as heat, when 1 g of the substance is completely oxidized by igniting it in a small chamber filled with oxygen under pressure. The result obtained represents the heat of combustion of food which is usually expressed as kcal or kJ/g. If the calorie value of sucrose is expressed in this way, it is found to be 3.95 kcal/g. This means that when 1 g sucrose is completely oxidized the heat produced is sufficient to raise the temperature of 1000 g of water by 3.95°C. The average values of the heats of combustion of the energy-providing nutrients are shown in Table 1.1.

In order to express the energy value of nutrients in terms of the energy actually made available to the body it is necessary to calculate the available energy values. Such values are always lower than heats of combustion because of losses within the body. A small loss results from incomplete absorption from the intestine; such loss is suffered by carbohydrate, fat and protein, and with protein there is an additional loss because protein, unlike carbohydrate and fat, is incompletely oxidized in the body. In addition a correction may need to be made for non-starch polysaccharides (NSP, see p. 96), previously called dietary fibre. The magnitude of these energy losses may be appreciated from Table 1.1. There is some variation and uncertainty about nutrient availability; the ones quoted may be taken as being sufficiently reliable for most purposes, but in special conditions these may be different. With malabsorptive diarrhoea availability is obviously low, and varies between nutrients. There may, for example, be selective fat malabsorption (steatorrhoea) with liver or pancreatic disease. Mild malabsorption may cause no symptoms.

Although the available energy values given in Table 1.1 are approximate values which can be used to calculate the energy value of any given diet, the available energy value of any food can be found using the average figures, provided that its composition in terms of carbohydrates, fats and proteins is known. The energy value of summer milk, for example, can be calculated from its analysis, as shown in Table 1.2. By similar calculations the available energy value of other foods may be estimated; some average values are given in Table 1.3. This table shows that foods, such as butter and margarine, which contain a high proportion of fat have the highest energy values. Foods rich in carbohydrates, containing a high proportion of sugar (jam) or starch (bread and potatoes), are less concentrated sources of energy. Despite this, such foods supply a considerable proportion of the energy in an average British diet. Indeed, cereal foods contribute no less than one-third of our total energy intake, which is a greater proportion than that supplied by any other class of foodstuff. In many other countries, starchy foods, often in the form of rice, supply an even greater proportion of the total energy content of the diet. As a general rule, the proportion of fat has increased in 'advanced' Western market economies.

Table 1.1 Average energy value of nutrients (per gram)

	Heat of combustion		Available energy value	
Nutrient	(kcal)	(kJ)	(kcal)	(kJ)
Carbohydrate	*4.1*	*17*	*3.75*	*16*
Fat	*9.4*	*39*	*9.00*	*37*
Protein	*5.7*	*24*	*4.00*	*17*

Table 1.2 The energy value of summer milk

Nutrient	Amount in 100 g milk (g)	(kcal/g)	(kJ/g)	Energy/100 g milk (kcal)	(kJ)
Carbohydrate	*4.1*	*3.75*	*16*	*15.4*	*65.6*
Fat	*4.0*	*9.00*	*37*	*36.0*	*148.0*
Protein	*3.4*	*4.00*	*17*	*13.6*	*57.8*
Total energy provided by 100 g of summer milk				*65.0*	*271.4*

Reference: Food Standards Agency (2002). *McCance and Widdowson's The Composition of Foods*, 6th summary edition. Cambridge: Royal Society of Chemistry.

Table 1.3 Typical energy values of some foods with nutrients as percentage of energy

Food	Per 100 g (kcal)	(kJ)	As percentage of energy Fat	Carbohydrate	Protein
Apples	*47*	*199*	*2.0*	*94.0*	*3.5*
Tomatoes	*17*	*73*	*16.0*	*68.0*	*16.5*
Lettuce	*14*	*59*	*32.0*	*45.0*	*23.0*
Cabbage (boiled)	*16*	*67*	*22.5*	*51.5*	*25.0*
Dates	*270*	*1151*	*0.7*	*94.5*	*4.8*
Bread (white)	*219*	*931*	*6.5*	*79.0*	*14.5*
Potatoes (old)	*74*	*306*	*1.3*	*88.5*	*10.0*
Pasta (boiled)	*159*	*677*	*8.5*	*75.0*	*16.5*
Rice (white)	*138*	*587*	*8.5*	*84.0*	*7.5*
Beef (stewing)	*203*	*852*	*42.5*	*0*	*57.5*
Haddock (steamed)	*89*	*378*	*6.0*	*0*	*94.0*
Chicken (roasted)	*177*	*742*	*38.0*	*0*	*62.0*
Eggs (boiled)	*147*	*612*	*66.0*	*Tr*	*34.0*
Milk (summer)	*65*	*270*	*55.4*	*23.6*	*21.0*
Cheese (cheddar)	*416*	*1725*	*75.5*	*0.1*	*24.4*
Yogurt (plain)	*79*	*333*	*34.2*	*37.0*	*28.8*
Jam (fruit)	*261*	*1114*	*0*	*99.1*	*0.9*
Sugar	*394*	*1680*	*0*	*99.9*	*Tr*
Chocolate	*520*	*2177*	*53.1*	*41.0*	*5.9*
Butter	*744*	*3059*	*99.4*	*0.3*	*0.3*
Margarine (polyunsaturated)	*746*	*3067*	*99.9*	*0.1*	*Tr*
Fat spread (60%) (polyunsaturated)	*553*	*2274*	*99.0*	*0.9*	*0.1*
Sunflower oil	*899*	*3696*	*100.0*	*0.0*	*Tr*

Tr, trace.
Reference: Food Standards Agency (2002). *McCance and Widdowson's The Composition of Foods*, 6th summary edition. Cambridge: Royal Society of Chemistry.

THE USE OF ENERGY BY THE BODY

As we have already noted, energy is produced in the body from food by a series of precisely controlled steps. Each step results in the release of a small amount of energy which is used in the promotion of bodily functions and may finally produce heat. Without attempting at this stage any chemical explanation of the nature of the steps in the oxidation process, it is possible to gain a simple picture of how energy is used by the body.

Energy is required in the body for *basal metabolism*, which includes all the normal processes of cell respiration, maintenance and repair in the resting status, for *thermogenesis* or heat production, for growth and for physical activity. A proportion of food energy is also used for *diet-induced thermogenesis* to digest and process (store) the nutrients after each meal. This amount is more for protein and carbohydrate than for fat.

