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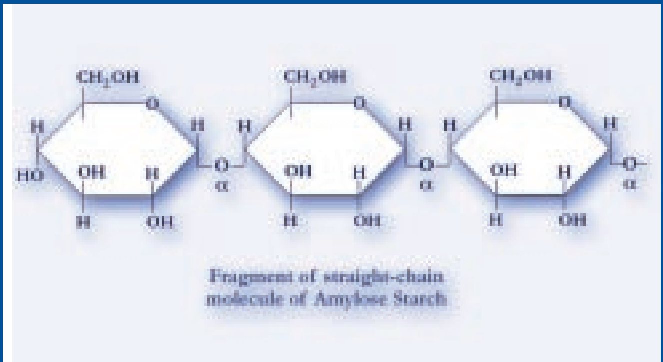

CARBOHYDRATES: NUTRITIONAL AND HEALTH ASPECTS

ILSI

International Life Sciences Institute

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FOREWORD

Over the past twenty to thirty years, knowledge of the physiological roles of different types of carbohydrates and their involvement in health and disease has developed considerably and has challenged many long-held beliefs about sugars, starches and dietary fibre. Carbohydrates comprise a great variety of different structures, which in turn determine a wide range of different physiological effects in the human body.

This booklet, "*Carbohydrates: Nutritional and Health Aspects*", reviews the latest scientific knowledge and understanding of the nutritional and health aspects of carbohydrates. It updates and supersedes the ILSI Europe Concise Monograph entitled "*Starches and Sugars: A Comparison of their Metabolism in Man*" which was published in 1991.

The production of this Concise Monograph was stimulated by the publication in 1997 of the Joint FAO/WHO Expert Consultation on "*Carbohydrates in Human Nutrition*", recommending the consideration of new terminology based on the physiological function of carbohydrates. Topics addressed are the classification of carbohydrates, carbohydrate intake, digestion and metabolism, as well as the health effects of carbohydrates: control of body weight, physical activity, intestinal physiology and tolerance, disease relationships, oral health, cognitive function and immune system effects.

Further details on sugars may still be found in the ILSI Europe Concise Monograph on "*Nutritional and Health Aspects of Sugars – Evaluation of New Findings*".

Janet Lambert
Masterfoods

CARBOHYDRATES IN FOODS

As the term implies, carbohydrates are based on the elements carbon, hydrogen, and oxygen. However, carbohydrates in foods comprise a great variety of structures, which in turn determine a wide range of physiological effects in the human body. Carbohydrates can be classified in several ways, either according to their chemical structures or to their physiological effects.

Structural classification of carbohydrates

A report issued by the Food and Agriculture Organization and the World Health Organization (FAO/WHO, 1998) suggests that carbohydrates should be classified primarily by molecular size, according to the degree of polymerisation (DP), i.e. the number of monosaccharide units. In this classification, carbohydrates are divided into sugars, oligosaccharides, polysaccharides, and hydrogenated carbohydrates (polyols) (Table 1). Each group can be divided into various sub-groups, based on the number and composition of monosaccharide units.

Sugars comprise monosaccharides and disaccharides (Figure 1). The most commonly occurring monosaccharides are glucose (dextrose) and fructose, and the most common disaccharides are sucrose and lactose.

Glucose and fructose are present in varying amounts in honey, maple syrup, fruits, and vegetables. They are also present in processed foods, such as soft drinks, confectionery, and bakery products, that contain starch hydrolysis and conversion products such as corn syrups or high-fructose corn syrups. Maltodextrins, which are used as food product ingredients, may contain small amounts of glucose.

Sucrose (composed of glucose and fructose) is the major disaccharide in most diets, and the term "sugar" is generally used to describe purified sucrose. Sucrose occurs in fruits and vegetables, honey, and maple syrup. Purified sucrose to be used as a food ingredient is derived from sugar cane and sugar beet. Sucrose is an important ingredient in baked goods, desserts, ice cream, confectionery, and soft drinks.

Lactose (milk sugar, comprising glucose and galactose) occurs in milk and milk products. It is also found in food products that contain dairy products among their ingredients, including various baked goods, and in foods that use whey as an ingredient, such as sausages.

Hydrogenated carbohydrates (polyols), such as sorbitol and xylitol (Figure 1), mannitol, maltitol, and erythritol, are the chemically reduced forms of sugars. They retain some sweetness, but they behave quite differently in physiological terms. Although some occur in small amounts in fruits, they are mainly used as bulk sweeteners in food products because of their physicochemical properties and relative sweetness. Polyols, in particular mono- and disaccharide types, are non-cariogenic and have a low energy content and low glycaemic response. They are used in products such as chewing gum and confectionery.

Oligosaccharides occur widely in small quantities in plant foods and in food products. In some vegetables the amounts of undigestible oligosaccharides, such as the trisaccharide raffinose, the tetrasaccharide stachyose, and the pentasaccharide verbascose, may exceed the amounts of other simple sugars. Fructooligosaccharides (FOS) occur in cereals, such as wheat and rye, in various vegetables, including onions, garlic, asparagus, chicory, and jerusalem artichokes, and in bananas and honey. Recent market developments are galactooligosaccharides and condensed oligosaccharides.

TABLE 1

A possible structural classification of the major dietary carbohydrates

CLASS (DP*) AND SUBGROUP	FOOD APPLICATION
Sugars (1–2)	
Monosaccharides	Glucose, galactose, fructose, tagatose
Disaccharides	Sucrose, lactose, trehalose, maltose, isomaltulose
Oligosaccharides (3–9)	
Maltooligosaccharides	Maltodextrins
Other oligosaccharides	Raffinose, stachyose, fructooligosaccharides, galactooligosaccharides
Polysaccharides (>9)	
Starch	Amylose, amylopectin, modified starches
Non-starch polysaccharides	Cellulose, hemicelluloses (e.g. galactans, arabinoxylans), pectins, inulin, hydrocolloids (e.g. guar)
Hydrogenated carbohydrates (polyols)	
Monosaccharide type	Sorbitol, mannitol, xylitol, erythritol
Disaccharide type	Isomalt, lactitol, maltitol
Oligosaccharide type	Maltitol syrups, hydrogenated starch hydrolysates
Polysaccharide type	Polydextrose

*DP=Degree of polymerization
Source: Adapted from FAO/WHO Expert Consultation (1998). Carbohydrates in human nutrition.

Although previously overlooked, such non-digestible oligosaccharides are now recognised as having particular physiological significance. Digestible maltooligo-saccharides are derived from starch hydrolysis and are present in glucose syrups used as food ingredients.

Polysaccharides are sub-divided into starches and the non-starch polysaccharides. They include polydextroses and inulin, polymers of glucose and fructose respectively, which are used as bulking agents and as sucrose replacements in food products.

Starch is the main food reserve in plants and consequently the major carbohydrate in the human diet. It is a mixture of two large polymers: amylose, which comprises mainly linear chains, and amylopectin, which is a highly branched polymer with a higher molecular weight (Figure 2).

Starch is produced during photosynthesis and stored as partially crystalline granules in specific locations, such as tubers, grains, and kernels. The shape and size of the granules and their physical characteristics, notably the

FIGURE 1
Structures of some dietary carbohydrates

MONOSACCHARIDES

Glucose

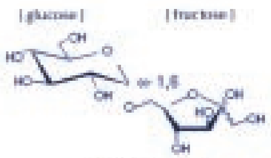
Fructose

DISACCHARIDES

Sucrose

Trehalose

Lactose



Isomaltulose

Maltose

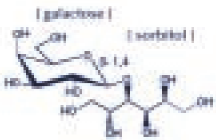
HYDROGENATED (MODIFIED) CARBOHYDRATES

Sorbitol

Erythritol

Xylitol

Maltitol



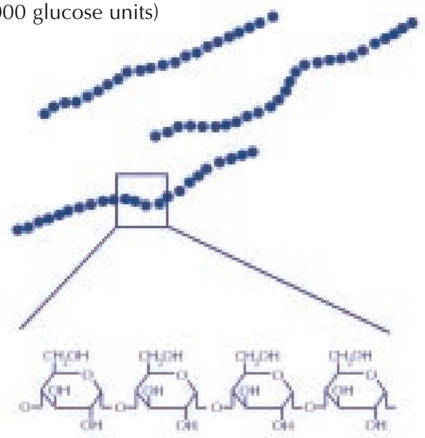
Lactitol

Isomalt

FIGURE 2
The structures of amylose and amylopectin

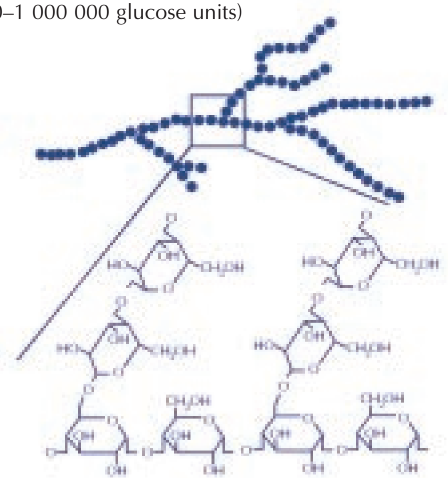
AMYLOSE

Linear molecule
(200–2 000 glucose units)



AMYLOPECTIN

Branched molecule
(10 000–1 000 000 glucose units)



Source: Gray, J. (1991). Starches and Sugars: A Comparison of their Metabolism in Man. *ILSI Europe Concise Monograph Series*. Springer-Verlag, London, UK

TABLE 2

Approximate amylose and amylopectin content of different starches

	Amylose (%)	Amylopectin (%)
Standard maize	24	76
Waxy maize	<1	>99
High amylose maize	70	30
Potato	20	80
Rice*	18.5	81.5
Tapioca	16.7	83.3
Wheat	25	75

* Proportions vary among rice varieties.

