

Energy requirements

A moderately active woman requires about 8400 kJ (2000 kcal) of energy intake per day. For an adult male undertaking physical work this increases to about 14,700 kJ (3500 kcal). Energy is provided by lipids, carbohydrates and proteins. Carbohydrates provide the main source of energy but, like proteins, they are already partially oxidized, so do not provide as much energy weight for weight as fats, which are used to store energy. The amount of energy in a dried food can be determined by combustion experiments (see Chapter 5) using a food calorimeter.

In many countries rice is the main source of dietary energy. For example, in Bangladesh 75% of the energy intake of the population comes from rice. Boiled rice has an energy content of about 150 kcal per 100 g, which means that a man undertaking manual labour needs to consume the equivalent of about 2.5 kg of rice each day.

Use of a food calorimeter

1.13 g of rice raises the temperature of 525 g of water by 3.31 °C.
 Energy evolved = $0.525 \times 4.18 \times 3.31 = 7.26$ kJ
 Energy content of rice = $7.26 \times 100/1.13$
 = 642 kJ (154 kcal) per 100 g

Proteins

Proteins are also an essential part of a healthy diet. In addition to being an energy source rice contains about 7–8% protein. Other rich sources of protein include meat, fish, cheese, eggs and nuts.

Proteins have many different functions in the body. They can act as biological catalysts (enzymes) for specific reactions, and act as transporters e.g. hemoglobin in the blood. They can give structure (for example, hair and nails consist almost entirely of polypeptides coiled into proteins called **keratin** and composed of α -helices), and provide a source of energy. Some hormones are proteins or protein-based, for example insulin and FSH (follicle-stimulating hormone), which is responsible for triggering the monthly menstrual cycle in females.

2-amino acids

Proteins are large macromolecules made up of chains of 2-amino acids. About 20 2-amino acids occur naturally. These have the general formula $\text{H}_2\text{NCHRCOOH}$ and are listed in the IB Data Booklet. The structure of amino acids in aqueous solution alters at different pH values. At low pH (acidic medium) the amine group will be protonated. At high pH (alkaline medium) the carboxylic acid group will lose a proton. For each amino acid there is a unique

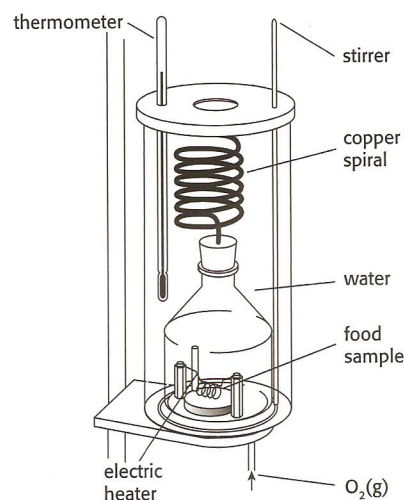


Figure 1 A food calorimeter.

pH value, known as the **isoelectric point**, where the amino acid will exist as the zwitterion (Figure 2).

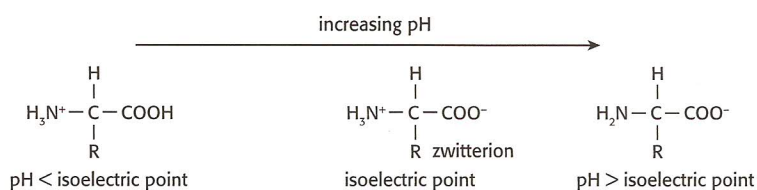


Figure 2 The structure of 2-amino acids at different pH values.

2-amino acids function as good buffers, because they can combine with either protons or hydroxide ions, thus helping to maintain the existing pH of the solution.

Two 2-amino acids can condense together to form a dipeptide with the elimination of water. Two different 2-amino acids can react to form two different dipeptides (Figure 3).

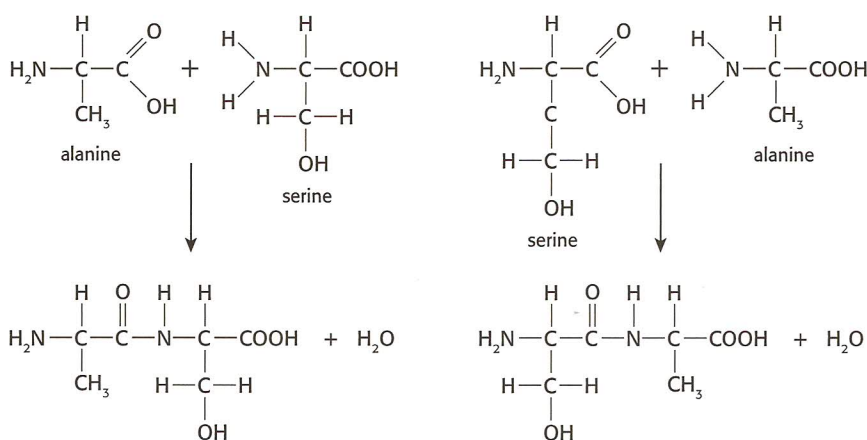


Figure 3 The condensation of alanine and serine to make two different dipeptides.

The link between them, which has the structure $-\overset{\text{O}}{\parallel}{\text{C}}-\overset{\text{H}}{\text{N}}-$, is known as a **peptide bond**. Because dipeptides still contain a reactive functional group on each end they can react further in the presence of enzymes to form long chains of amino acid residues linked by peptide bonds (Figure 4). This is an example of **condensation polymerization**, and the products are known as **polypeptides**.

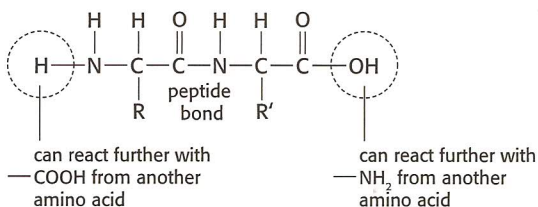


Figure 4 The ability of 2-amino acids to undergo condensation polymerization.