Basal metabolism

The term metabolism refers to the sum of all the chemical reactions going on in the body, and the energy needed to sustain the body at complete rest is known as the energy of basal metabolism or the basal metabolic rate (BMR).

The body requires a constant supply of energy to maintain its internal processes even when resting. Even during sleep, when the body is apparently at rest, energy is needed to ensure that essential internal processes continue. For example, energy must be supplied to maintain the powerful pumping action of the heart, the continual expansion and contraction of the lungs and the temperature of the blood. It is needed to maintain the ceaseless chemical activity of the millions of body cells and the tone of muscles. Living muscle must constantly be ready to contract in response to stimuli transmitted to it by nerves. Such a degree of readiness can only be achieved if energy is continually supplied to keep the muscles in a state of mild tension. Muscle tension decreases during sleep but does not become zero, so that a certain amount of energy, which ultimately appears as heat, is necessary to maintain it. The BMR is mainly determined by body weight and composition, which vary with both age (older people tend to have less muscle and more body fat, so relatively lower BMR) and sex (women tend to have higher proportion of body fat, so relatively lower BMR).

Table 1.4 gives average BMR values for men and women of different ages and body weights. It will be noted that the BMR of men is greater per kilogram of body weight than that of women of the same weight. This is because, for a given body weight, women's bodies contain more fat than those of men and fat contributes little to BMR.

Basal metabolic rate also varies with age. As age increases, BMR (per unit weight) falls; this decrease is rather greater for men than for women. Climate also affects BMR, its value being increased by 5–10 per cent in very cold and very hot climates. We are most comfortable, and BMR is lowest, between 20 and 28°C with light clothing. The thyroid gland regulates cellular metabolism throughout the body.

Table 1.4 Basal metabolic rate (BMR) values

	Males		Females	
Age (years)	Weight (kg)	BMR (MJ/day)	Weight (kg)	BMR (MJ/day)
10–17	*30*	*5.0*	*30*	*4.6*
	65	*7.6*	*60*	*6.3*
18–29	*60*	*6.7*	*45*	*4.8*
	80	*7.9*	*70*	*6.4*
30–59	*65*	*6.8*	*50*	*5.2*
	85	*7.7*	*70*	*5.9*

Reference: Department of Health (1991). *Dietary Reference Values for food Energy and Nutrients for the United Kingdom. Report on Health and Social Subjects No. 41.* London: HMSO.

Excess thyroid activity increases BMR. If thyroid function is defective, BMR declines. Many other hormones affect metabolic rate including insulin and adrenaline.

Growth

During the 9 months of pregnancy it is calculated that some 70 000 kcal (293 MJ) (DOH 1991, p. 30) of energy are required to produce the baby, increase the size of the placenta and reproductive organs, allow for the energy (increased BMR) needed for the newly formed baby tissues and create additional stores of fat in the mother which will be used during lactation. Once the baby has been born, lactation requires around 600 kcal (2.5 MJ) per day (Garrow *et al*. 2000).

Newly born infants grow at a remarkable rate and in the first 3 months of life 23 per cent of food energy is required for growth. This figure falls to 6 per cent by the time the infant is 1 year old and to 2 per cent by the fifth year. In general terms it has been estimated that the formation of 1 g of new tissue requires 20 kJ of food energy.

Physical activity

Energy is needed to enable the body to perform external work. Physical activity requires a supply of energy additional to that needed to maintain muscle tone and other internal processes. The simplest physical act, such as standing up, involves the use of many muscles, and the greater the degree of physical activity in daily life the greater is the energy requirement of the muscles. It is useful, therefore, to relate the degree of physical activity to the energy that must be supplied by the diet.

The problem of equating physical activity with energy requirement is complicated by the fact that the body is unable to convert energy that is supplied by food completely into mechanical work. The efficiency of conversion by the body, considered as a machine, is of the order of 15–20 per cent. If the higher value is taken it means that 100 units of energy supplied by food enable the body to perform physical work, for example, running, equivalent to 20 units. The other 80 units appear as heat and account for the fact that heat is lost from the body surface at an increased rate when physical work is done. However, this total energy cost and thus dietary need is 100 units.

Overweight and obese people need more energy for movement, in proportion to their extra weight.

ENERGY REQUIREMENTS

The energy requirement of an individual is the same as energy expenditure, unless there is some growth or weight loss. The *estimated average requirement* for energy by a group of people may be defined using the concept of physical activity level (PAL). This is the ratio of overall daily energy expenditure to BMR. Daily energy expenditure may be calculated by adding together energy expenditure on an hour-by-hour basis at work, in non-work activities and while sleeping.

The values of PAL in different activities are shown in Table 1.5. Different occupations can be grouped

Table 1.5 Calculated physical activity level (PAL) of adults

Non-occupational activity	Occupational activity					
	Light		Moderate		Moderate/heavy	
	Male	Female	Male	Female	Male	Female
Non-active	*1.4*	*1.4*	*1.6*	*1.5*	*1.7*	*1.5*
Moderately active	*1.5*	*1.5*	*1.7*	*1.6*	*1.8*	*1.6*
Very active	*1.6*	*1.6*	*1.8*	*1.7*	*1.9*	*1.7*

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to indicate approximate PAL figures for estimated average 24 hour energy expenditure is as follows:

1 *Light.* Includes professional and technical workers, administrative and managerial, sales representatives, clerical workers,
2 *Moderate.* Includes sales workers, domestic helpers, transport workers, light construction workers, e.g. joiners,
3 *Moderate/heavy.* Includes labourers, agricultural and fishing and forestry workers, heavy construction workers, e.g. bricklayers.

In general terms, most population groups in the UK may be assumed to have light occupations and non-active, non-work activities and, consequently, have a PAL value of 1.4.

The EAR values shown in Table 1.6 are obtained by multiplying the appropriate PAL value by BMR, values of which are shown in Table 1.4.

For people over 60 years of age a standard PAL value of 1.5 is used. The EAR values for men and women aged over 60 years decrease with increasing age, although precise information for the energy requirements of the elderly is lacking. It is estimated that for men and women aged over 75 years the EAR values are 8.8 and 7.6 MJ/day respectively.

For young children and babies EAR values are calculated by interpolating from values calculated from data for older children.