Source: Gray, J. (1991). Starches and Sugars: A Comparison of their Metabolism in Man. *ILSI Europe Concise Monograph Series*. Springer-Verlag, London, UK.

temperature at which the starch gelatinises, are dependent on the relative amounts of amylose and amylopectin present. This ratio varies with the type of starch (Table 2) and is an important determinant of the functional and nutritional properties of starches, as is the degree of processing.

Common food starches are derived from seeds, (such as wheat, maize, rice, and barley) and roots, (such as potato and cassava). Chemically modified starches are used in smaller quantities as food additives for their technological functions in some foods, as they influence physical properties such as viscosity, texture, appearance, emulsification, and stability.

Non-starch polysaccharides (NSP) are composed of a mixture of different polysaccharides containing the pentoses (xylose and arabinose) or the hexoses (rhamnose, mannose, glucose, and galactose), and uronic acids. Some are present in plant cell walls, and others occur in the form of gums and mucilages. NSP are organised as complex structures of the plant cell wall and thus perform a structural role in plants.

Cellulose is the major structural component of plant cell walls. It consists of an unbranched (linear) chain of several thousand glucose units that is resistant to digestion by human digestive enzymes.

Hemicelluloses may be present in plant foods in water-soluble or insoluble forms. They include a range of different polysaccharides with structures that comprise both branched and linear chains of pentose units (xylose and arabinose) and hexose units (glucose, galactose, mannose, rhamnose, glucuronic, and galacturonic acids). They have much lower molecular weights than cellulose.

In particular, the ß-glucans have generated interest as "soluble fibre". These glucans are a major component of the cell wall material in oats and barley, and in recent years oat bran has been incorporated into some food products as a source of these glucans.

Pectins are present in vegetables and fruits and are used widely as gelling agents in foods such as jams and jellies. They are composed mainly of chains of galacturonic acids and rhamnose, branched with chains of pentose and hexose units (arabinose, galactose, etc.). Pectins are water-soluble.

Hydrocolloids, which are derived from seaweed extracts, plant exudates, and seeds, include gums and mucilages, such as guar, locust gum, agar, and carrageenan. Chemically, they comprise a wide range of mixed polysaccharides. They are used in small amounts as thickening, gelling, stabilising, or emulsifying agents in some food products.

Physiological classification of carbohydrates

Various attempts have been made to classify carbohydrates according to their physiological effects. For example, the FAO/WHO Expert Consultation on Carbohydrates in Human Nutrition recommended adopting the concept of glycaemic carbohydrates, defined as "providing carbohydrate for metabolism", i.e. carbohydrates that are digested and absorbed in the small intestine, leading to a rise in blood glucose, to distinguish from non-glycaemic carbohydrates that escape hydrolysis (digestion) in the small intestine, not leading to a blood glucose response, and are loosely classified as dietary fibre (*see below*). Although this grouping of carbohydrates is nutritionally relevant, further study and debate are needed to establish more accurate ways of classifying carbohydrates. For example, it does not take account of the different rates of digestion of the digestible fraction of carbohydrates, dividing them into those that are rapidly digested and those that are slowly digested.

Dietary fibre is not an exact description of a single dietary component but comprises a heterogeneous group of components with diverse functional properties. Originally, the term described plant cell wall material that passed through the gut unchanged and provided faecal bulk, but it is now recognised that dietary fibre moderates digestion and absorption of other nutrients in the small intestine and provides substrate for fermentation in the colon. Currently, dietary fibre is defined as "the edible parts of plants or analogues of carbohydrates that are resistant to digestion and absorption in the small intestine, with complete or partial fermentation in the large intestine" (American Association of Cereal Chemists, 2001).

The principal components of dietary fibre are the non-starch polysaccharides (NSP) derived from the cell walls

BOX 1

RS1: starch that is physically enclosed, e.g., within intact cell structures in partly milled cereal grains and seeds.

RS2: raw starch granules, e.g., in maize rich in amylose, raw potatoes, green bananas.

RS3: retrograded amylose in processed foods. Food starches may be rendered partially indigestible by physical or chemical processes and by cooling, e.g. in bread, cornflakes and cooled cooked potato.

RS4: chemically modified starch.

of plant foods in the diet. According to the current definition, resistant starch (RS), defined as "starch and starch degradation products that are not absorbed in the small intestine of healthy humans", should be included in the definition of dietary fibre (Box 1). The proportion of total starch that is resistant to digestion in some common foods is listed in Table 3.

According to this definition of dietary fibre, non-digestible saccharides should also be included. For example, fructooligosaccharides (FOS) and galacto-oligosaccharides (GOS) pass through the small intestine unchanged but are fermented by the microflora in the large intestine. A fraction of hydrogenated carbohydrates also reaches the colon, where they are fermented.

Lignin, which is a non-carbohydrate component of the plant cell wall, may also be included as dietary fibre.

TABLE 3

Proportion of total starch that is resistant in some foods

Food	Total Starch g/100g dry matter	Resistant Starch g/100g total starch
White bread	77	1.2
Wholemeal bread	60	1.7
Shredded wheat	71	nil
Corn flakes	78	3.8
Porridge oats	65	3.1
Rye crisp bread	61	4.9
Potato, boiled, hot	74	6.8
Potato, boiled, cold	75	13.3
Spaghetti, freshly cooked	79	6.3
Peas, cooked	20	25
Haricot beans, cooked	45	40

Source: Englyst, H.N., Kingman, S.M., and Cummings, J.H. (1992). Classification and measurement of nutritionally important starch fractions. *European Journal of Clinical Nutrition*, **46**;S33–S50

Soluble and insoluble dietary fibre

The classification of dietary fibre as soluble or insoluble evolved from the early chemistry of NSP, which showed that different fractions could be extracted by controlling the pH and temperature of solutions. The terms provided a useful, simple division of the physiological properties of dietary fibre into NSP that principally affect glucose and fat absorption from the small intestine (soluble), because they are viscous and form gels in the intestine, and those that have a greater influence on bowel function (insoluble). With time, it has become apparent that this simple distinction is inappropriate: much insoluble fibre is rapidly fermented, and not all soluble fibre has an effect on glucose and fat absorption. However, the use of the term "soluble" to describe gel-forming fibres has been retained.

EFFECTS OF COOKING AND TECHNOLOGY ON CARBOHYDRATES

Processing can have substantial influences on carbohydrates, notably on the rate and extent of digestion of starch in the small intestine and on the content and functional properties of dietary fibre components.

Influence of heat on starch characteristics

When starch is heated in the presence of water, an irreversible loss of the crystalline structure of the starch granules occurs as the process of gelatinisation takes place. The availability of starch for enzymic digestion is increased dramatically by this process. During cooking and other processing, starch granules are not completely dissolved, although the degree of gelatinisation that normally occurs is sufficient to permit a large proportion of starch to be rapidly digested. Where this process is incomplete, such as in the steaming and flaking of cereal and in the manufacture of plain biscuits, a large proportion of slowly digestible starch is preserved.

Gelatinised starch is unstable, and as it ages or cools down, a progressive process of re-association of the starch granules occurs, known as retrogradation. The tendency towards retrogradation depends on the relative proportions of amylose and amylopectin in the starch: amylose re-associates more quickly. Reheating starchy foods also influences this process.

The digestibility of starch is therefore particularly influenced by the degree of processing and by retrogradation, which may reduce the digestibility of starch in the small intestine. Retrograded starch also contributes to the proportion of resistant starch in foods, e.g. in cooked and cooled potato (Table 3).

Influence of processing on content and composition of dietary fibre

The milling of cereal grains to produce refined flours removes the fibre-rich outer layers of the grain and considerably reduces their total fibre content. Flours derived from whole grains contain large amounts of cellulose and hemicelluloses, whereas certain hemicelluloses – arabinoxylans – dominate in the refined flours of wheat, rye, and maize. Although oat and barley lose some dietary fibre during milling, the refined grains are rich in soluble ß-glucans. Heat treatment can also influence the physical structure and therefore the functional and physiological properties of dietary fibre.

CARBOHYDRATE INTAKES

Estimates of carbohydrate intake

Carbohydrates provide 40 to 75% of total energy intake, thus constituting the most important energy source in human diets. The Western countries (Western Europe, North America, and Australia) are at the low end of the range, and the countries in Asia and Africa are at the high end. The type of carbohydrate is also variable, with starch providing 20 to 50%, and in some cases more, of total energy intake and sugars accounting for 9 to 27% of total energy intake. In developed countries, carbohydrate intake declined over the second half of the past century, generally reflecting a decreasing intake of starchy carbohydrates, although a slight increase has occurred during the past two decades as fat intake has fallen.

Estimates of the intake of sugars, available only for developed countries, reflect similar proportions of sugars derived from cereal products, milk products, and beverages, but there are variations in the amounts of sugars derived from fruit, soft drinks and confectionery.

The FAO/WHO Expert Consultation on Carbohydrates in Human Nutrition recommended an optimum carbohydrate level of at least 55% of total energy intake, obtained from a variety of food sources, and noted that levels of carbohydrate consumption at or above 75% of total energy should be avoided because of the exclusion of adequate amounts of protein, fat, and other essential nutrients.