Structure of proteins

Proteins are made up from a fixed number of amino acid residues connected to each other in a unique linear sequence. This sequence, for example NH₂-leu-his-ala- ... -val-ala-ser-COOH, is known



Find the structures of the three amino acids cysteine, phenylalanine and threonine.

- How many tripeptides can be obtained by reacting these three different amino acids together? (Assume that each tripeptide contains the residues from all three amino acids.)
- Give the full structural formula of one of the tripeptides.

as the **primary structure** of proteins. The **secondary structure** describes the way in which the chain of amino acids, often with repeating sequences of amino acids, folds itself because of intramolecular hydrogen bonding. The folding can either be β -helix, in which the protein chain twists in a spiralling manner, rather like a coiled spring, or β -pleated to give a sheet-like structure (Figure 5).

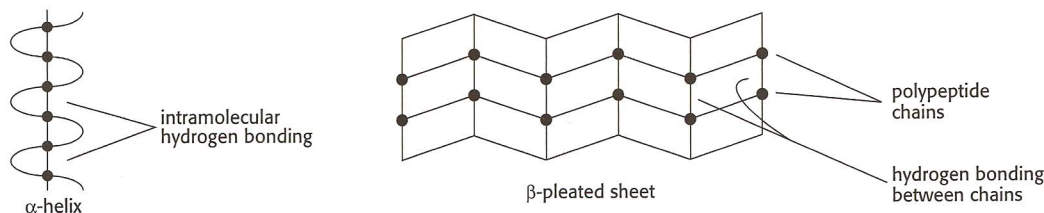


Figure 5 Secondary structure of proteins.

The **tertiary structure** describes the overall folding of the chains by interactions between distant amino acids to give the protein its three-dimensional shape. These interactions may be due to hydrogen bonds, van der Waals' attraction between non-polar side groups, or ionic attractions between polar groups. In addition, two cysteine residues can form **disulfide bridges** when their sulfur atoms undergo enzyme-catalysed oxidation (Figure 6).

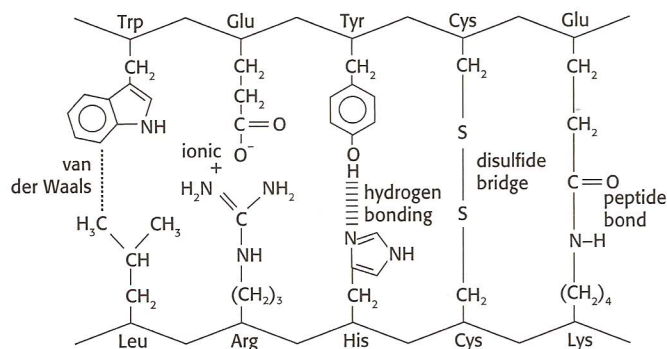


Figure 6 Examples of interactions between side groups on adjacent polypeptide chains.

Separate polypeptide chains can interact together to give a more complex structure: this is known as the **quaternary structure**. Haemoglobin has a quaternary structure that includes four protein chains (two α -chains and two β -chains) grouped together around four haem groups.

Analysis of proteins

To determine the primary structure the protein must first be completely hydrolysed by dilute hydrochloric acid to successively release the amino acids. These can then be identified by chromatography or by electrophoresis. The method for paper chromatography is described in Chapter 14. In order to observe the colourless amino acids the chromatogram is developed by spraying with ninhydrin, an organic dye that colours the amino acids (Figure 7), so that the retention factor, R_f , values of the spots can be determined and compared with known values.

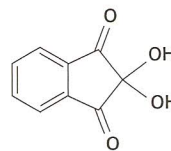


Figure 7 The structure of ninhydrin (triketohydrindane hydrate). Ninhydrin forms coloured compounds by reacting with the amine group of amino acids. It is used in forensic science to detect the residual peptides and proteins left behind in fingerprints.

In PAGE (PolyAcrylamide Gel Electrophoresis) the sample is placed in the centre of a polyacrylamide gel and a potential difference is applied across it. Depending on the pH of the buffer, the different amino acids will move at different rates towards the positive and negative electrodes. At its isoelectric point a particular amino acid will not move, because its charges are balanced (Figure 8). When separation is complete the amino acids can be sprayed with ninhydrin and identified by comparing the distance they have travelled with standard samples or from a comparison of their isoelectric points.

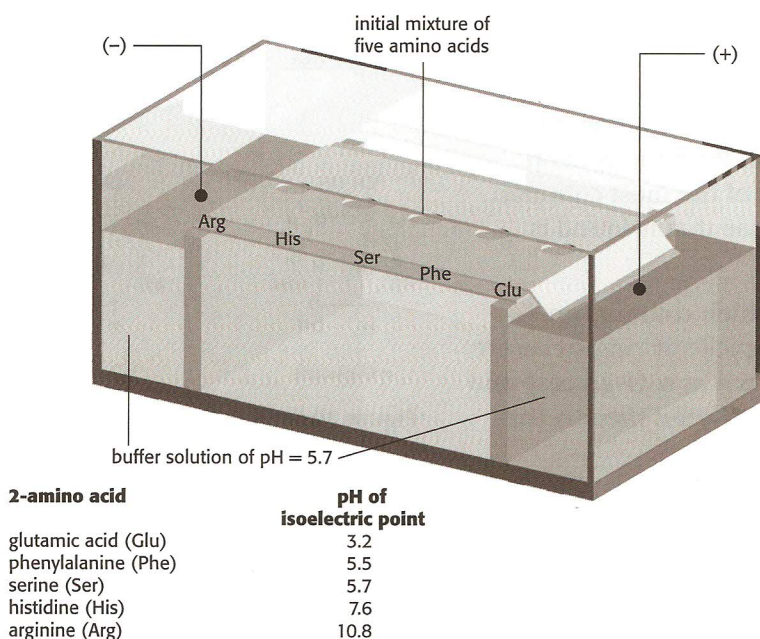
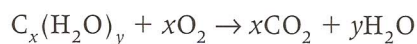


Figure 8 Separation of a mixture of five amino acids by electrophoresis. Serine does not move, because its isoelectric point is the same pH as the buffer. Histidine and arginine contain $-\text{NH}_3^+$ at pH 5.7, so move towards the negative electrode. Glutamic acid and phenylalanine contain $-\text{COO}^-$ at pH 5.7, so move towards the positive electrode.