Table 1.6 Estimated average requirements (EAR) for energy (MJ/day)

	Physical activity level (PAL)				
Weight (kg)	**1.4**	**1.5**	**1.6**	**1.8**	**2.0**
Males 10–18 years					
30	*7.0*	*7.5*	*8.0*	*9.0*	*9.9*
45	*8.5*	*9.1*	*9.7*	*11.0*	*12.2*
60	*10.1*	*10.8*	*11.5*	*12.9*	*14.4*
Males 19–29 years					
60	*9.3*	*10.0*	*10.7*	*12.0*	*13.4*
70	*10.2*	*11.0*	*11.7*	*13.2*	*14.6*
80	*11.1*	*11.9*	*12.7*	*14.3*	*15.9*
Males 30–59 years					
65	*9.5*	*10.2*	*10.8*	*12.2*	*13.5*
75	*10.2*	*10.9*	*11.6*	*13.1*	*14.5*
85	*10.8*	*11.6*	*12.4*	*13.9*	*15.5*
Females 10–18 years					
30	*6.4*	*6.9*	*7.3*	*8.2*	*9.2*
45	*7.6*	*8.1*	*8.7*	*9.8*	*10.8*
60	*8.8*	*9.4*	*10.0*	*11.3*	*12.5*
Females 18–29 years					
45	*6.8*	*7.2*	*7.7*	*8.7*	*9.7*
60	*8.1*	*8.7*	*9.2*	*10.4*	*11.5*
70	*8.9*	*9.6*	*10.2*	*11.5*	*12.8*
Females 30–59 years					
50	*7.3*	*7.9*	*8.4*	*9.4*	*10.5*
60	*7.8*	*8.4*	*8.9*	*10.0*	*11.2*
70	*8.3*	*8.9*	*9.5*	*10.7*	*11.8*

Reference: Department of Health (1991). *Dietary Reference Values for food Energy and Nutrients for the United Kingdom. Report on Health and Social Subjects No. 41.* London: HMSO. Crown copyright material is reproduced with the permission of the Controller of HMSO and the Queen's Printer for Scotland.

Key points

Definitions

- Nutritional science
  - What people eat and absorb
  - What people are
  - How these effect what people (can) do
- Food science: what is in food
- Food technology: optimises quality and/or profitability of foods

Chapter summary

Foods provide a variety of nutrients in a matrix form. All foods and most nutrients contribute to the energy supply, as part of a chain which harnesses energy (calories) from the sun and presents it as a form which can contribute to metabolism, growth and physical activity. Amongst the macronutrients which supply energy, the richest source is fat (9 kcal/g) followed by protein (4) and carbohydrate (3.75).

FURTHER READING

DEPARTMENT OF HEALTH (1991). *Dietary Reference Values for Food Energy and Nutrients for the United Kingdom. Report on Health and Social Subjects No. 41*. London: HMSO.

EUROPEAN PARLIAMENT (2001). Directive 2001/83/EC of the European Parliament on the Community code relating to medicinal products for human use. *Official Journal* L311 28.11 2001, p. 71.

FOOD STANDARDS AGENCY (2002). *McCance and Widdowson's The Composition of Foods*, 6th summary edition. Cambridge: Royal Society of Chemistry. ftp://ftp.fao.org/codex/manual/Manual12ce.pdf

GARROW JS, JAMES WPT, RALPH A (2000). *Human Nutrition and Dietetics*, 10th edn. London: Churchill Livingstone.

2

Enzymes and digestion

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The human body is composed of some hundred-thousand million cells, each of which is a functional unit, enclosed within its cell membrane. These cells are grouped together in the body to form tissues with specialized functions. Thus, some cells comprise connective tissue and bind together the various organs of the body, others are concerned with muscular and nervous tissue, while others form the skeletal framework of bone that contributes strength and rigidity to the body. Most organs contain several functional cell types.

Individual cells are so tiny that their internal structure can only be observed when magnified many hundreds or thousands of times with the help of an electron microscope. Within the cell there are a number of different types of very much smaller 'subcellular organelles'. These have specialized functions, and their size, structure and number vary widely according to demands, or to regulation by local nutrient supply, and instructions delivered by nerves or hormones to the cell.

The complex activities needed to sustain life in the human body take place within the body's cells. The activity of a cell is often likened to that of a chemical factory in which a great variety of raw materials are processed and converted into finished products. In a single cell many different raw materials are required, though they are largely composed of only four elements: carbon, hydrogen, oxygen and nitrogen. The processing stage, which is concerned with the conversion of these simple raw materials into the more complex substances required to carry out the many functions of the cell, involves thousands of different reactions. Each of these reactions comprises many steps which must be carried out in a definite sequence with the result that the chemical operations of a cell are much more complicated, and need much greater integration, than those of a chemical factory. They must also be capable of adaptation to enormous variations in conditions and fluctuating nutrient supply.

In order to sustain life, the cell's activities must be controlled and organized into a self-regulating and self-renewing pattern. But how can such control be achieved, and how is it that although almost all human cells are built according to the same basic pattern, they are able to perform a multitude of different functions? The answer to these questions is to be found in the existence of a group of crucially important protein substances called enzymes.

Enzymes control all the chemical changes (that is, the metabolism), which occur in living cells. They regulate the building up (anabolic) reactions that result in the formation of complex substances such as proteins from single building units. They also regulate the breaking-down (catabolic) reactions that result in release of energy. Enzymes can activate or catalyse chemical reactions or inhibit them. Enzymes often increase the cycling or turnover of substances in cells (i.e. stimulate both synthesis and breakdown of compounds). This allows processes to be more rapidly regulated (in terms of direction and speed of reaction) by other factors. Anabolic and catabolic processes involve very many steps, and each step is

controlled by its own enzyme. This control must be carefully regulated so that the life of the cell continues smoothly at all times, with the whole metabolic process being kept carefully balanced.

ENZYMES

How different cells perform different functions can be explained in terms of the enzymes that are present. Some 1000 different enzymes have been recognized in the body, but in any one cell only a selection are present. Even so, most cells contain about 200 different enzymes, each of which is responsible for controlling a particular step. The complement of enzymes present in a cell automatically selects and controls those reactions which are to proceed. Since enzymes are proteins, their presence in cells in turn depends on the DNA of the cell, including the DNA sequence which for the synthesis of each enzyme and for its own storage and metabolism.

The chemical nature of enzymes

One of the most widely known sources of enzymes is yeast, which is one of the simplest possible types of living organism. This is how the name enzyme arose, for it means literally 'in yeast'. The fermentation of sugar in grape juice by yeast and the leavening effect of yeast in making bread have been used for many centuries. These are actions of enzymes.