Relationship between carbohydrate and fat intakes

It is recognised that there is usually an inverse relationship between the proportions of fat and carbohydrate in the diet. Thus, on a percentage basis, as fat intake falls, carbohydrate intake rises, and *vice versa*. While the proportion of energy intake from fat and carbohydrate has changed over time, protein intake as a proportion of energy intake has remained relatively constant. There is now considerable evidence to suggest that higher fat intakes are accompanied by higher total energy intakes, compared with high-carbohydrate diets. This may be related to the lower energy density of high-carbohydrate diets.

Implications for intakes of other nutrients

As total carbohydrate intake from natural foods increases or decreases, the intake of nutrients associated with the carbohydrate food sources also increases or decreases. In particular, foods that are naturally rich in glycaemic carbohydrates, such as cereals, pulses, seeds, fruit and vegetables, provide a wide range of important micronutrients (vitamins and minerals), dietary fibre, and phytochemicals, which are now recognised to have a beneficial effect on health.

Concern is frequently expressed that dietary sugars, especially added sugars, may displace micronutrients from the diet. However, survey research among British adults indicates that micronutrient intake is not compromised at intake levels of added sugars providing up to 17% of food energy. The highest micronutrient intakes were found among consumers of average levels of added sugars (10 to 16% of food energy), and the lowest among those with the lowest added sugars intake (6% of food energy). On the other hand, such cross-sectional analyses of survey data do not permit any distinction to be made between displacement of micronutrients as a result of sugar intake level and generally poor eating habits.

CARBOHYDRATE DIGESTION AND ABSORPTION

Digestion and absorption in the small intestine

The different processes and components of digestion and absorption of major digestible carbohydrates, which take place in the digestive system, are illustrated in Figure 3.

Starch digestion begins in the mouth, by salivary amylase, but digestion in the small intestine, by pancreatic amylase, is quantitatively more important. The cells lining the small intestine, the enterocytes, provide a highly interactive surface between the lumen of the intestine and the blood and lymphatic system. They produce the hydrolytic enzymes essential for the breakdown of maltooligosaccharides and disaccharides (maltose, sucrose, and lactose) into their constituent monosaccharides. The enterocyte is also the site of absorption of the free monosaccharides.

With the typical Western diet, which is relatively high in rapidly digestible carbohydrates, the main part is absorbed mainly in the upper part of the small intestine. If the diet contains a greater proportion of less easily digested carbohydrates, more carbohydrates are shifted to the lower regions of the small intestine and to the colon, where they are fermented.

Factors affecting rates of digestion

Starch digestion is influenced by the nature and the degree of processing of the starch and by the presence of dietary fibre. In some foods, e.g. legumes, the starch is trapped in fibrous, thick-walled cells, so the enzymes have limited access to it.

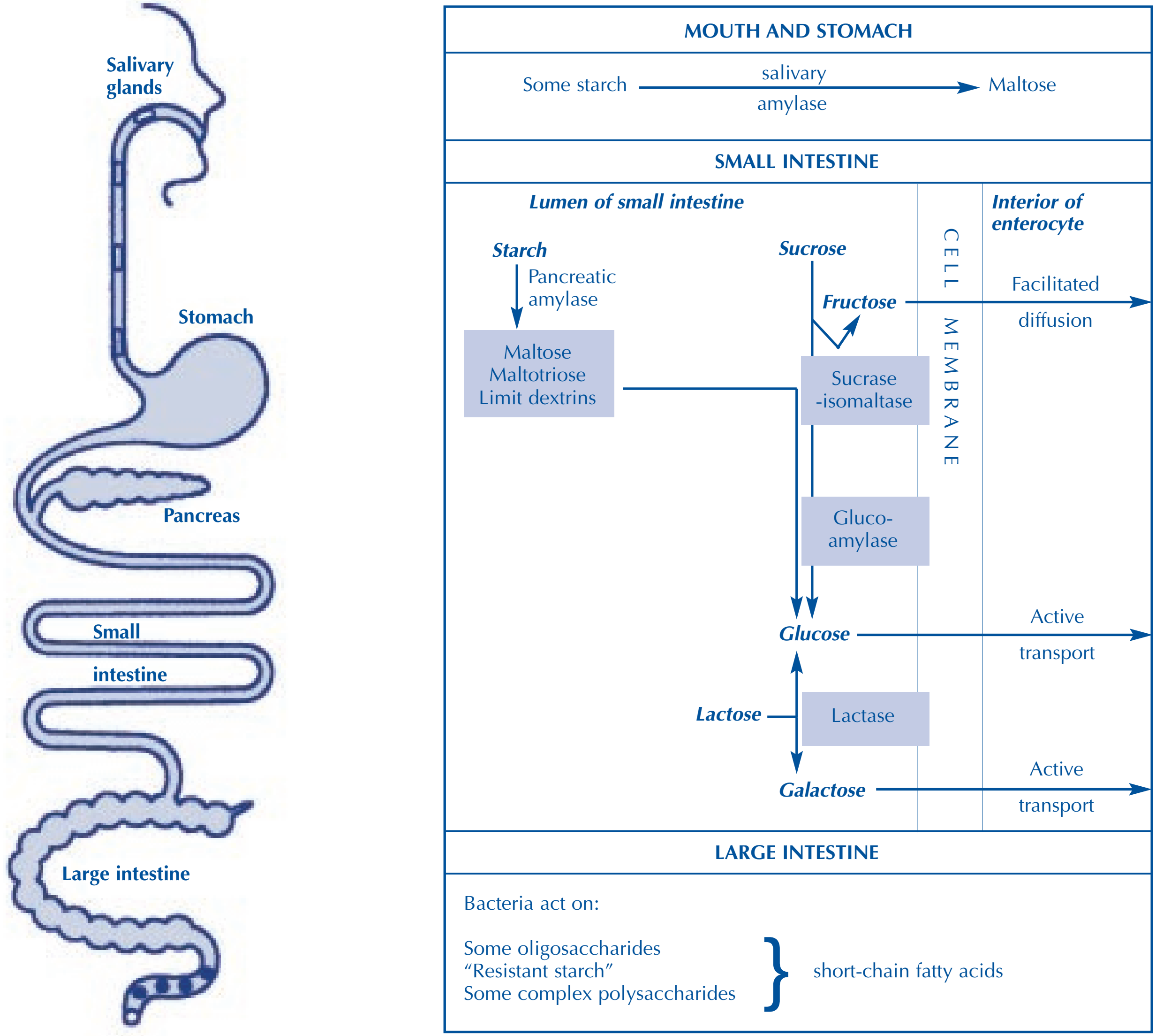
Digestion of carbohydrates is influenced by gastrointestinal factors, such as the rate of gastric emptying and the speed of intestinal transit. The rate of gastric emptying itself is influenced by many factors in a mixed meal, including fat and energy content, viscosity, the ratio of solid to liquid contents of the meal, the quantity of dissolved solids, and the particle sizes of the food. The dietary fibre content of the diet also has an important influence on gastric emptying. A high fibre content may slow gastric emptying. The mixing of some soluble fibres with liquid meals increases the viscosity of the gastric contents, and also influences gastric emptying. Soluble fibres also build gels that entrap carbohydrates, making them less accessible to enzymes and reducing contact with the intestinal mucosa.

Fermentation of carbohydrates in the large intestine

Carbohydrates that resist digestion in the small intestine, such as dietary fibre (including resistant starch, which represents up to one fifth of ingested starch), many oligosaccharides (except those derived from glucose syrups), and a proportion of hydrogenated carbohydrates (polyols), pass into the large intestine, where they are partially or completely fermented by the gut microflora. Lactose may also escape digestion and absorption in the small intestine because of low activity of the enzyme lactase and pass into the colon. These so-called non-digestible carbohydrates, originally viewed only as bulking agents, are now seen to have important physiological effects as a result of their fermentation.

The bacterial flora in the large bowel produces a wide range of enzymes that hydrolyse carbohydrates and generate short-chain fatty acids (SCFA) (acetate, propionate, and butyrate) and gases (carbon dioxide, hydrogen, and methane). The process of fermentation is

FIGURE 3
Principle digestive processes of carbohydrates



Source: Gray, J. (1991). Starches and Sugars: A Comparison of their Metabolism in Man.
ILSI Europe Concise Monograph Series. Springer-Verlag, London, UK

essential to large bowel function. Bacteria use the products of fermentation to generate the energy and extract the carbon that are required for growth. One of the SCFA, butyric acid, is considered to be a primary nutrient for the normal growth of the epithelial cells lining the colonic mucosa and may play a role in preventing disease of the colon. The fermentation process also has effects on systemic metabolism, as some SCFA are absorbed and metabolised to provide energy. The amount of energy yielded by carbohydrate fermentation is estimated to be about 8 kJ/g (2 kcal/g), which is about half the energy value of carbohydrates digested in the small intestine. A large proportion of the gases produced during fermentation is liberated as flatus or appears in the breath, and some is consumed by the colonic bacteria.

The rate and extent of carbohydrate fermentation depends on the solubility and structure of the polysaccharides and on the accessibility of bacteria to these polysaccharides. For example, most soluble polysaccharides, hydrogenated carbohydrates and oligosaccharides are completely and rapidly fermented, whereas resistant starch is completely fermented but only slowly, and cellulose and hemicelluloses are partially resistant to fermentation. The nature of the fermentation products also depends on the specific carbohydrates, but the factors governing the preferential production of individual SCFA have not been definitively ascertained.