Carbohydrates

Carbohydrates are produced in plants by photosynthesis. This requires energy provided by sunlight. When taken into the human body this process is reversed, and carbohydrates are a principal source of chemical energy.



Foods such as bread, biscuits, cakes, potatoes, rice and cereals are all high in carbohydrates. The body also uses carbohydrates to store energy. In the livers and skeletal muscles of animals it is stored in the form of **glycogen**—known as animal starch. Carbohydrates are also used as precursors for other important molecules: for example, they are components of nucleic acids and play a key role in the biosynthesis of proteins. Humans also need one other form

of carbohydrates, which they cannot break down. This is cellulose, hemicellulose, lignin and pectin, known collectively as **dietary fibre** or roughage. Dietary fibre is mainly plant material that cannot be hydrolysed by enzymes secreted in the human digestive tract, although it can be digested by microflora in the gut. Roughage is needed to provide good bowel movements, and a lack of dietary fibre can lead to such conditions as diverticulosis, irritable bowel syndrome, constipation, obesity, haemorrhoids, diabetes and bowel cancer.

Monosaccharides

Monosaccharides have the empirical formula CH_2O and contain a carbonyl group ($\text{C}=\text{O}$) and at least two hydroxyl, $-\text{OH}$, groups. They generally have between three and six carbon atoms.

Monosaccharides with the general formula $\text{C}_5\text{H}_{10}\text{O}_5$ are known as **pentoses** (e.g. ribose) and monosaccharides with the general formula $\text{C}_6\text{H}_{12}\text{O}_6$ are known as **hexoses**. One of the most common hexoses is glucose. In nature the form of glucose that is found is known as D-glucose (Figure 9).

As well as having a straight-chain formula, which contains an aldehyde group, D-glucose can also exist in a cyclic or ring structure, which has two separate crystalline forms known as α -D-glucose and β -D-glucose (Figure 10). The only difference between them is that the $-\text{OH}$ group on the first carbon atom is inverted.

Polysaccharides

Sugars can condense together in the presence of appropriate enzymes to form polysaccharides. **Sucrose** is a disaccharide formed from the condensation of α -D-glucose and β -D-fructose (Figure 11).

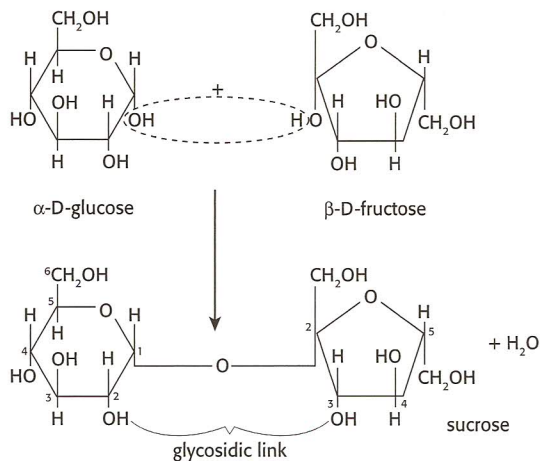


Figure 11 Formation of sucrose by a condensation reaction.

The link between the two sugars is known as a **glycosidic link**. In the case of sucrose the link is between the C-1 atom of glucose in the α configuration and the C-2 atom of fructose. The link is known as an **α -1,2 bond**.

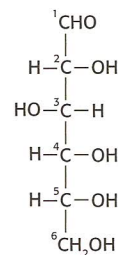


Figure 9 Straight-chain formula of D-glucose.

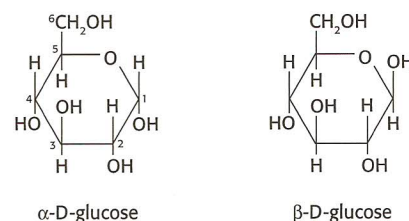


Figure 10 Cyclic (ring) structures of D-glucose.

Lactose is a disaccharide in which the β -D-galactose is linked at the C-1 atom to the C-4 atom of β -D-glucose. This is called a **β -1,4 linkage** (Figure 12).

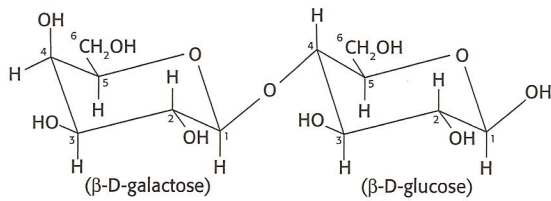


Figure 12 The structure of lactose showing the 1,4 link.

Maltose, another disaccharide, is formed when two glucose molecule condense together, forming an α -1,4 linkage.

One of the most important polysaccharides is **starch**. Starch exists in two forms: **amylose**, which is water soluble, and **amylopectin**, which is insoluble in water. Amylose is a straight-chain polymer of α -D-glucose units with α -1,4 bonds (Figure 13). Amylopectin also consists of α -D-glucose units, but it has a branched structure with both α -1,4 and α -1,6 bonds (Figure 14).

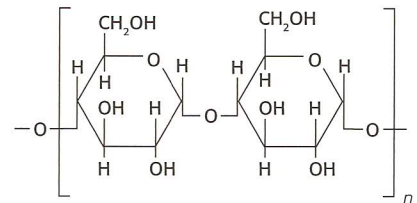


Figure 13 The structure of amylose.

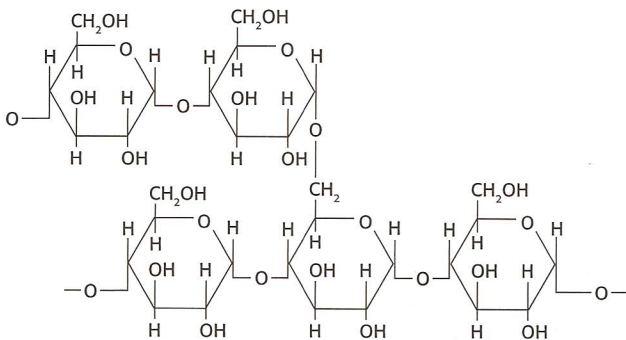


Figure 14 Structure of amylopectin.