A long time elapsed between the discovery of the first known enzyme in yeast and the isolation of an enzyme in the pure state. For many years it was believed that enzymes were living organisms. This idea was only shown to be false at the end of the last century when the German chemist Buchner extracted a cell-free liquid from yeast cells that had a similar enzyme activity to the original living cells. So, although enzymes are made by living cells, they themselves are not living.

All enzymes are proteins, the structure of which is described in Chapter 10. The properties of proteins – their ability to change their shape, their sensitivity to changes of conditions of temperature and acidity, their capacity to oppose changes of acidity that would upset the smooth working of the cell – make them peculiarly suited to control cell metabolism. A feature of all enzymes is that their tertiary structure includes a site that 'recognizes' and can bind temporarily to immobilize its substrate.

Classification of enzymes

The substance upon which an enzyme acts is called the *substrate*, and enzymes are usually named after this substance. Thus, the enzyme that acts on (breaks down) urea is called urease and that which acts on maltose is called maltase. It is a general rule that enzymes are named after the substrate upon which they act and given the suffix *-ase* (from Latin). In common with most general rules, however, there are notable exceptions, mainly those enzymes which were named before the rule gained general acceptance. Some of these, such as pepsin and trypsin, will be encountered later.

Enzymes may be classified in a number of ways, but one of the most useful is to group them according to the type of reaction which they control. The five main groups of enzyme are shown in Table 2.1. Of these, the first two are the most important in connection with what follows. Hydrolases control the hydrolysis of the substrate, that is its reaction with water and, as we shall see later in the chapter, this type of enzyme is of paramount importance in digestion. Oxidases control the oxidation of the substrate, and this usually takes the form of removal of hydrogen as indicated in the equation shown in Table 2.1. There is often more than one enzyme which carries out a particular function – very similar 'iso-enzymes' may be produced in different tissues – each with its own gene and separate

Table 2.1 Classification of enzymes

Name	Reaction catalysed	General equation
Hydrolases	*Hydrolysis*	$AB + H_2O \rightarrow AOH + BH$
Oxidases	*Oxidation*	$ABH_2 \rightarrow AB + 2H$
Isomerases	*Intramolecular rearrangement*	$ABC \rightarrow ACB$
Transferases	*Transfer of a group*	$AB + C \rightarrow A + BC$
Synthetases	*Addition of one molecule to another*	$A + B \rightarrow AB$

system for regulation. A very common feature of enzyme function is that activation of an enzyme, or the expression of the gene, are often inhibited by the product of the reaction catalysed. This prevents wastage of energy on unnecessary metabolism, and prevents accumulation.

Catalytic action of enzymes

Enzymes are organic catalysts; they operate by speeding up a chemical process while remaining unchanged at the end of the reaction. In many respects their action is similar to that of the more familiar inorganic catalysts such as are often used in manufacturing processes. In the manufacture of margarine, vegetable oils are converted into solid fats by chemical reaction with hydrogen. In the absence of a catalyst the conversion of the oils into fats is very slow indeed, but the addition of small quantities of finely divided nickel produces a remarkable increase in the rate of the reaction; moreover, the nickel catalyst may be used time after time, as it is not used up in the process.

It is remarkable that only one part of nickel is needed to catalyse the conversion of several-thousand parts of oil into fat, but this achievement appears quite insignificant when compared with the startling catalytic power of enzymes. One of the enzymes concerned with the breakdown of starch during digestion is amylase, produced by the pancreas. Only one part of amylase is needed to effect the conversion of four million parts of starch into the sugar maltose. Where the efficiency of man-made catalysts is measured in thousands, that of nature's catalysts is measured in millions.

How do enzymes work? We can best approach this by considering first how an ordinary non-catalytic reaction proceeds. Suppose a reaction involves the conversion of reacting substances represented by A into products represented by B. The reaction will not start until A has received a 'push' in the form of energy, often supplied in the form of heat. The reason for this can be appreciated from Fig. 2.1.

Before A can react to form B it must surmount the energy hump shown by moving along path (i), and this requires an amount of energy DG* (uncatalysed). When A has absorbed energy DG* (uncatalysed), known as the *activation energy*, it is in an activated state and can decompose to form B.

This process can be likened to that of transferring a ball from one side of a hill to the other. If Fig. 2.1 represents a hill, the problem is that of transferring a ball from X to Y. If the only path lies over the summit of the hill, then it is necessary to push the ball up the hill – that is, to work on it by supplying energy – until it reaches the top. Once there, it will run down the other side to Y of its own accord. The ball may now be at a lower level than it was at its starting point, as is the case in Fig. 2.1. This means that an amount of energy DG* has been released, though this could not have been achieved without first pushing the ball to the top of the hill, which involved supplying it with energy DG* (uncatalysed).

In the cells of the human body, activation energy cannot be supplied in normal ways, such as heat, because this would damage the cells. The function

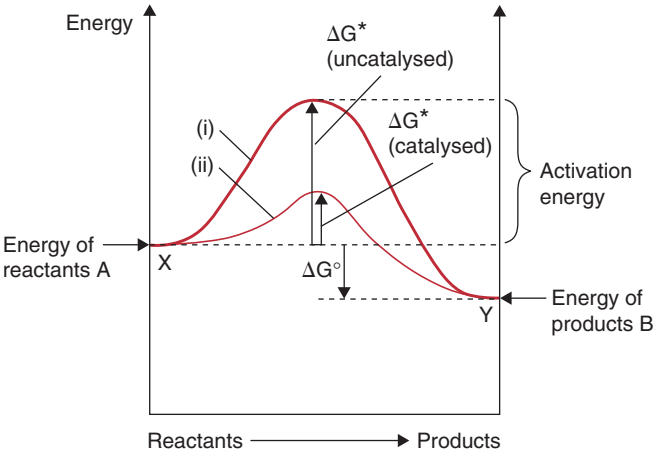


Figure 2.1 *Reaction paths: (i) non-catalytic path; (ii) catalytic path*

of enzymes is to enable the reaction to proceed at a much lower activation energy than would otherwise be possible. In terms of Fig. 2.1, we must replace the reaction path (i) over the summit of the hill by one at a lower level such as (ii) involving a lower activation energy DG* (catalysed).