When the enterocytes fail to produce a given carbohydrate-splitting enzyme, the corresponding specific sugars are not absorbed. These sugars are then transported to the large intestine and fermented. This may cause laxation and abdominal pains and is referred to as "intolerance". Such enzyme deficiencies are rare, with the exception of low lactase activity. Reduced lactase activity after weaning or later childhood, resulting in the reduced capacity to digest and absorb lactose, is a normal phenomenon in most of the world and most prevalent in Asia and Africa. Most individuals with low lactase activity can tolerate moderate amounts of milk, especially when distributed throughout the day and in meals.

A high intake of any fermentable carbohydrate may cause an increase in the water content of the faeces and therefore may result in loose stools and flatulence. However, there are considerable variations in individual response to different carbohydrates.

Gut microflora

The gut microflora constitutes a highly complex ecosystem, with more than 200 and sometimes as many as 500 different species of anaerobic and aerobic micro-organisms in a single individual. A considerable degree of variation in bacterial species is seen among individuals, which may be influenced by factors such as age and diet, but the flora is remarkably stable within individuals.

Recent research suggests that non-digestible carbohydrates, in particular oligosaccharides, are selectively used by certain groups of bacteria and may modify the bacterial composition of the dominant flora by increasing bifidobacteria and other lactic acid bacteria. Consequently, several types of oligosaccharides have been used as "prebiotic" food additives (e.g. in foods with claims of specific health benefits). For example, they have been added to "probiotic" dairy-based products that contain bifidobacteria (e.g. yogurt), in order to encourage the growth of these bacteria. It has been suggested that this process may be beneficial to health maintenance, but further research with acceptable clinical end points is required to confirm this.

METABOLISM OF ABSORBED CARBOHYDRATES

Disposal and metabolic conversion of carbohydrates

Glucose, free and bound in digestible polymers, is the main ingested carbohydrate, and glucose is one of the body's main metabolic fuels. After the consumption of meals containing glycaemic carbohydrates, the constituent monosaccharides, principally glucose, are absorbed into the blood, thus increasing the blood glucose level. After a test dose of glucose or starch has been consumed, the blood glucose level reaches a peak in 20 to 30 minutes and then slowly returns to the fasting level over 90 to 180 minutes as glucose is taken up by different tissues under the influence of insulin.

Absorbed monosaccharides enter the bloodstream via the portal vein, which takes them to the liver. A proportion of glucose is taken up by the liver and converted to glycogen. Fructose is preferentially taken up by the liver and is also converted to glycogen, although at high intakes some of it (30–40%) is rapidly metabolised in the intestinal mucosa to lactate, which passes to the liver and is transformed into glucose. Because the majority of the absorbed fructose and galactose is taken up by the liver and requires conversion to intermediates before entering the blood and undergoing metabolism (see below), the effect of these sugars on blood glucose levels is very small. Any remaining carbohydrates are taken up by other tissues, especially muscle, where they are either oxidised or converted to glycogen for storage.

The various monosaccharides and their corresponding alcohols can be interconverted by various metabolic pathways (Figure 4). However, under normal physiological conditions glucose is the preferred fuel for the central nervous system, the red blood cells, and certain muscle fibres.

Most of the metabolic pathways that generate energy are common to all dietary sugars: eventually they are metabolised to carbon dioxide and water via the citric acid cycle (Figure 4). The same enzymes and co-enzymes (often B vitamins) are involved.

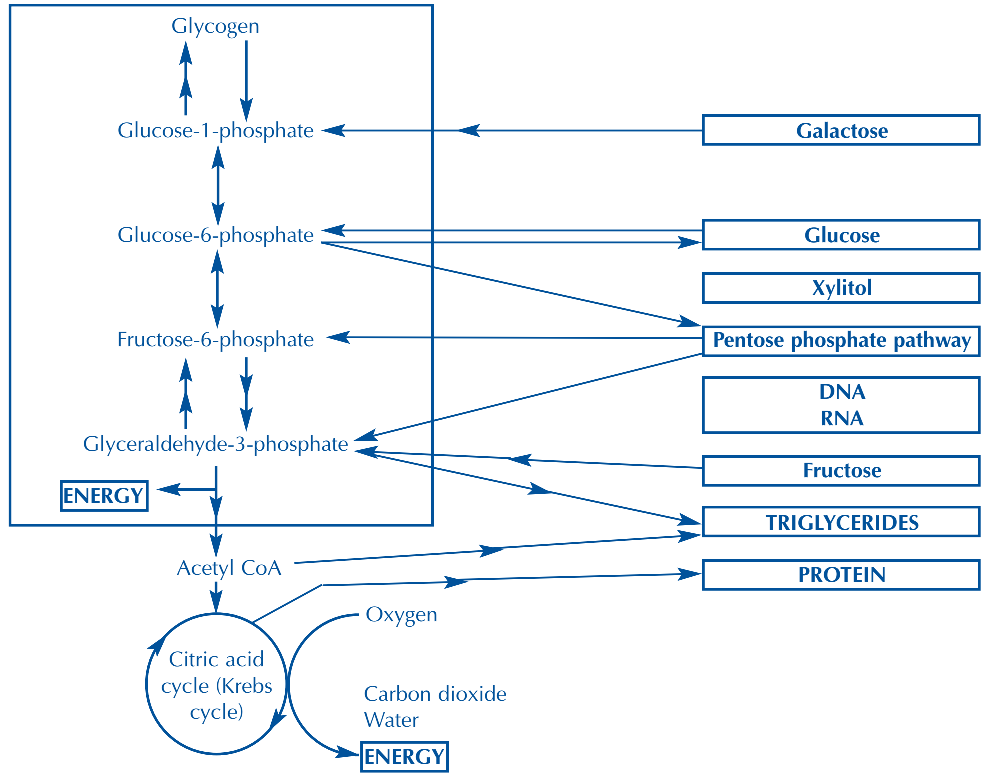
The differences in metabolism of glucose and fructose are shown in Figure 5. Galactose enters the glycolytic pathway (Figure 4). The uptake of galactose by the liver is inhibited by alcohol, leading to a transient high blood level of galactose when foods containing it are consumed simultaneously with alcohol. Whether this has metabolic consequences is unknown.

The hierarchy for substrate oxidation

Protein, carbohydrate, and fat all supply fuel for energy expenditure. This fuel may come from the diet or from body stores. Alcohol is an additional source of fuel. Substrate oxidation occurs in a hierarchical order, which is determined by the body's storage capability for each macronutrient, the energy costs of converting the macronutrient to a form that can be stored more effectively, and the specific fuel requirements of certain tissues (Figure 6).

Alcohol takes the highest priority for oxidation, as there is no storage pool for it and the conversion of alcohol to fat is costly in energetic terms. Amino acids are second in the hierarchy, as again there is no specific storage pool for them. Third in the oxidative hierarchy are carbohydrates. The body has a limited capacity to store carbohydrates as glycogen. A typical adult male can store 400 to 500g of glycogen, predominantly in the liver

FIGURE 4
The metabolism of sugars



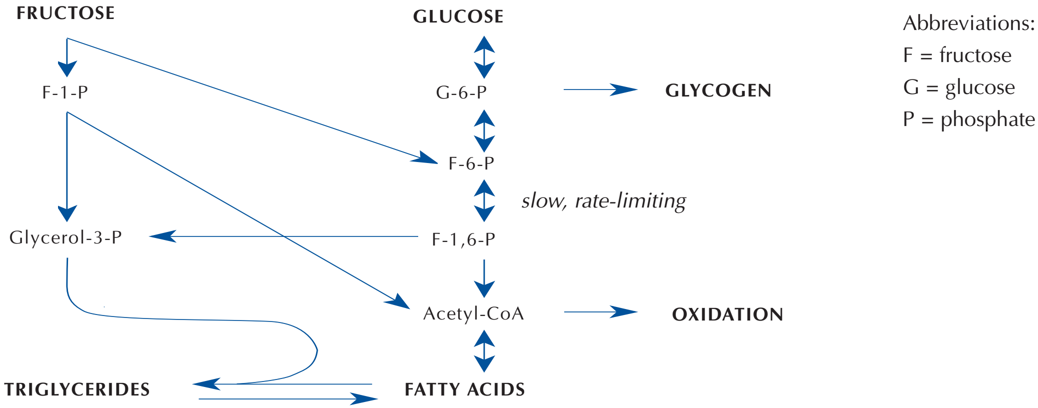
Source: Gray, J. (1991). Starches and Sugars: A Comparison of their Metabolism in Man. *ILSI Europe Concise Monograph Series*. Springer-Verlag, London, UK.

and in muscles. However, conversion of carbohydrate to fat is energetically costly. By contrast, the body has an almost unlimited storage capacity for fat in adipose tissue, and the storage efficiency is high (96–98%). Thus fat is theoretically lowest in the oxidative hierarchy.