Cellulose, a polymer of β -D-glucose, contains β -1,4 linkages (Figure 15). Cellulose, together with lignin, provides the structure to the cell walls of green plants. Most animals, including all mammals, do not have the enzyme cellulase and so are unable to digest cellulose or other dietary fibre polysaccharides.

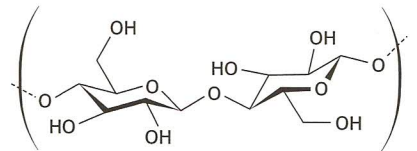


Figure 15 Repeating unit of cellulose showing β -1,4 linkages.

Lipids

Lipids are organic molecules with long hydrocarbon chains that are soluble in non-polar solvents. They are used mainly for energy storage, insulating and protecting vital organs, forming cell membranes and, in some cases, acting as hormones. Three important types of lipids are triglycerides (fats and oils), phospholipids (lecithin), and steroids (cholesterol).

Cholesterol

Cholesterol (Figure 16) has the characteristic four-ring structure possessed by all steroids (Figure 17). It is formed in the liver, and is found in all tissues, the blood, brain and spinal cord. It is transported by lipoproteins. **Low-density lipoproteins** (LDL) are in the order

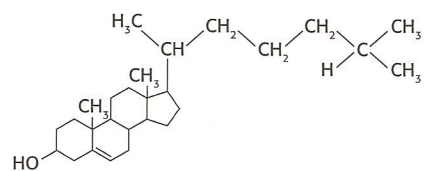


Figure 16 The structure of cholesterol.

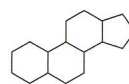


Figure 17 Steroid four-ring "backbone".

of 18–25 nm and transport cholesterol to the arteries, where they can line the walls of the arteries, leading to cardiovascular diseases. The major source of these low-density lipoproteins are saturated fats, and in particular those derived from lauric (C_{12}), myristic (C_{14}) and palmitic (C_{16}) acids. Smaller lipoproteins, in the order of 8–11 nm, known as **high-density lipoproteins** (HDL), can remove the cholesterol from the arteries and transport it back to the liver.

Fats and oils (triglycerides)

Fats and oils are triesters (triglycerides), formed from the condensation reaction of propane-1,2,3-triol (glycerol) with long-chain carboxylic acids (fatty acids) (Figure 18).

Fats are solid triglycerides: examples include butter, lard and tallow. Oils are liquid at room temperature, and include castor oil, olive oil and linseed oil. The essential chemical difference between them is that fats are **saturated** (that is, they do not contain carbon-to-carbon double bonds). Oils contain at least one carbon-to-carbon double bond and are said to be **unsaturated**. Most plant oils contain several carbon-to-carbon double bonds and are known as **polyunsaturated**. In the body, fats and oils are hydrolysed by enzymes, known as **lipases**, to glycerol and fatty acids. These in turn are broken down by a series of redox reactions to produce, ultimately, carbon dioxide, water and energy. Because they are essentially long-chain hydrocarbons with only two oxygen atoms each on the three carboxyl atoms, fats are in a less oxidized form than carbohydrates, so weight for weight produce more energy.

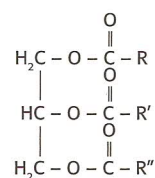


Figure 18 General formula of a fat or oil. R, R' and R'' are long-chain hydrocarbons formed from carboxylic acids, which may be the same or different.

Table 1 Formulas of some fatty acids

Name	Formula	Number of C atoms per molecule	Number of C=C bonds	Melting point / °C
saturated fatty acids				
lauric acid	$\text{CH}_3(\text{CH}_2)_{10}\text{COOH}$	12	0	44.2
myristic acid	$\text{CH}_3(\text{CH}_2)_{12}\text{COOH}$	14	0	54.1
palmitic acid	$\text{CH}_3(\text{CH}_2)_{14}\text{COOH}$	16	0	62.7
stearic acid	$\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$	18	0	69.6
unsaturated fatty acids				
oleic acid	$\text{CH}_3(\text{CH}_2)_7\text{CH}=\text{CH}(\text{CH}_2)_7\text{COOH}$	18	1	10.5
linoleic acid	$\text{CH}_3(\text{CH}_2)_4\text{CH}=\text{CHCH}_2\text{CH}=\text{CH}(\text{CH}_2)_7\text{COOH}$	18	2	-5.0

The body requires two essential unsaturated fatty acids that it is unable to synthesize. These are the ω -6 linoleic acid (Figure 19) and the ω -3 linolenic acid. From these the body is able to synthesize longer and more unsaturated fatty acids. Green leaves are a good source of ω -3 fatty acids, whereas most seeds and vegetable oils are a good source of ω -6 fatty acids.

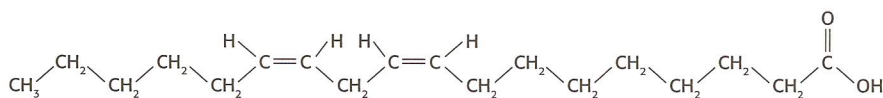


Figure 19 The structure of linoleic acid (*cis,cis*-9,12-octadecadienoic acid).

The double bonds in linoleic acid are on the ninth and twelfth carbon atoms of the acid, but it is known as an omega (ω)-6 fatty acid because the first double bond is on the sixth carbon atom from the end of the hydrocarbon chain (that is, counting from the other end). ω -3 fatty acids have the first double bond on the third carbon atom from the end of the hydrocarbon chain.

When fatty acids are made synthetically by partially hydrogenating other polyunsaturated fatty acids, then the *trans*-isomers may be formed (Figure 20). *Trans*-fatty acids are present in fried foods such as French fries and some margarines. They increase the formation of LDL cholesterol and thus increase the risk of heart disease.