Enzymes catalyse reactions by replacing a single-step of a high-energy mechanism with a two- or multi-stage process, each step of which involves a low activation energy. If the enzyme catalyst is represented as E and the substrate as A we have:

$$A + E \rightleftharpoons AE$$
$$AE \rightleftharpoons B + E$$

Overall reaction: $A \rightleftharpoons B$

Within each cell is its *nucleus*, which mainly contains genetic material (chromosomes) and this is surrounded by a watery fluid called *cytoplasm*, which contain water-soluble enzymes. The cytoplasm contains a network of membrane-like material, the *endoplasmic reticulum*, which is studded with small dark bodies known as *ribosomes*. The cytoplasm also contains a number of bodies, among which are the egg-shaped *mitochondria* and the smaller *lysosomes*. These bodies contain enzymes which are lipid-soluble within their membranes. Ribosomes are responsible for translating the DNA code in chromosomes by assembling amino acids in the correct order to make proteins and enzymes. Mitochondria house the enzymes for oxidation (combustion) of nutrients to generate chemical energy (as ATP). Lysosomes include the enzymes which release enzymes to attack foreign material and infecting organisms.

Enzymically catalysed reactions proceed by way of a temporary enzyme–substrate complex represented by AE. If both stages require little energy the reaction path is as represented by Fig. 2.1 (ii) and the reaction will be a rapid and near spontaneous one with the enzyme E being regenerated. Thus, we have a simple picture of how enzymes act as catalysts.

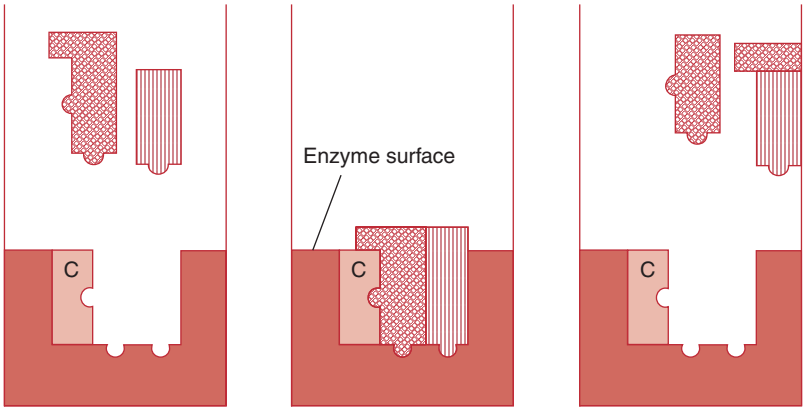
It should be noted that although enzymes speed up reactions, and direct substrates towards one specific reaction when others are possible, they cannot turn impossible reactions into possible ones. Neither can they affect the equilibrium position of a reversible reaction; this means that the *amount* of product in a reaction is the same whether an enzyme is involved or not. The presence of the enzyme merely reduces the time taken to reach the equilibrium position. In the absence of the enzyme the reaction may be so slow that, for all practical purposes, it does not proceed at all. In a cell, thousands of different reactions are possible but the function of the enzymes present is to speed up particular ones, so that some reactions proceed rapidly while others proceed at a relatively insignificant rate. In this way, cell metabolism is controlled and directed so that different cells are able to fulfil different functions.

Selectivity of enzymes

Enzymes are usually highly selective in which reaction they catalyse. Frequently one enzyme will catalyse only one cell reaction. It is this characteristic which allows them to preserve order in living cells. Thus, although many other reactions may occur in a cell, the rate at which they proceed is insignificant compared with that of the catalysed reaction.

The selective power of enzymes is sometimes compared with the action of a key in a lock: the enzyme is the lock and only certain molecules can act as the key which exactly fits it. If a reaction between two molecules is catalysed by an enzyme the lock can be imagined as having grooves into which the two molecules fit side by side; this leads to a brief union between the enzyme and the two molecules which are acting as keys, as is shown in stage 2 of Fig. 2.2. The key molecules are thus brought together and converted into an active state which enables them to react with each other. After reaction new molecules are formed, but as shown in stage 3 of the diagram, the enzyme remains unchanged and can catalyse further reaction.

In order to achieve a good fit between lock and key molecules, an enzyme frequently needs the help of another substance to be effective. Three main types of enzyme promotor have been distinguished, namely *coenzymes*, *cofactors* (or activators) and *prosthetic groups* (see p. 149). Coenzymes are smaller than enzyme molecules and are not proteins. They are not permanently bound to the enzyme but may become attached to it during enzyme reaction (Fig. 2.2, stage 1) only to be released later (once stage 3, Fig. 2.2, has been completed). Coenzymes are closely related to vitamins or are the vitamins themselves. One of the functions of the B group of vitamins seems to be to provide the body with suitable



Stage 1
Lock and key molecules before union.
C is the coenzyme or prosthetic group

Stage 2
Union and activation of lock and key molecules

Stage 3
New molecules formed leaving enzyme surface unchanged

Figure 2.2 *The lock and key theory of enzyme reaction*

starting materials from which to make the coenzymes that it needs. The exact function of coenzymes is still only partly understood, but they certainly play an active and vital part in many reactions involving oxidizing enzymes. This is shown by the fact that if a coenzyme needed by an enzyme is absent, the enzyme can exert no catalytic effect. This can be used to measure the status of essential nutrients. For example, thiamine (vitamin B_1) is a coenzyme for the enzyme transketolase. Transketolase activity in blood is a simple laboratory measure of thiamine status.

In some cases it is found that metallic ions, such as magnesium, or non-metallic ions, such as chloride, are required to increase the activity of enzymes. Such substances are known as cofactors (or activators). Prosthetic groups are non-protein groups which are permanently bound to the enzyme.

Sometimes several molecules, which are similar to each other, can approximately fit the grooves of the same lock. In such cases the enzyme does not distinguish between them and acts as a catalyst to them all. In most cases, however, enzymes show great powers of discrimination as the following examples show. The three enzymes, maltase, lactase and sucrase, are present in the small intestine, and during digestion these enzymes catalyse the hydrolysis of the sugars maltose, lactose and sucrose respectively. These three enzymes have considerable specificity, and in the case of lactase, complete specificity, since it will catalyse the hydrolysis of lactose and of no other substance (not even a similar sugar). Maltase and sucrase, however, catalyse the hydrolysis not only of maltose and sucrose but also that of certain other similar sugars.

A further example of enzymes which show a remarkable selectivity are those which catalyse the hydrolysis of proteins. The three enzymes, pepsin, trypsin and chymotrypsin, each select certain links of protein molecules and catalyse hydrolysis only at these links (see p. 148).

Sensitivity of enzymes

Enzymes are very sensitive to effects of temperature and the environment. All enzyme activity is destroyed on boiling because, being proteins, enzymes are denatured (see p. 141) by high temperatures. At low temperatures enzyme activity is greatly slowed down but as the enzymes are not denatured and, because enzyme reactions have a low activation energy, enzymes may retain some catalytic activity even at subzero temperatures. In general, plant enzymes work best at about 25°C and those in warm-blooded animals at about 37–40°C. An increase in temperature usually increases the rate of a chemical reaction, but in the case of an enzyme reaction it may also lead to inactivation of the enzyme.