Regulation of blood glucose concentration

The pancreas secretes insulin in response to an increase in blood glucose concentration, but insulin secretion is also influenced by other endocrine and neural stimuli. Dietary factors other than carbohydrates also may influence secretion, e.g. the amino acid composition of

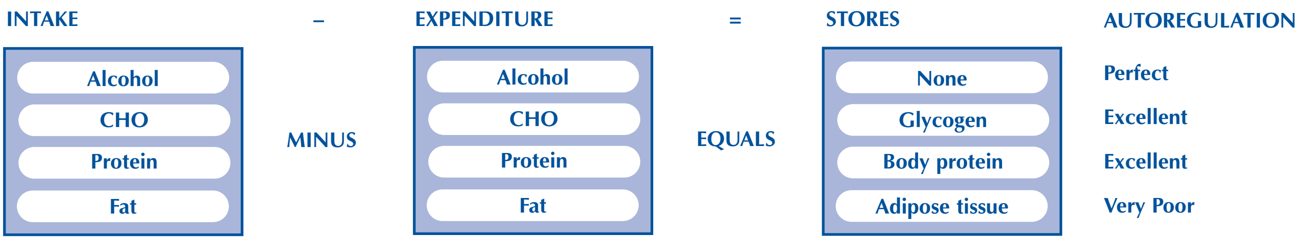
FIGURE 5
Metabolism of glucose and fructose



- The ubiquitous enzyme (hexokinase) that catalyses the addition of a phosphate group to position 6 of glucose does not carry out this reaction efficiently with fructose. Glucose formation from fructose is important only if available fructose provides a major source of dietary carbohydrate.
- The metabolism of fructose is confined mainly to the liver, where a special enzyme is present that utilises fructose *(*fructokinase, which phosphorylates position 1 of fructose).
- Fructose-1-phosphate bypasses the slowest step in the pathway for glucose metabolism, which results in faster metabolism of fructose than glucose in the liver.
- Fructose metabolism produces end products that may be readily made into triacylglycerols (triglycerides).
- Fructose also seems to facilitate the transport of fatty acids stored in adipose tissue to the liver, where they can be used to make more triacylglycerols, which may be exported into the plasma as very low density lipoproteins (VLDL).
- Fructose can slow down the removal of VLDL from the plasma, thus helping to maintain already high blood concentrations.

Source: Gurr, M. (1995). Nutritional and Health Aspects of Sugars: Evaluation of New Findings. *ILSI Europe Concise Monograph Series*, ILSI Press, Washington, DC, USA.

FIGURE 6
The oxidative hierarchy for macronutrients



Source: Rolls, B.J. and Hill, J.O. (1998). Carbohydrates and Weight Management. ILSI North America, ILSI Press, Washington, DC, USA.

dietary proteins. The digestion of food also causes the release of various hormones (regulatory peptides) from the intestine into the blood stream. Two of these, gastric inhibitory peptide (GIP) and glucagon-like peptide I (GLP I), are involved in regulating carbohydrate metabolism through influencing insulin secretion as well as gastric emptying.

Different carbohydrates induce different blood glucose levels and hence induce different insulin responses. The insulin response to carbohydrates is closely related to the rate of digestion and/or absorption of its component sugars. However, the carbohydrate in a mixed meal generates a greater insulin response than a similar amount of carbohydrate consumed as glucose, probably because of the effects of the proteins contained in the meal on insulin secretion. Table 4 summarises the various factors that influence insulin release.

TABLE 4

Factors influencing the release of insulin

Stimulation of insulin release

1. Increase in blood glucose concentration
2. Increase in blood levels of certain amino acids
3. Glucose in intestine (probably mediated by gastric inhibitory peptide)
4. Other gut hormones such as gastrin and secretin
5. Glucagon from alpha cells of pancreas
6. Nerve (parasympathetic) stimulation

Inhibition of insulin release

1. Adrenaline
2. Nerve (sympathetic) stimulation
3. Pancreatic secretion of the hormone somatostatin

Source: Gray, J. (1991). Starches and Sugars: A Comparison of their Metabolism in Man. *ILSI Europe Concise Monograph Series*. Springer-Verlag, London, UK.

Blood glucose responses to food and the glycaemic index

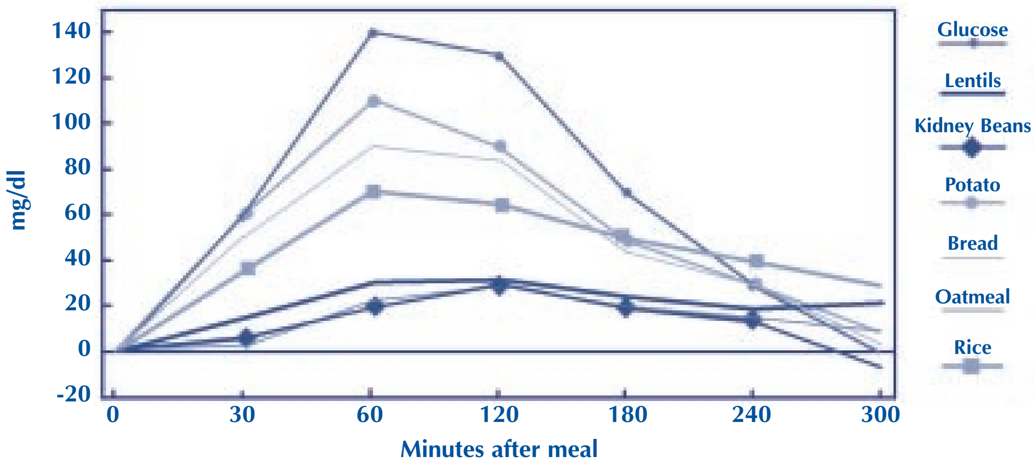
The rise in the blood glucose level that occurs when foods containing glycaemic carbohydrates are eaten is termed the glycaemic response. The concept of glycaemic index (GI) has been developed to classify foods on the basis of their potential for increasing the blood glucose concentration.

The GI is defined as the incremental area under the blood glucose response curve (change in blood glucose concentration plotted against time) (Figure 7) after consumption of a 50g carbohydrate portion of a test food, expressed as a percentage of the response to the same amount of carbohydrate from a standard (reference) food consumed by the same subject.

The reference food, taken to have a glycaemic index of 100, can be 50g of glucose or an amount of white bread containing 50g of starch, although the current recommendation is to use glucose as the reference food. The GI values obtained with white bread as the reference are about 1.4 times those obtained when glucose is the reference.

In addition to the quantity and digestibility of starches and the quantity and sources of sugars in a meal, many factors influence the glycaemic responses to foods (Table 5). These include the presence of fat and protein, the degree of processing and cooking, and the amount of dietary fibre present. The ratio of amylose to amylopectin in the starch is important in determining GI: amylopectin is more rapidly degraded than amylose.

FIGURE 7
Serum Glucose Responses to Ingestion of 50g CHO



Source: Krezowski, P.A., Nuttal, F.Q., Gannon, M.C., *et al*. (1987). Insulin and glucose responses to various starch-containing foods in type 2 diabetic subjects. *Diabetes Care*. HighWire Press, Palo Alto, CA, USA.

There are important differences between the GIs of different sugars. The GI of a sugar is determined primarily by its content of readily available glucose residues. Thus maltose (a disaccharide with two glucose units) has a GI close to 100, whereas sucrose (glucose plus fructose) has a GI of only 87. The GI of fructose (using bread as a standard) is only 32, which is explained by the partial conversion of fructose into glucose at high intakes of a standard test.

The use of the GI method has also revealed interesting information about the influence of carbohydrate foods on blood glucose levels, overturning certain long-held beliefs. For example, it was assumed that the blood glucose response to starches is less than the response to sugars because of the slower digestion of starch. However, many cooked starches are digested so rapidly that the glycaemic response is similar to that of glucose (Table 6). The GI correlates well with the hydrolysis rate of the starch, so that, e.g., the starch in lentils generates only a small glycaemic effect compared with the starch in bread.

Physiological effects of GI and its practical implications

Clinical trials with normal, diabetic, and hyperlipidaemic individuals indicate that the consumption of meals containing low-GI foods is associated with reduced blood glucose and insulin responses after meals and with improved lipid profiles, including reductions in elevated serum triglyceride concentrations in subjects with hypertriglyceridaemia. It has also been suggested that low-GI foods may have longer lasting satiating effects than high-GI foods, but this idea is still controversial and requires further study. Hence the practical application of

TABLE 5

Food factors that influence glycaemic response

Nature and amount of carbohydrate	
Nature of the monosaccharide components	
	Glucose
	Fructose
	Galactose
Nature of the starch	
	Amylose
	Amylopectin
	Starch-nutrient interaction
	Resistant starch
Cooking or food processing	
	Degree of gelatinisation of starch
	Particle size
	Food form
	Cellular structure
Other food components	
	Fat and protein
	Dietary fibre
	Antinutrients
	Organic acids

Source: Adapted from FAO/WHO Expert Consultation (1998). Carbohydrates in human nutrition.

the GI, used in combination with other information on food composition, looks promising in guiding food choice, especially for people with diabetes.

Hypoglycaemia

Hypoglycaemia (a low blood glucose concentration) occurs when the uptake of glucose by tissues exceeds the rate of supply from the liver and/or meals. This may occur with or without symptoms. Contrary to popular opinion, reactive hypoglycaemia, in which symptoms occur 2 to 5 hours after meals, in resting conditions, is not a common but a rare disorder. Symptoms include sweating, lightheadedness, dizziness, tremor, thirst, mental lethargy, irritability, headache, and increased respiration rate. Treatment involves consumption of frequent small low-carbohydrate meals.

It is frequently assumed that sugars are more likely to cause such symptoms, but there may be a differing response to specific sugars, depending on their effects on insulin secretion and how they are metabolised. A study of individuals with hypoglycaemia suggested that whereas glucose produced symptoms in all subjects, fructose did not produce symptoms in any of them, and sucrose caused symptoms in only one-third of the subjects.