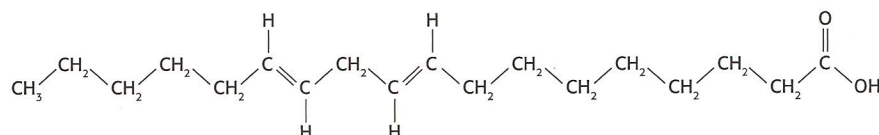


Figure 20 The structure of the *trans,trans*- form of linoleic acid.

The amount of unsaturation in an unsaturated fat or oil can be determined by titrating with iodine solution. One mole of iodine molecules will add quantitatively to 1 mol of carbon-to-carbon double bonds in the fat or oil. As the iodine is added, the purple colour of the iodine will disappear as the addition reaction takes place. The **iodine number** of a fat or oil is the number of grams of iodine that add to 100 g of the fat or oil.

Micro- and macro-nutrients

Good health requires a balanced diet. Micro-nutrients are required only in trace amounts (measured in mg or μg), which make up less than 0.005% of body mass. They include vitamins and minerals (Fe, Cu, Zn, I, Se, Mn, Mo, Cr, Co and B). Their main function is to act as a co-factor with enzymes. Macro-nutrients are required in larger quantities ($> 0.005\%$ body mass). These include carbohydrate (about 60%), protein (20–30%) and lipids (10–20%). They also include some minerals (Na, Mg, K, Ca, P, S and Cl).

Vitamins

Apart from vitamin D the body is not capable of synthesising vitamins, but it cannot function correctly without them, so they must be obtained from the diet. Vitamins can be classified as fat-soluble or water-soluble. The structure of fat-soluble vitamins is characterised by long, non-polar hydrocarbon chains or rings (Figure 21). They include vitamins A, D, E, F and K. They can accumulate in the fatty tissues of the body. The molecules of water-soluble vitamins, such as vitamin C (Figure 22) and the eight B-group vitamins, contain hydrogen attached directly to electronegative oxygen or nitrogen atoms that can hydrogen-bond with water molecules. They do not accumulate in the body, so a regular intake is required.



- 1 Linolenic acid contains 18 carbon atoms. It has three double bonds, all in the *cis* position. Its IUPAC name is *cis,cis,cis*-9,12,15-octadecatrienoic acid. Draw the structure of linolenic acid.
- 2 The iodine number of a fatty acid ($M_r = 278$) is 274. Determine the number of carbon-to-carbon double bonds in the fatty acid.
- 3 Explain why eating large amounts of fatty food and taking little physical exercise may lead to obesity.

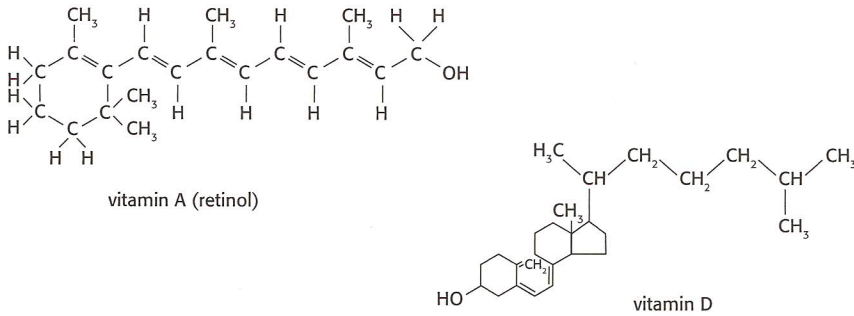


Figure 21 Examples of fat-soluble vitamins.

Table 2 Sources of nutrients and associated deficiency diseases

Nutrient	Some sources	Deficiency disease
iron, Fe	red meat, fish, lentils, beans	anaemia
iodine, I	sea fish, shellfish, (enhanced) salt	goitre
vitamin A, retinol	cod liver oil, green vegetables, fruit	xerophthalmia (night blindness)
vitamin B ₃ , niacin	fish, chicken, brewer's yeast	pellagra
vitamin B ₁ , thiamin	brewer's yeast, oatmeal	beriberi
vitamin C, ascorbic acid	fruit and vegetables	scurvy
vitamin D, calciferol	fish oils, egg yolk and sunlight	rickets
protein	meat, fish, cheese, egg, nuts	marasmus and kwashiorkor

Hormones

Hormones are chemicals produced in endocrine glands and transported to the site of action by the bloodstream. The endocrine glands themselves are controlled mainly by the pituitary gland, which in turn is controlled by the hypothalamus in the brain. Hormones act as chemical messengers, and perform a variety of different functions. Examples of specific hormones include epinephrine (adrenaline), thyroxin, insulin and the sex hormones.

Epinephrine (adrenaline) is produced in the adrenal glands—two small organs located above the kidneys. It is a stimulant closely related to the amphetamine drugs (see Chapter 16). It is released in times of excitement; it causes a rapid dilation of the pupils and airways, and increases heartbeat and the rate of release of glucose into the bloodstream. It is sometimes known as the “fight or flight hormone”.

Thyroxin (Figure 23) is produced in the thyroid gland located in the neck. It is unusual in that it contains iodine. A lack of iodine in the diet can cause the thyroid gland to swell to produce the condition known as goitre (Figure 24). Thyroxin regulates the body's metabolism. Low levels of thyroxin cause hypothyroidism, characterized by lethargy as well as sensitivity to cold and a dry skin. An overactive thyroid gland can cause the opposite effect. This is known as hyperthyroidism, with the symptoms of anxiety, weight loss, intolerance to heat and protruding eyes.

Human **insulin** is a protein containing 51 amino acid residues. It is formed in the pancreas—an organ located at the back of the

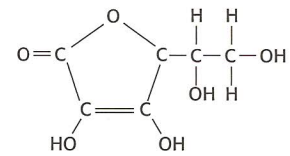


Figure 22 Vitamin C is water-soluble, because the many hydroxyl (–OH) groups in the small molecule can form hydrogen bonds with water.



Consider the problems of malnutrition that occur in your country. Include overnourishment as well as undernourishment. Which of the solutions listed below might be applicable to solve the problems?