Figure 2.3 shows the effect of temperature on the rate of catalysis. At 37°C, the initial rate of reaction is

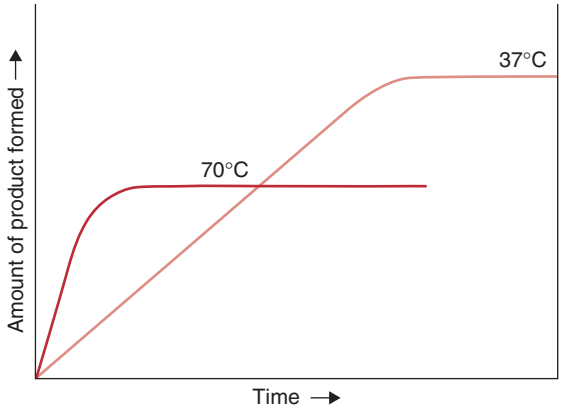


Figure 2.3 *The effect of temperature on the rate of catalysis by an enzyme*

rapid, but after a time the reaction rate slows down and stops, no further product being formed. This may have one of several causes. For example, the reaction may be complete, all the substrate having reacted, or it may be that the products of reaction have made the environment unfavourable for enzyme activity and the enzyme has been deactivated. If the temperature is raised to 70°C, the initial rate of reaction is increased. This is because the greater energy input increases the energy of substrate and enzyme molecules, and these molecules gain the activation energy needed for reaction to take place more rapidly. Although the initial rate of formation of products is rapid, it soon stops because the enzyme is rapidly inactivated at the higher temperature. The net result is that less product is formed at the higher temperature than at the lower. Enzymes catalyse reaction efficiently in man, the temperature being high enough to give rapid formation of products but low enough to avoid inactivation of the enzyme.

Enzyme activity is also dependent upon the acidity or alkalinity (the pH) of the medium in which the enzyme acts. Most enzymes operate most efficiently in an environment that is nearly neutral, and if the medium becomes strongly acid or alkaline the enzyme becomes completely inactivated. Some enzymes, however, can only operate in an acid or alkaline solution. For example, the enzyme pepsin is present in gastric juice and during digestion it catalyses the initial hydrolysis of proteins. It can only act in strongly acid conditions such as are produced by the hydrochloric acid in the stomach. Conversely, the enzyme trypsin which is present in pancreatic juice requires a slightly alkaline medium before it can catalyse protein hydrolysis. When food passes from the stomach into the small intestine the hydrochloric acid is completely neutralized and the medium becomes alkaline. Under these conditions pepsin becomes inactivated and trypsin carries on the digestion of proteins.

CELL METABOLISM

All activities that occur in cells are controlled by enzymes. However, these enzymes are not evenly distributed throughout the cell but are dispersed among the different parts of the cell so that each part has a distinct role in maintaining the life of the cell.

The nucleus of a cell contains all the genes (coded in DNA), which can produce any of the enzymes found in cells. The nucleus also contains a small number of enzymes that, together, specifically control cell (nuclear) growth and division. The surrounding cytoplasm contains water-soluble enzymes that control a variety of anabolic and catabolic processes. The mitochondria are important because they are the powerhouses of the cell and contain a number of oxidases responsible for the manufacture of high-energy materials used for energy production. The important job of protein synthesis in the cell is controlled by enzymes found in the endoplasmic reticulum. Some of the enzymes found only in mitochondria are synthesized from RNA inside mitochondria, rather than from DNA in the nucleus. Mitochondria reproduce in a parallel but separate way to the rest of the cell. Finally, one of the most interesting bodies in the cell is the lysosome, also sometimes called the 'suicide bag'. Lysosomes contain a sufficient variety of hydrolases capable of destroying nearly all the components of the cell. Normally these 'suicide' enzymes are safely contained within the impermeable membrane that encloses the lysosome, but if the cell becomes injured or dies, the enzymes are released and the cell destroys itself and also any infecting agent.

Each cell, and each component of a cell, is surrounded by a membrane. The membrane allows only those raw materials needed by the cell to pass through it, all other substances being prevented from

entering. This selection mechanism ensures that only those substances required for a particular job are available, and it also ensures that only those enzymes required to control this function are allowed through the membrane. Most cell membranes are 'semi-permeable', that is, they allow water, and sometimes small molecules dissolved in water, to pass freely but larger molecules can only pass through if there are specific transport mechanisms.

In later chapters we shall develop the theme of what happens to nutrients in metabolism in rather more detail, but enough has been said in this introductory survey to show that all the activities and functions of the body which constitute life are entirely dependent upon enzymes.

DIGESTION

> 'You are what you eat.'
>
> *(An error! – Anon)*

It is indeed a very odd thing – an extraordinary and remarkable thing – that no matter what we eat, the structure of the body, both flesh and blood, changes very little. There is no obvious similarity between the nature of the food we eat and the nature of our bodies. Yet within a few hours of being eaten, food is transformed into flesh and blood. This transformation is so complete that it cannot be accomplished before food has undergone a drastic breaking-down process known as *digestion*.

Digestion is both physical and chemical: the physical process involves the breakdown of large food particles into smaller ones while the chemical process involves the breakdown of larger molecules into smaller ones. Foodstuffs are mainly complicated, insoluble substances that must be converted into simpler, soluble, more active ones before they can be used by the body. Not all nutrients need digesting, however, as there are some such as water and simple sugars (e.g. glucose) that do not need to be broken down and many vitamins and mineral salts which must not be broken down if they are to be useful. Whether or not nutrients need to be broken down by digestion they cannot be utilized by the body until they have passed into the bloodstream, a process which is known as absorption. The availability of a nutrient, or food component, is the proportion that is actually absorbed after passing through the two (incomplete) processes of digestion and absorption. Once in the bloodstream, nutrients are distributed to all the cells of the body where they sustain the complex processes of metabolism. So you are *not* what you eat – although what you are reflects what you eat.