TABLE 6

Glycaemic index (GI) of some selected foods using white bread as the reference standard

	GI*	n**
Cereal products		
White bread	100 ± 0	5
Wholemeal flour	99 ± 3	12
Rye crispbread	93 ± 2	5
Corn flakes	119 ± 5	4
Porridge oats	87 ± 2	8
Macaroni	64	1
Spaghetti, white	59 ± 4	10
Spaghetti, brown	53 ± 7	2
Rice, white	81 ± 3	13
Rice, brown	79 ± 6	3
Rice, low amylose	126 ± 4	3
Rice, high amylose	83 ± 5	3
Plain biscuits	71 ± 11***	1
Potatoes		
New	81 ± 8	3
White, boiled	80 ± 2	3
White, mashed	100 ± 2	3
French fries	107	1
Baked	121 ± 16	4
Legumes		
Baked beans	69 ± 12	2
Beans, kidney	42 ± 6	7
Beans, soya	23 ± 3	3
Peas, green	68 ± 7	3
Lentils	38 ± 3	6

	GI*	n**
Fruit		
Apple	52 ± 3	4
Apple juice	58 ± 1	2
Apricots, dried	44 ± 2	2
Apricots, canned	91	1
Banana	83 ± 6	5
Orange	62 ± 6	4
Orange juice	74 ± 4	4
Dairy products		
Milk, whole	39 ± 9	2
Milk, skimmed	46	1
Yogurt (sugar)	48 ± 1	2
Yogurt (artificial sweetener)	27 ± 7	2
Ice cream	84 ± 9	6
Sugars		
Honey	104 ± 21	2
Fructose	32 ± 2	4
Glucose	138 ± 4	8
Sucrose	87 ± 2	5

*GI = Glycaemic index (white bread = 100), mean ± SEM of mean values from various studies
** n = Number of studies
*** Brand Miller, J., Lang, V., Nantel, G., Slama, G., eds. (2001).

Data for plain biscuits are from Glycaemic Index and health: the quality of the evidence. John Libbey Eurotext.

Source: FAO/WHO Expert Consultation (1998). Carbohydrates in human nutrition.

CARBOHYDRATES IN HEALTH AND DISEASE

Carbohydrates and gut health and function

An adequate intake of fibre-rich carbohydrates is vital to normal gut function. Along with the long-recognised bulking effects of fibre, the importance of carbohydrates to the health of the colon and the maintenance and stimulation of the gut microflora as well as the importance of the fermentation product butyric acid for the colonic epithelium is now acknowledged.

The physical characteristics of the gastric and intestinal contents are altered by the presence of different types of fibre. A greater proportion of fibre in foods produces more bulk, and the volume of the gut contents increases further because of the water-holding capacity of particular fibres. Within the gastrointestinal tract, some fibres swell, trapping water and nutrients, especially those that are water-soluble, such as sugars. Changes in the physical characteristics of the gut contents may influence gastric emptying, dilute enzymes and absorbable compounds in the gut, prevent the hydrolysis of starch in the small intestine, and reduce the mobility of enzymes, substrates, and nutrients to the absorptive surface. This slows the appearance of nutrients, such as glucose and some lipids, in the blood after a meal.

Colonic motility and transit time are also modified by different dietary fibres. The increased bulk and volume of the colonic contents distends the colon wall, stimulating the muscle to propel the contents onwards through the large bowel. It has also been suggested that compounds trapped in the fibre in the small intestine (such as biliary salts and fatty acids), which are released during fermentation, stimulate motility.

Carbohydrates and cancer

Most epidemiological studies that have examined the role of carbohydrates in cancer have focused on dietary fibre and, to a much lesser extent, on monosaccharides, disaccharides, and starches. Evidence from recent intervention studies does not support any effect of fibre intake on the early phases of colorectal carcinogenesis. The effect of fibre on the late phases of colorectal carcinogenesis is currently unknown. However, there is some evidence that the short-chain fatty acid butyrate, which is the product of carbohydrate fermentation in the large intestine, may have a positive influence on intestinal health, including cellular changes involved in colorectal cancer. This is the focus of current research. There are no consistent findings linking the intake of simple carbohydrates to cancers at specific sites.

Carbohydrates and type 2 diabetes

More than 40 studies in the scientific literature have examined the role of various sugars and starches in the aetiology and management of type 2 (non–insulin dependent) diabetes. About half of them suggest that there is a positive association between sucrose intake and diabetes, and a similar proportion suggest that there is no association; some studies even suggest that there is an inverse association between the two. The restriction of carbohydrate and specifically the need to avoid "simple sugars" was the mainstay of dietary recommendation for people with diabetes for many years. This was based on the premise that sugars, including sucrose, would aggravate hyperglycaemia to a greater extent than other carbohydrates. There is now evidence to the contrary. Research on the GI of foods has demonstrated that blood glucose levels following an oral sucrose or fructose load are lower than after a comparable oral glucose load. Subsequent longer-term studies, incorporating sucrose in mixed meals, have confirmed that a moderate intake of sucrose (up to about

50 g per day) can be consumed by people with both type 1 (insulin-dependent) and type 2 diabetes.

There is little evidence that readily digested starches increase the risk of type 2 diabetes. However, there is support for the contention that eating foods that are rich in slowly digested (low GI) and resistant starch or high in soluble fibre, as well as the avoidance of overweight and physical inactivity, reduces the risk of developing type 2 diabetes.

Research in the 1970s demonstrated that high-carbohydrate diets (up to 60% total energy from glycaemic and non-glycaemic carbohydrates) were associated with improved blood glucose control and lower low-density lipoprotein (LDL) cholesterol levels, compared with diets providing only 40% of total energy as glycaemic and non-glycaemic carbohydrate. Modern diabetic dietary recommendations emphasise the importance of high carbohydrate intake as well as modifications to fat intake because of the associated problems with lipid metabolism and the risk of cardiovascular disease (CVD) among those who have diabetes. Fibre-rich carbohydrates such as staple cereals, pasta, rice, bread, pulses, vegetables, and fruit should provide the major components of meals, with an emphasis on those that have a low GI and are rich in soluble types of fibre.

Carbohydrates and the insulin resistance syndrome

Type 2 diabetes is often associated with insulin resistance, which is an impairment of insulin action, especially the insulin-stimulated uptake of glucose by tissues and the inhibition of glucose output by the liver and of fat breakdown (lipolysis). Insulin resistance is often associated with aberrations in other aspects of metabolism, especially of lipids, as well as obesity. In the past decade the concept of the "insulin resistance syndrome", also termed "metabolic syndrome" or "syndrome X" has developed.

The term has been adopted to describe a constellation of conditions that are frequently associated with insulin resistance, such as impaired glucose tolerance, hyperinsulinaemia, hypertension, and dyslipidaemia, which tend to cluster together along with patterns of abdominal storage of excess fat. The description of this syndrome arises from the observation that insulin-resistant patterns of glucose and fat metabolism are more prevalent among individuals with hypertension and abnormal blood lipid patterns than those with normal blood pressures and blood lipids.

The genetic predisposition to type 2 diabetes and the other disorders linked to insulin resistance has resulted in a major effort to define the molecular biology of the disorder. However, so far, there does not appear to be one or even a small group of genetic mutations that provide the molecular basis for insulin resistance. Increased body fat, and particularly intra-abdominal fat, in combination with a low level of physical activity, causes insulin resistance, and in people with a limited capacity to secrete insulin, this results in type 2 diabetes.

Among the numerous environmental factors that may interact with the genetic potential to develop insulin resistance, the role of dietary carbohydrate and fibre intake has been investigated, but reliable evidence is sparse.

Evidence on fibre intake and insulin action is also limited and contradictory. Some epidemiological studies have linked high-GI diets and low cereal fibre intakes with the incidence of type 2 diabetes, but mechanistic studies to support the epidemiology are lacking. Soluble fibres, such as ß-glucans, are of interest because of their influence on blood glucose and insulin responses, but again information on their effects on insulin action is lacking.

Carbohydrates, lipid metabolism, and cardiovascular disease

Alterations in plasma lipid concentration following long-term excessive consumption of large amounts of carbohydrates, particularly fructose and sucrose, have been reported from animal studies, but the significance in humans is still the subject of scientific debate. In humans the usual response is an elevation in triglyceride concentration, but depression of high-density lipoprotein (HDL) cholesterol has also been observed.

Many different dietary and environmental factors, including obesity and excessive alcohol consumption, influence blood triglyceride concentration. Some people are more sensitive to these effects of dietary sugars than others, and in such individuals blood triglyceride levels may increase in response to atypically high intakes of sucrose or fructose. There is some evidence that these effects occur mainly in men and are less important in women.

Carbohydrate-induced increases in blood triglyceride levels appear to result from the overproduction of both very low density lipoprotein (VLDL) triglyceride and VLDL particle numbers, as well as the impaired clearance of VLDL from the blood. Individual responses in VLDL metabolism are highly variable and are more apparent in individuals who already have elevated blood triglyceride and insulin concentrations or who are obese, especially those with abdominal obesity. If the carbohydrate content of a high-carbohydrate diet is predominantly in the form of fructose, there is a greater elevation of blood triglyceride concentration than if polysaccharides predominate. Experimental diets containing purified forms of starch or monosaccharides induce the rise in triglycerides more readily than fibre-rich diets, in which the carbohydrate may be more slowly digested.