- A Providing food rations containing fresh foods rich in vitamins and minerals
- B Adding nutrient supplements
- C Genetic modification of food
- D Adding nutrients directly to foodstuffs
- E Educating the population in healthy eating
- F State subsidies for healthy living
- G Any other solutions

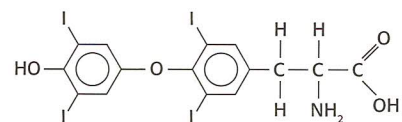


Figure 23 Thyroxin.

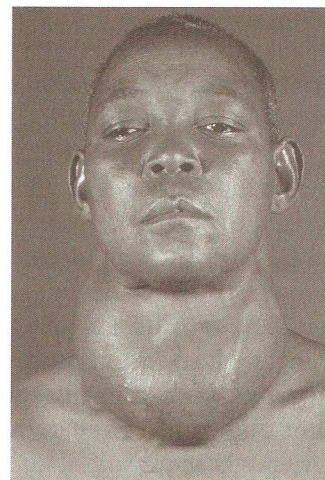


Figure 24 A patient suffering from goitre.

abdomen—and regulates blood sugar levels. In most diabetics the levels of insulin are low or absent, and glucose is not transferred sufficiently from the bloodstream to the tissues. This is known as **hyperglycemia** and results in thirst, weight loss, lethargy, coma and circulation problems. Long-term sufferers from diabetes can suffer blindness or kidney failure, and may need limbs amputated because of poor circulation. Diabetes is treated by reducing sugar intake and taking daily insulin injections. Too much insulin can cause **hypoglycemia**, where the blood sugar level falls, resulting in dizziness and fainting.

Sex hormones

The male sex hormones are produced in the testes, and comprise mainly testosterone and androsterone (Figure 25). They are anabolic—encouraging tissue, muscle and bone growth—and androgenic—conferring the male sexual characteristics. The female sex hormones are structurally very similar, with just small changes in the functional groups attached to the steroid framework (Figure 26). They are produced in the ovaries from puberty until the menopause. The two main female sex hormones are oestradiol and progesterone. They are responsible for sexual development, and for the menstrual and reproductive cycles in women.

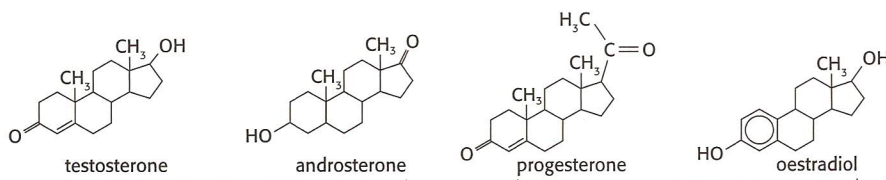


Figure 25 Male sex hormones.

Figure 26 Female sex hormones.

Oral contraceptives

At the beginning of the menstrual cycle the pituitary releases the follicle-stimulating hormone (FSH). FSH travels to the ovaries, causing the release of oestradiol, which prepares for the release of the ovum or egg and the build-up of the uterine wall. After about two weeks a negative feedback system stops the release of FSH and triggers the release of luteinizing hormone (LH). This travels to the ovaries and releases progesterone. The progesterone causes the egg to be transported to the uterus, as well as continuing to build up the uterine wall. If the egg is fertilized the egg embeds itself in the uterine wall and hormone levels rise dramatically; otherwise hormone levels fall, and menstruation begins.

The most common “pill” contains a mixture of oestradiol and progesterone, and mimics pregnancy by intentionally keeping the hormones at a high level so that no more eggs are released. It is usual to take the pill for 21 days and then a placebo for 7 days so that a mild period will result, but without the risk that the hormone levels will fall and allow the unexpected release of an egg.

Oestradiol and progesterone may also be given to post-menopausal women as hormone replacement therapy (HRT), partly to prevent brittle bone disease (osteoporosis).



- 1 Compare the structures of testosterone and progesterone. Identify the steroid backbone present in both compounds and two other functional groups that are common to both. Identify one functional group that is present in testosterone but absent in progesterone.
- 2 Some athletes cheat by taking anabolic steroids. Find out the structures of some anabolic steroids, and explain why they are used both legally and illegally. How can they be detected in the urine or blood?
- 3 Guidelines for healthy eating include:
 - Eat a variety of foods
 - Maintain a healthy weight
 - Eat a diet low in fat, saturated fat and cholesterol
 - Include plenty of fresh fruit and vegetables
 - Use salt and sugar sparingly
 - Moderate the intake of alcohol
 Explain the chemistry behind why each of these bullet points is important.

HL : Enzymes

Enzymes are protein molecules that catalyse biological reactions. Each enzyme is highly specific for a particular reaction, and extremely efficient, often being able to increase the rate of reaction by more than one hundred million times. Like all catalysts, enzymes work by providing an alternative pathway for the reaction with a lower activation energy, by creating an environment in which the transition state is stabilized.

The specificity of enzymes depends on their particular shape. This is determined by their secondary, tertiary and quaternary structure. The part of an enzyme that reacts with the substrate is known as the **active site**. This is the part of the enzyme where the substrate will bind and undergo chemical reaction. The active site is not necessarily rigid, but can alter its shape to allow for a better fit—known as the **induced fit theory**.

Enzyme kinetics

At low substrate concentrations the rate of reaction is proportional to the concentration of the substrate. However, at higher concentrations the rate reaches a maximum, known as V_{\max} . This can be explained in terms of enzyme saturation. At low substrate concentrations there are enough active sites present for the substrate to bind to and react. Once all the sites are used up the enzyme cannot work any faster.

V_{\max} was first identified by a German-born American biochemist, Leonor Michaelis (1875–1949), and a Canadian doctor, Maud Menten (1879–1960). They also identified a constant K_m , known as the Michaelis–Menten constant, which is the substrate concentration when the rate of the reaction is $\frac{1}{2}V_{\max}$. K_m for a particular enzyme with a particular substrate will always be the same. It indicates whether the enzyme functions efficiently at low substrate concentrations or whether high substrate concentrations are necessary for the reaction to be catalysed efficiently.