The role of enzymes in digestion

The chemical processes involved in digestion are brought about by enzymes. The chemical breakdown of food molecules into absorbable components, which in the absence of enzymes would be very slow indeed, is thereby speeded up so that digestion is completed in a matter of hours. Thus, in the space of some 3–4 hours a remarkable change in the nature of the food has occurred. Substances such as starch, which may contain as many as 150 000 atoms in a single molecule, have been converted into molecules containing only 24 atoms (simple sugars such as glucose). The breakdown of protein molecules is almost equally spectacular, as an average protein molecule is split up into about 500 amino acid molecules during digestion. These two examples perhaps make clearer the magnitude of the chemical task performed by the enzymes of the digestive system.

Each stage of digestion involves hydrolysis and is catalysed by a hydrolysing enzyme or hydrolase. The hydrolysis can be represented:

$$AB + H_2O = AOH + BH.$$

The equation shows how water is involved in splitting up a molecule AB into two smaller molecules AOH and BH. In some instances (e.g. sucrose), a single step involving the breakdown of a molecule into two parts is sufficient to produce a smaller soluble molecule that can be absorbed. In other instances (e.g. proteins), a very large number of hydrolytic steps is required before breakdown is complete.

The digestive process involves a fairly small number of different enzymes which catalyse the chemical breakdown of proteins, carbohydrates and fats. The names of the hydrolases that catalyse the hydrolysis of these different nutrients are shown in Table 2.2. Unfortunately, different authorities use different names for these enzymes. There is an

Table 2.2 Hydrolases involved in digestion

Name	Substrate	Product
Amylases	*Starch*	*Maltose*
Maltases	*Maltose*	*Glucose*
Lipases	*Fats*	*Fatty acids and glycerol*
Peptidases	*Proteins*	*Amino acids*

internationally agreed which can be used to classify and identify all enzymes, but the older descriptive terms are still the most widely used. The names given, however, are descriptive of the main changes brought about by hydrolases in digestion. Peptidases can be conveniently subdivided into exopeptidases, which split off amino acids from the ends of protein molecules, and endopeptidases, which attack and split the inside of protein molecules.

We have already noted the high selectivity of some enzymes such as peptidases. Amylases and enzymes which break down sugars show a similar high degree of selectivity. It is therefore evident that a whole series of such enzymes is required to achieve the stepwise breakdown of proteins and carbohydrates. In contrast, lipases are relatively unselective, so that only a few lipases are required to break down fats.

Stages of digestion

The digestive system can be regarded as functioning in a series of tube-like organs which pass through the body from the mouth at one end to the anus at the other, together with associated organs such as pancreas, liver and gall bladder, which produce and release enzymes. The lumen of the gut is thus outside the body. Chewing is important for grading and mixing and also stimulates the flow of salivary juices into the mouth. Saliva contains the first enzymes met by food. For example, if one chews bread it begins to taste sweet. This is because amylase in saliva has catalysed the breakdown of starch in bread into glucose. Food enters the system at the mouth, passes down the oesophagus into the stomach and then through the small intestine and large intestine, being gradually digested and absorbed in the process. Any that remains leaves the body at the other end of the system. In the following text, the stages of digestion are described in a very simple way to provide an overall picture of the process. The chemical details will be filled in later after a discussion of the chemical nature of the nutrients concerned. The main parts of the digestive system are illustrated in Fig. 2.4 and the digestive process is summarized in Fig. 2.5.

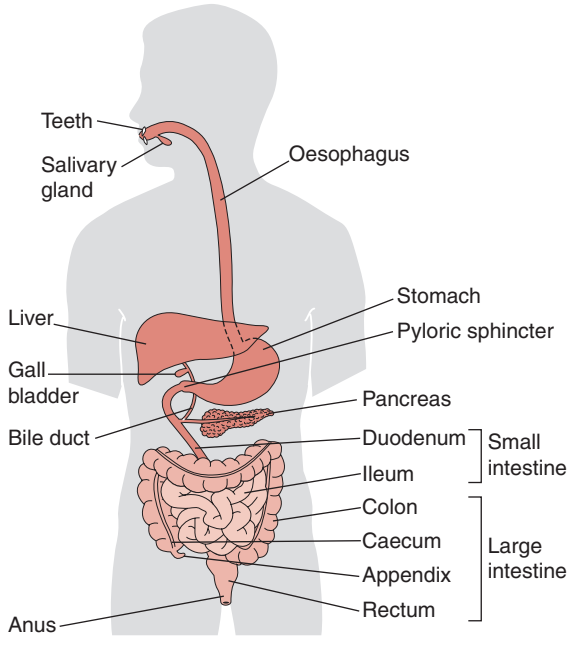


Figure 2.4 *The digestive system*

Digestion in the mouth

When food is chewed, the size of the individual pieces is reduced and saliva is secreted by the salivary glands. The secretion of saliva takes place in response to various sorts of stimuli; the sight of a well-cooked meal, an appetizing smell or even the thought of a good meal may cause the salivary glands to produce saliva. This fluid becomes well mixed with food during mastication, lubricating it and so making it easier to swallow. Saliva is a dilute aqueous solution having a solid content of only about 1 per cent. Its main constituent is a slimy substance called *mucin* which assists lubrication. It also contains the enzyme *salivary amylase*, and various inorganic salts, the most abundant being sodium chloride which furnishes chloride ions that activate the enzyme. The initial hydrolysis of cooked starchy food is catalysed by salivary amylase in the mouth, and this catalytic action is continued as the food moves down the oesophagus and into the stomach. The enzyme soon becomes inactivated in the