Most studies of these factors have been of short duration and have measured only fasting blood levels, not postprandial concentrations (those following food consumption). The few long-term studies that have been conducted indicate that the lipid-raising effects of sugars may be reduced after several weeks. Low-fat, high-carbohydrate diets have also been shown to have favourable effects on other important risk factors of cardiovascular disease, such as blood pressure, clotting and fibrinolytic factors, and endothelial function, provided that foods high in both carbohydrate and dietary fibre are adequately represented.

There are in fact various ways in which diets rich in carbohydrates may actually help reduce, rather than increase, cardiovascular disease risk. These include decreasing the energy density and increasing the satiating power of the diet, thereby helping to prevent obesity; displacing fat in the diet; reducing the risks of high blood glucose and insulin levels and thereby maintaining optimal insulin sensitivity; and providing micronutrients and phytochemicals that are believed to have a protective effect on the cardiovascular system.

Carbohydrates and regulation of body weight

The prevalence of overweight and obesity is rapidly increasing in Western countries and among affluent people in developing countries. It is therefore important to understand how carbohydrates may influence body weight.

The maintenance of stable body weight requires a balance between the total amount of energy consumed and the total amount of energy expended. Increases in body weight, specifically in body fat, occur when intake exceeds expenditure. There is no conclusive evidence that dietary sugars have a direct effect on either total energy intake (see below) or on energy expenditure in human subjects. However, current scientific evidence suggests strongly that the ratio of fat to carbohydrate consumed influences the regulation of body weight and that high-fat diets that are low in carbohydrates are more likely to promote weight gain and obesity than diets in which carbohydrates, including sugars, predominate.

The major reasons for this are as follows. High-carbohydrate meals are generally more bulky than high-fat meals, and carbohydrates are more satiating than fat, joule for joule (or calorie for calorie). Storage of carbohydrate in the body as glycogen is limited. When stores are full, the body adapts to oxidise any carbohydrate that is in excess of requirements. In comparison, storage of dietary fat is almost unlimited, and the body adapts only very slowly to oxidise excess fat. The human body has a limited ability to convert carbohydrate into fat, and under normal circumstances it is negligible. However, each gram of fat consumed has more than twice the energy content of each gram of carbohydrate. Thus, high-fat, energy-dense diets are more likely to promote passive over-consumption of energy. Energy balance is therefore more easily regulated at high carbohydrate intakes than at high fat intakes.

A substantial amount of research has demonstrated the importance of the energy density of the diet (joules or calories per gram) to energy intake and body weight regulation. Consumption of high-energy-density diets increases the chances that a positive energy balance, and therefore weight gain, will occur. Research consistently indicates that there is a spontaneous reduction in energy intake when the energy density of the diet is reduced. Low-energy-density diets are characterised as low in fat and high in carbohydrate- and fibre-rich foods such as cereal products, fruits, and vegetables.

Appetite, satiety, and food intake

Food intake is regulated by the complex interaction of physiological and psychological factors that are associated with eating and drinking. The energy density of food is an important determinant of the amount eaten, but other properties of food may also be important. These include palatability, macronutrient composition, and the relative proportions of solids and liquids.

Studies of the effects of individual carbohydrates on hunger, satiety, and food intake have yielded conflicting results because of the numerous methodological difficulties encountered in conducting this type of research. Overall, it seems unlikely that controlling a single dietary component, such as the type of sugar or starch, will have any significant effect on the amount of energy consumed, because this is also influenced by other components of the meal, including protein and dietary fibre.

The popular belief that sugar, because of its innate sweetness and hedonic properties, may over-ride the regulatory controls on food intake and promote excessive consumption is not supported by robust scientific evidence. Research suggests that many people prefer foods high in fat and sugar because of their palatability. A large European multicentre trial demonstrated that under conditions in which overweight subjects had *ad libitum* access to two low-fat diets, high either in sugars or in starchy carbohydrates, they lost similar amounts of body weight. However, it remains to be evaluated whether sugars obtained from soft drinks have a lesser satiating effect than sugars obtained from solid foods.

Carbohydrates and physical activity

Physical activity requires the metabolism of body fuel reserves to provide energy for muscle contraction. The nature of that fuel depends on whether the body is in a fasting or a postprandial state and on the intensity and duration of the activity. Under fasting conditions, the metabolism of fat provides the greater proportion of energy for resting metabolism and for muscle contraction at low exercise intensities. Under postprandial conditions, the greater part of energy for resting metabolism or low-intensity exercise comes from glucose metabolism. At greater exercise intensities, the metabolism of carbohydrate reserves, including liver and muscle glycogen and blood glucose, is also the predominant source of energy for muscle contraction. If the exercise requires more energy, because of its intensity or duration, then the proportion of energy generated by fat oxidation will gradually increase relative to that generated by glucose metabolism. Under normal circumstances, protein (in the form of amino acids) is only minimally metabolised as an energy reserve and is mobilised only under conditions of starvation or when carbohydrate reserves are at low levels.

In recent years the optimisation of performance by manipulation of carbohydrate availability has received much attention. It is now well established that endurance capacity can be improved dramatically by an increased intake of carbohydrate, which augments muscle and liver glycogen stores. For endurance sports activities, the amounts and types of dietary carbohydrates and the timing and frequency of consumption (during training, immediately before and during exercises, and immediately after) can be critical in determining the optimal availability of fuel for maximising performance. Pre-exercise consumption of carbohydrate ensures maximal availability of carbohydrate for substrate during the activity, whereas post-exercise carbohydrate consumption promotes the recovery of liver and muscle glycogen reserves. Performance in endurance activities can generally be improved by carbohydrate consumption during exercise. It is generally recommended that foods with a moderate to high GI be consumed after exercise.

The replacement of fluids and electrolytes lost during exercise is also important to performance. The effects of the ingestion of different carbohydrates on carbohydrate reserves and performance, and of other components such as fluid and electrolytes, at various times during different types of exercise and during the recovery period, have been the subject of extensive investigation. Glucose, maltose, sucrose, and maltodextrins are all absorbed and oxidised at high rates and have been used as components of sports drinks. However, if the carbohydrate concentration of the drink is too high, gastric emptying is reduced and the water and carbohydrate become less available for absorption.

Research suggests that the consumption of glucose, sucrose, or glucose polymers (4–5 g/kg body weight) 3 to 4 hours before exercise, and a more dilute source of carbohydrate (1–2 g/kg body weight) 1 hour before exercise, will elevate or maintain blood glucose levels, enhance carbohydrate oxidation during exercise, and improve endurance. During exercise, when replacing fluid loss is a priority, the greatest rate of water replacement can be achieved by using dilute solutions of carbohydrate (30–70 g/L) and sodium salts.

Carbohydrates and human behaviour

The idea that food, specifically sucrose, might adversely affect behaviour dates back to the early 1920s. It gained more attention in 1947, with the description of "tension fatigue syndrome", attributed to sugar. A plausible mechanism for proposed links between carbohydrate and behaviour was developed in the early 1970s, when increases in the synthesis of the brain neurotransmitter 5-hydroxytryptamine (serotonin) in response to carbohydrate consumption were demonstrated in animal studies. Serotonin is involved in the regulation of many aspects of human behaviour, including mood, sleep, and appetite.

Mood and cognition

The hypothesis that carbohydrate consumption may alter mood because of effects on brain serotonin has driven much research in this area. However, results in healthy experimental subjects, mostly conducted at lunchtime, have shown either no specific effect of carbohydrate, or no difference between high- and low-carbohydrate meals. Alterations in mood, including anger, depression, and reductions in vigour, have been reported in the early afternoon, irrespective of the type of food eaten at lunchtime. There is stronger evidence that some individuals use carbohydrate to counteract negative mood states in various situations, including tobacco and alcohol withdrawal, premenstrual syndrome, seasonal affective disorder, and obesity.

There is increasing evidence that carbohydrate, but specifically glucose, can influence central nervous system activity and enhance cognitive function. The retention of memory is an important part of cognition and has been the focus of research both in animals and in different groups of human subjects, including children and elderly people. Acute doses of glucose have been shown to improve memory function within 1 hour. Some studies suggest that the effects vary with the complexity of the task. The effect is most evident in elderly subjects, who may have pre-existing memory deficits. However, positive effects have also been seen in cognitive tests in children after consumption of a carbohydrate-containing drink. More research is required before conclusions about the practical implications of these findings can be made.

Sugar and hyperactivity

During the 1970s, the idea that sugar intake was associated with hyperactive behaviour in children, and even with criminal and antisocial behaviour, prevailed strongly, especially in the United States. It has been investigated by numerous research studies over the past fifteen to twenty years. An analysis of the results from these studies does not support the hypothesis that sucrose affects hyperactivity or adversely influences attention span or cognitive performance in children.

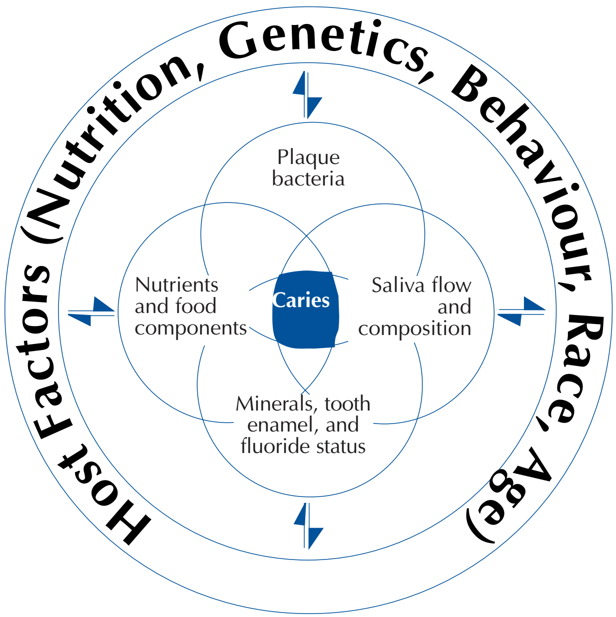
Carbohydrates and oral health

Dental caries is one of the most widespread conditions affecting the oral cavity. It is a multifactorial disorder in which both bacteria and fermentable carbohydrate play key roles, generating acids that demineralise the hard tissues of the teeth.