Figure 27 Maud Menten (1879–1960). Born in Ontario, Maud Menten was one of the first Canadian women to gain a medical doctorate, and went on to become Professor of Medicine at Pittsburgh University. As well as being the co-discoverer of the Michaelis–Menten equation in 1913 she is also credited with being the first to separate proteins by electrophoresis. She was an accomplished painter, and held several exhibitions of her work.

Inhibition of enzymes

Inhibitors are substances that decrease the rate of enzyme-catalysed reactions. **Competitive inhibitors** resemble the substrate in shape but cannot react. They slow down the reaction because they can occupy the active site on the enzyme, thus making it less accessible to the substrate. **Non-competitive inhibitors** also bind to the enzyme, but not on the active site. This is thought to cause the enzyme to change its shape so that the substrate cannot bind. As the substrate concentration is increased, the effect of competitive inhibitors will be diminished, because there is increased competition for the active sites by the substrates. With non-competitive inhibitors increasing, the substrate concentration will not increase the effectiveness of the enzyme, because the enzyme's shape still remains altered by the non-competitive inhibitor. See Figure 28.

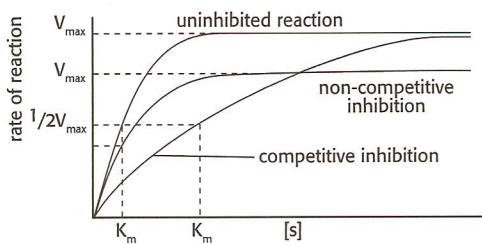


Figure 28 Effect of substrate concentration on enzyme inhibitors. For non-competitive inhibitors V_{max} is lower, but K_m is the same. For competitive inhibitors V_{max} is the same, but K_m is increased.

Factors affecting enzyme activity

Several factors can affect the efficient functioning of enzymes. The catalytic action of an enzyme clearly depends on its specific shape. Increasing the **temperature** will initially increase the rate of enzyme-catalysed reactions, because more of the reactants will possess the minimum activation energy (Figure 29). The optimum temperature for most enzymes is about 40 °C. Above this temperature enzymes rapidly become denatured as the weak bonds holding the tertiary structure together become broken. High and low **pH** can also affect enzymes in a similar way (Figure 30). At different pH values the charges on the amino acid residues change, affecting the bonds between them and so disrupting the specific tertiary structure and making the enzyme ineffective. **Heavy metals** can poison enzymes by reacting irreversibly with $-SH$ groups, replacing the hydrogen atom with a heavy metal atom or ion so that the tertiary structure is permanently altered.

Nucleic acids

Nucleic acids are natural polymers with relative molecular masses of up to several million, made up of nucleotides. All cells in the human body, with the exception of red blood cells, contain **DNA** (deoxyribonucleic acid). A nucleotide of DNA contains deoxyribose (a pentose sugar; Figure 31), which is covalently bonded to a phosphate group and one of four nitrogen-containing bases: adenine, guanine, cytosine or thymine (Figure 32). Nucleotides of ribonucleic acid, **RNA**, contain a different sugar, ribose, but also

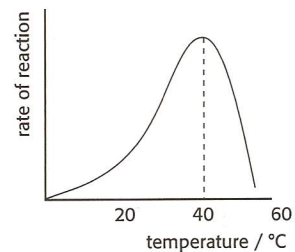


Figure 29 Effect of temperature on enzyme activity.

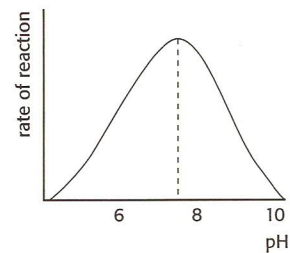


Figure 30 Effect of pH on enzyme activity.

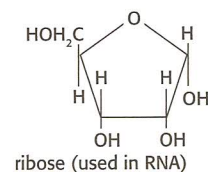
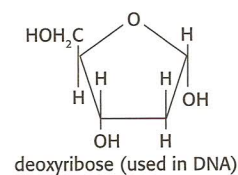


Figure 31 The different sugars in DNA and RNA. The difference is that deoxyribose lacks an oxygen atom on the second carbon atom.

contain a phosphate group and four nitrogen-containing bases. Three of the bases are the same as those in DNA, but the fourth, uracil, replaces thymine.

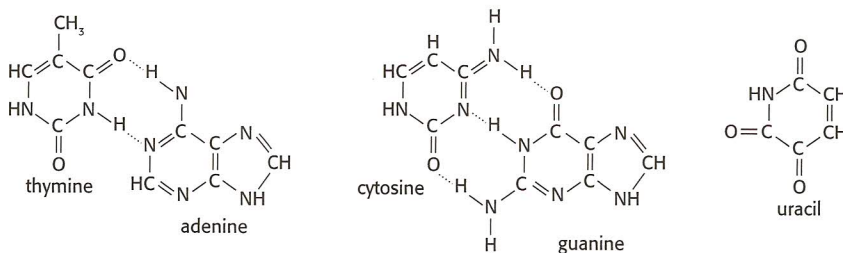


Figure 32 Hydrogen bonding between the nitrogen-containing bases in DNA and RNA.

The nucleotides are condensed together by a phosphodiester bond between the third carbon atom in the sugar and the neighbouring phosphate group to form a polynucleotide (Figure 33). These form the backbone of the nucleic acid, with a repeating pattern of –sugar–phosphate–sugar–phosphate–. The nitrogenous bases are attached to the first carbon atom in the sugar of the backbone.

The **double helix** structure of DNA (Figure 34) was discovered by the American biologist James Watson (1928–) and the British physicist Francis Crick (1916–2004), working together at Cambridge University in the early 1950s. They realized that the backbone was wound into helices, and that the two helices were held together by hydrogen bonds between the bases. The hydrogen bonds are very specific. Cytosine can only hydrogen-bond with guanine and adenine can only hydrogen-bond with thymine (uracil in RNA).

From the molecular to the astronomical: a double helix in the stars

In 2006 astronomers reported the discovery of a highly ordered double helix nebula, possibly made up of spiral galaxies of stars near to the centre of the Milky Way galaxy some 25,000 light-years away from Earth.