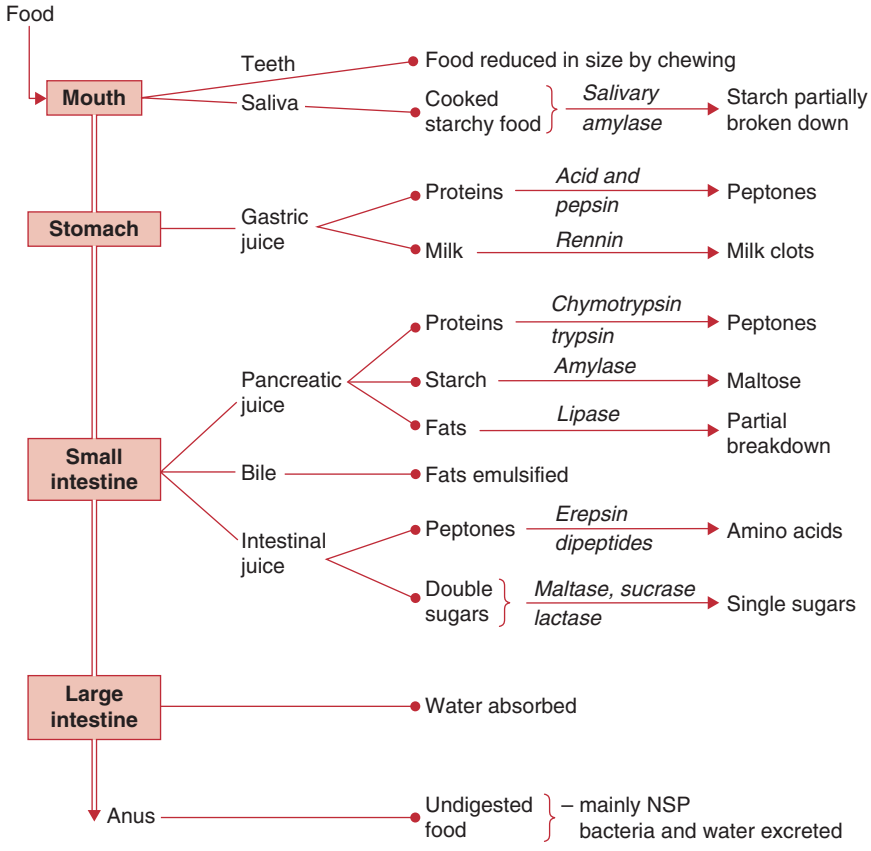


Figure 2.5 *Summary of the digestive process. NSP, non-starch polysaccharide*

stomach, however, because it cannot tolerate a strongly acid environment. In quantitative terms, salivary amylase contributes little to digestion, but does help to make certain starchy foods more palatable by releasing glucose, which sweetens it.

Food is carried down the oesophagus by gentle muscular action called peristalsis. The muscles contract, producing a peristaltic wave and this moves down the oesophagus, carrying the food with it.

Digestion in the stomach

The stomach may be regarded as a reservoir in which food is prepared for the main stage of digestion in the small intestine. This does not mean that no digestion takes place there, however, as cells in the lining of the stomach produce a fluid called gastric juice. The two essential constituents of this dilute aqueous solution are its enzymes and its acid content. The main enzyme is pepsin, secreted as the inactive pepsinogen and becoming activated when it comes into contact with the hydrochloric acid that forms the acid constituent of the gastric juice.

Some 20 minutes after starting to eat a meal, vigorous muscular movements begin in the lower region of the stomach. Muscular contraction produces an inward pressure and this moves down the stomach wall as a peristaltic wave, so moving food through the stomach and causing it to become intimately mixed with the gastric juice. In this way, the acidity of the semi-fluid food mixture called chyme increases, until the endopeptidase pepsin is able to catalyse the conversion of part of the protein into slightly simpler molecules called peptones. The other major enzyme in the gastric juice is rennin, which also acts in an acid medium and brings about the coagulation or clotting of milk. The acidity of the gastric juice also causes some bacteria, which enter with the food, to be killed.

A copious flow of gastric juice is necessary during a meal and its production is stimulated both by

psychological and chemical means. The former is the more important and is governed by involuntary nervous action which may be brought about by the appearance, smell and taste of food. The mere thought of food may be sufficient to stimulate gastric secretion; conversely, the flow of gastric juice may be inhibited by factors such as excitement, depression, anxiety and fear. Certain foodstuffs act as chemical stimulants to secretion. Meat extractives, for example, which are dissolved out of meat when it is put in boiling water, are particularly potent in this respect. Soups and meat dishes in which the extractives have been preserved are therefore valuable aids to digestion in the stomach.

Peristaltic action moves the chyme into the lower region of the stomach which is separated from the upper region of the small intestine, called the duodenum, by the pyloric valve. The valve opens at intervals, so allowing small portions of chyme to leave the stomach. This process continues for about 6 hours after eating a meal until no chyme remains in the stomach.

Digestion in the small intestine

The main stage of digestion occurs during the passage of chyme through the long small intestine. As soon as food enters the duodenum, digestive juices pour forth. There are three sources: the liver secretes bile which is then stored by the gall bladder, and the pancreas secretes pancreatic juice. These two secretions enter the small intestine through a single duct situated a short way down the duodenum; the third secretion is produced in the lining of the small intestine and is called the intestinal juice. They are all produced at the same time and, as they are alkaline, they neutralize the acidity of the chyme. Under these conditions the enzymes of the three secretions are able to exert their catalytic influence.

The pancreatic juice contains enzymes which enable it to help in the digestion of the three main types of nutrient. The endopeptidases trypsin and chymotrypsin, among others, carry on the degradation of proteins begun by pepsin in the stomach; they complete the breakdown of proteins into peptones. Pancreatic amylase is another enzyme present in the pancreatic juice; its capacity for catalysing the hydrolysis of large amounts of starch and converting it into maltose has already been mentioned. Finally, pancreatic lipase brings about the partial hydrolysis of some fat molecules, converting them into simpler substances which can be absorbed.

The bile has no important enzyme action, but contains bile salts that convert fats in food (liquefied by the warmth of the stomach) into a fine emulsion of tiny oil droplets which may then be acted upon by the lipase of the pancreatic juice. If the liver is damaged, a lack of bile allows dietary fats to remain in a separated, liquid, form which escapes lipolysis. Fat malabsorption then occurs with loose greasy stools (steatorrhoea) and weight loss. With steatorrhoea there is a loss from the gut of fat soluble vitamins (A, D, E and K) and other compounds.

The intestinal juice contains a number of enzymes, three of which have already been mentioned, namely maltase, lactase and sucrase, which break down the double sugars maltose, lactose and sucrose respectively into simple sugars that can be absorbed. In addition to these, a group of exopeptidases, called erepsin, continue the breakdown of proteins begun by the endopeptidases pepsin, trypsin and chymotrypsin. The exopeptidases attack the ends of the chain-like peptone molecules until they are broken down into small units called dipeptides containing only two amino acids. Finally, another group of enzymes called dipeptidases break down the dipeptides into free amino acids which can be absorbed.

Apart from these chemical changes, muscular activity continues, so causing the various substances to move slowly down the small intestine.

Absorption in the small intestine

The digestive process is almost complete after the food material has been in the small intestine for some 4 hours in humans (much quicker in small animals). The most complicated of all nutrients, the proteins, have been converted by stages into amino acids; all carbohydrates, except non-starch polysaccharides (NSPs), have been broken down into simple soluble sugars, while fats have been emulsified and partly split into simpler component parts called fatty acids and glycerol. However, before digested nutrients can be used by the body they must pass through the walls of the digestive tube into the blood, a process known as absorption.