Development of dental caries

The various interacting factors involved in the development of caries are illustrated in Figure 8. Cariogenic plaque bacteria play a central role, especially species that ferment sugars to produce lactic acid. These bacteria may be relatively harmless when present in thin layers, but when they accumulate as thick layers of plaque on the surfaces of the teeth, they are cariogenic. Salivary flow and composition are also important. Saliva protects teeth by its buffering action, preventing extremes of acidity and alkalinity. It also contains antibacterial substances and is a source of minerals, including calcium, phosphorus, and fluoride, which counteract the acid demineralisation of the enamel and promote remineralisation of early lesions. The incorporation of fluoride during remineralisation, such as from fluoride added to toothpaste, generates enamel that is more resistant to decay.

FIGURE 8
Factors influencing the development of dental caries



Source: Navia, J.M. (1994). Carbohydrates in human nutrition: the importance of food choice in a high-carbohydrate diet. *American Journal of Clinical Nutrition*, HighWire Press, Palo Alto, CA, USA. © American Society for Clinical Nutrition

Starches and sugars are important components of food residues trapped in niches in the mouth. They provide the nutrients for the bacteria and the material for the development of plaque. Carbohydrates cause no direct damage to the teeth, but their presence can promote caries by creating conditions for local fermentation and acid accumulation. Starches are readily hydrolysed and fermented, and under certain circumstances they are as able to promote caries as sugars, especially when present in forms that adhere to the teeth or lodge in niches between them.

There are various ways to minimise the risks of dental caries and improve oral health. A key approach is improved oral hygiene involving the removal of food residues and dislodging of plaque by regular brushing with a fluoride-containing toothpaste. Additional sources of fluoride are water, tea supplements, and rinses. Controlling the frequency of eating and drinking occasions, to allow remineralisation between them, also has an important role. Hydrogenated carbohydrates (polyols), which are not fermented by the oral flora, are used as substitutes for sugar in sugar-free confectionery and chewing gum. Overall there have been notable declines in the prevalence of caries in developed countries in the past thirty years, which reflects improvements in oral hygiene and the use of fluoride, especially in dental hygiene products.

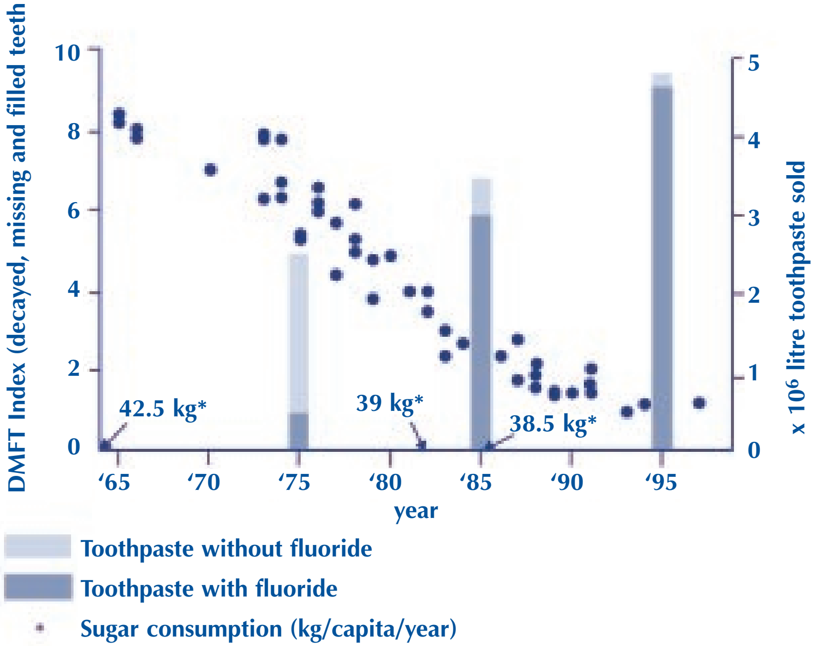
Sugars and caries prevalence

For many years, the role of sugars, specifically sucrose, has been emphasised in the aetiology of dental caries. However, sugars do not generate dangerous amounts of acids in the mouth when plaque is absent or is present only in thin layers, and the presence of fluoride protects against acid attacks.

Before the widespread introduction of fluoride and other improvements in oral hygiene, the association between sucrose consumption and dental caries was strong. A review of data from 47 nations up to the 1970s suggested that half of the variability in caries prevalence could be explained by sucrose availability. Over the past two decades, the situation has changed, and recent studies indicate that the prevalence of caries is well correlated with sucrose consumption only where oral hygiene is poor and where fluoride is absent, but not elsewhere.

FIGURE 9

DMFT of 12-year old children in the Netherlands, the sugar consumption per capita per year in 1961, 1982 and 1985 and the amount of toothpaste sold in the Netherlands



Adapted from: Gurr, M. (1995). Nutritional and Health Aspects of Sugars: Evaluation of New Findings. *ILSI Europe Concise Monograph Series*, ILSI Press, Washington, DC,USA.

In the Netherlands, for example, the prevalence of caries has declined rapidly in the past 25 years (Figure 9), although sucrose consumption is still more than 90% of what it was in 1965. In the United Kingdom, a study among young children (aged 1.5 to 4.5 years) demonstrated that the association between caries and the consumption of sugar confectionery was present only among children whose teeth were not brushed twice a day.

It can be concluded that although there is a relationship between the consumption of sugars and dental caries, the disease is complex. The diet plays a role in dental health by supplying nutrients to maintain mineralisation of the teeth, but it also supplies substrates for bacterial fermentation in the form of sugars and starches. Sugars are only one factor in the complex aetiology of caries, and it is not the amount of sugars but the frequency of intake that is important in the development of caries. Good oral hygiene and use of fluoride, together with a varied diet, are recommended for caries prevention.

GLOSSARY

Atherosclerosis: A disease of the arteries, in which fatty, fibrous plaques develop on the inner walls, eventually disrupting blood flow.

Carcinogen: A substance capable of causing cancer.

Degree of polymerisation (DP): The number of monosaccharide units in a specific carbohydrate.

Dietary fibre: The edible parts of plants or analogues of carbohydrates that are resistant to digestion and absorption in the small intestine and undergo complete or partial fermentation in the large intestine (American Association of Cereal Chemists, 2001).

Dyslipidaemia: Disordered blood lipid levels.

Endothelium: A layer of cells lining the inside of certain internal cavities such as the blood vessels.

Epithelium: The tissue covering external surfaces, such as the skin, and lining internal cavities, such as the intestine, consisting of a single layer of cells.

Enterocyte: The predominant cell type of the small intestinal mucosa, responsible for enzyme production and nutrient transport.

Epidemiology: The study of disease in relation to populations.

Fibrinolysis: The process by which blood clots are dissolved and removed from the circulation.

Gelatinisation: Formation of a gel.

Glycaemic index (GI): A comparison of the rise in blood glucose concentration produced by a standard amount of a test food to that produced by the same amount of a standard (reference) food in the same person.

Glycogen: The main form of storage carbohydrate in the body. It consists of branched chains of α-linked glucose units.

Glucagon: Hormone secreted by the pancreas that causes a release of glucose from the liver, resulting in an increase in blood glucose level.

HDL (high-density lipoprotein) cholesterol: Cholesterol carried on specific proteins in the blood out of the wall of the arteries. High levels are associated with a reduced risk of cardiovascular disease.

Hyperglycaemia: Abnormal elevations of blood glucose levels.

Hyperlipidaemia: Abnormal elevations of fat (lipids) in the blood, including triglycerides and cholesterol.

Hypertension: High blood pressure (excessive elevation of blood pressure, which is associated with an increased risk of organ damage, including stroke).

Hypertriglyceridaemia: Elevation of triglycerides (triacylglycerols) in the blood.

Insulin: Hormone secreted by the pancreas that has a central role in the control of carbohydrate metabolism by lowering blood glucose levels.

Insulin resistance: An impairment of insulin action, especially the insulin-stimulated uptake of glucose by tissues, the inhibition of glucose output by the liver, and the inhibition of fat breakdown.

LDL (low-density lipoprotein) cholesterol: Cholesterol carried on specific proteins from the liver to other tissues. High levels are associated with an increased risk of heart disease.

Microflora: A bacterial population.

Postprandial: Occurring after a meal.

Prebiotic: Non-digestible food components that benefit the host by selectively stimulating the growth and/or activity of one or a limited number of beneficial bacteria in the colon.

Probiotic: A live microbial food ingredient that is thought to be beneficial to health.

Phytochemicals: Plant chemicals often associated with health effects.

Triglycerides (triacylglycerols): The most common form of fat molecule, consisting of a molecule of glycerol linked to three fatty acid molecules.

Very low density lipoprotein (VLDL): Triglyceride-rich lipoprotein secreted into the blood by the liver.

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