The genetic code

When cells divide, the genetic information has to be replicated intact. The genetic information is stored in **chromosomes**, found inside the nucleus. In humans there are 23 pairs of chromosomes. A chromosome is effectively a very long DNA sequence. The DNA in the cell starts to partly unzip as hydrogen bonds between the bases become broken. Sugar base units will be picked up from a pool of nucleotides to form a complementary new strand. Because adenosine can only hydrogen-bond with thymine (A–T) and cytosine can only hydrogen-bond with guanine (C–G), the new strand formed will be identical to the original (Figure 35).

DNA resides mainly in the nucleus, whereas protein synthesis takes place in the cytoplasm part of a cell. The information required to make proteins is transferred from DNA to RNA by a similar enzyme-controlled unzipping process, except that the new strand of RNA contains a different sugar, and uracil in place of thymine.

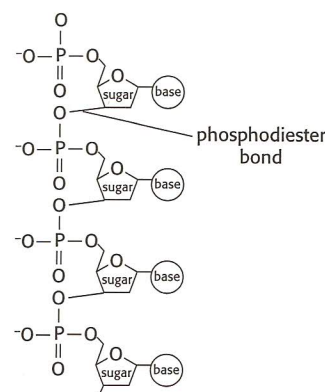


Figure 33 Part of a polynucleotide.

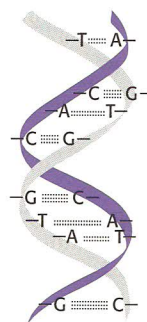


Figure 34 The double helix structure of DNA. Note the hydrogen bonds between the two different strands of polynucleotides.

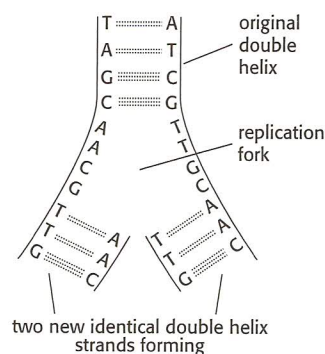


Figure 35 Replication of DNA.

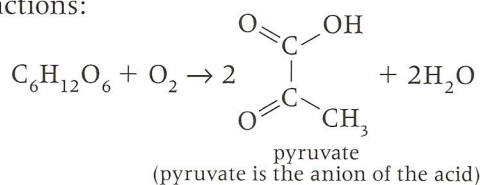
The coded information held by the DNA lies in the sequence of bases. Each sequence of three bases represents one amino acid, and is known as the **triplet code**. The triplet code allows for up to 64 permutations, known as **codons**. This is more than sufficient to represent the 20 naturally occurring amino acids, and several different codons may represent the same amino acid. In 2000 the **human genome**—the complete sequence of bases in human DNA—was finally determined and published on the Internet.

DNA profiling

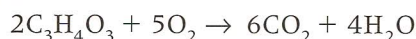
Some unsolved crimes that were committed more than 30 years ago are now being reopened, and sometimes solved, thanks to the advances in DNA “fingerprinting”. The DNA in traces of blood, semen, hair or saliva is extracted and broken down using restriction enzymes into smaller fragments known as **minisatellites**. Splits occur in the minisatellites in the regions where there are no codons. These regions are unique to each person. The fragments are separated into bands using gel electrophoresis. By labelling with radioactive phosphorus, and then using X-ray film to detect the radiation, a characteristic “fingerprint” of all the fragments is obtained. This is used not only in criminal cases but also to confirm paternity, and to map the evolutionary tree of species.

Respiration

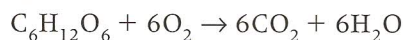
In the body 1 mol of glucose is broken down in a process known as **glycolysis** to 2 mol of pyruvate (2-oxopropanoate). Glycolysis produces energy by storing it in molecules of adenosine triphosphate, ATP. The pyruvate may then break down aerobically or anaerobically. In aerobic decomposition glucose is oxidized by molecular oxygen (which is reduced) to form carbon dioxide and water and release energy. It can be summarized by the following two reactions:



then



overall:

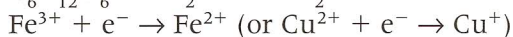


Theoretically 1 mol of glucose can produce 36 mol of ATP by aerobic decomposition, but only 2 mol of ATP are formed during anaerobic decomposition (in the absence of oxygen) when the product formed in humans is lactic acid (2-hydroxypropanoic acid), $\text{CH}_3\text{CH}(\text{OH})\text{COOH}$. However, ATP is created more quickly during anaerobic decomposition, so during short bursts of strenuous activity muscle cells may also use anaerobic respiration, which accounts for the build-up of lactic acid in the muscles. In yeast the pyruvate is decomposed not to lactic acid but to ethanol and carbon dioxide. This is the basis of fermentation:

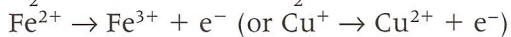
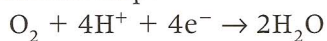


• The ability of transition metals such as iron and copper to form complexes in the form of cytochromes and to show variable oxidation states is important in the electron transfer process that takes place during the enzyme-catalysed oxidation of organic molecules in the body.

• Oxidation step:



• Reduction step:



• Iron, in the form of haem, is also responsible for carrying oxygen in the blood during respiration. Haemoglobin contains four large polypeptide groups and four iron(II) ions, each surrounded by a flat porphyrin ligand known as a **haem** group. Haem is a prosthetic group, a group essential for the protein to be able to carry out its function. At high oxygen concentrations the oxygen forms a coordinate bond, with the iron in the haem group functioning as an extra ligand. At low concentrations the reverse process occurs. Carbon monoxide molecules and cyanide ions are poisonous, because they form very stable complex ions with the iron, preventing it from carrying oxygen.



- 1 Discuss the difference in the catalytic ability of inorganic catalysts, such as nickel, and biological catalysts (enzymes).
- 2 Find the structure of cytochrome oxidase and the structure of the haem group present in haemoglobin. Describe the similarities and the differences between the two structures.
- 3 Should the DNA profile of all citizens be held on a central record to aid the police in identifying criminals, or is this a breach of civil rights?