The Scientific Update involved consideration of a number of key issues that have arisen since the Joint FAO/WHO Expert Consultation on Carbohydrates in Human Nutrition was held in 1997 (FAO, 1998) or where new data may have altered conclusions drawn some 10 years ago. The Scientific Update enabled some firm conclusions to be drawn and identified a number of areas where more research is required to enable definitive recommendations. The review papers prepared as part of this Scientific Update applied the criteria used by the 2002 WHO/FAO Expert Consultation on Diet, Nutrition and the Prevention of Chronic Diseases to describe strength of evidence for drawing the conclusions of the scientific review (WHO, 2003). The following are agreed-upon summaries of both the review papers, and discussions from the authors’ meeting (Geneva, 17–18 July 2006) on each issue area.

The experts who participated at the authors meeting were: John H Cummings, Hans Englyst Timothy Key, Simin Liu, Jim Mann (Chairman), Rob van Dam, Bernard Venn, Carolyn Summerbell (Rapporteur), Gabriele Riccardi, Ricardo Uauy, HH Vorster (Rapporteur) and Martin Wiseman. The FAO Secretariat members were Kraisid Tontisirin and Frank Martinez Nocito and the WHO Secretariat members were Chizuru Nishida and Denise Costa Coitinho.

Terminology and classification

Terminology and classification of carbohydrates remain difficult issues. The Scientific Update endorsed the primary classification, recommended by the 1997 Expert Consultation, based on chemical form, while acknowledging that classification of carbohydrates based on chemistry should also have dimensions of physical effects (food matrix), functional/physiological effects and health outcomes (Cummings and Stephen, 2007). The chemical classification provides a practical basis for measurement and labelling, but does not allow a simple translation into nutritional effects. Each chemical class of carbohydrate has overlapping physiological properties and health effects. As a result several terms have been used to describe their functional properties. For example, many terms exist to describe sugars in the diet. While it is straightforward from an analytical point of view to determine the total sugar content of food and their division into monosaccharides and disaccharides, it is acknowledged that the nature of the food matrix may influence the nutritional effects of foods-containing sugars. The term free sugars, defined as ‘all monosaccharides and disaccharides added to foods by the manufacturer, cook or consumer, plus sugars naturally present in honey, syrups and fruit juices’ (WHO, 2003), describes sugars which may have different physiological consequences from sugars incorporated within intact plant cell walls. This concept, which has been recommended by the 2002 WHO/FAO Expert Consultation (WHO, 2003), is theoretically useful to nutritionists but there is currently no standardized approach to their determination.

The terms ‘prebiotic’, ‘resistant starch’ and ‘dietary fibre’ are used to indicate some of the physiological properties and health effects of oligosaccharides and polysaccharides. The concepts of ‘prebiotic’ and ‘resistant starch’ are quite clearly defined. However, the current existence of several definitions of dietary fibre, reflecting different physiological and botanical properties or health effects of a range of naturally occurring and synthetic carbohydrates and their associated substances has resulted in confusion. The Scientific Update considered that the term ‘dietary fibre’ should be reserved for the cell wall polysaccharides of vegetables, fruits and whole-grains, the health benefits of which have been clearly established, rather than synthetic, isolated or purified oligosaccharides and polysaccharides with diverse, and in some cases unique, physiological effects. Thus, the Scientific Update agreed to define ‘dietary fibre’ as ‘intrinsic plant cell wall polysaccharides’.

It is acknowledged that certain fibre rich whole foods (for example, pulses) can affect glycaemic control in diabetes,
Characterization and measurement

Carbohydrate determinations should describe chemical composition accurately, and provide information of nutritional relevance (Englyst et al., 2007). The traditional calculation of carbohydrate 'by difference' does not conform to either of these criteria as it combines the analytical uncertainties of the other macronutrient measures and any unidentified material present, and a single value for carbohydrate cannot reflect the range of carbohydrate components or their diverse nutritional properties.

The first principle of chemical analysis is to ensure that the fraction of interest is completely extracted from the food matrix in its native form (for example, sugars), or dispersed to such an extent that it can be hydrolysed (for example, total starch and non-starch polysaccharides). Once appropriately isolated, oligosaccharides and polysaccharides may be subjected to enzymatic (adds specificity) or acidic (when appropriate enzyme is unavailable) hydrolysis to release their constituent sugars. Detection is then by gas chromatography or high-performance liquid chromatography, which can be used to measure specific monosaccharides, disaccharides and small oligosaccharides. More rapid colorimetric assays can be used to measure sugars with reducing groups, and individual sugar species can be determined with enzyme-linked assays.

There is more diversity of opinion regarding measurement of dietary components defined on the basis of functionality rather than chemical composition. However, the scientific update did recognize the nutritional importance of considering both chemical and food matrix aspects of carbohydrate-containing foods. Fundamental to any approach, where categorization is based on physiological or nutritional properties, is that they should be measured as chemically identified components. Such nutritional categories can reflect physiological fate (e.g. resistant starch), specific functionalities (e.g. prebiotics) or botanical origin (e.g. free sugars, dietary fibre).

In view of the considerable interest in the health effects of dietary fibre, much discussion centred around the various approaches to its measurement. Indigestibility in the small intestine was not considered to be a satisfactory basis for the definition of dietary fibre. It was agreed that the term 'dietary fibre' be limited to polysaccharides that are intrinsic to the plant cell wall, and the methods for measuring dietary fibre are, therefore, those which can reliably quantify the component polysaccharides. Direct chemical measurement was favoured over empirical gravimetric methods for this purpose.

Physiology

Carbohydrates are the principal energy source in the diets of most people and have a special role to play in energy metabolism and homoeostasis. Despite this the energy values of some carbohydrates continue to be debated. This is because of the use of different energy systems such as combustible, digestible and metabolizable. Furthermore, ingested macronutrients may not be fully available to tissues and the tissues themselves may not be fully able to oxidize substrates made available to them. Therefore, for certain carbohydrates the discrepancies between combustible energy, digestible energy, metabolizable energy (ME) and net metabolizable energy (NME) may be considerable.

In defining the role that carbohydrate plays in metabolism it is important to realize that the site, rate and extent of carbohydrate digestion in and absorption from the gut is key to understanding the many roles that this group of chemically related compounds and their metabolic products play in the body. However, even the concept of digestibility has different meanings. Within the nutrition community it is an accepted convention that digestion occurs in the small (upper) bowel, while fermentation occurs in the large (lower) bowel. Although both processes result in the breakdown of food and absorption of energy yielding substrates, the term digestibility is reserved for events occurring in the upper gut. However, in the discussion of the energy value of foods digestibility is defined as the proportion of combustible energy that is absorbed over the entire length of the gastrointestinal tract. For the sake of determining energy values of carbohydrate that are of practical use, and of ascribing health benefits to individual classes of them, some coherence needs to be brought to the use of the terms digestible, digestion and digestibility and to integrating the whole of the gut process into the equation of energy balance.

Three food energy systems are in use in food tables and for food labelling in different countries and regions in the world based on selective interpretation of the digestive physiology and metabolism of food carbohydrates. These are the systems which employ the Atwater specific factors; the Atwater general factors (17, 17, 37 kJ/g for carbohydrate, protein and fat, respectively); NME factors (typically applied to polyols) (Elia and Cummings, 2007). This is clearly
unsatisfactory and confusing to the consumer. Food labelling policy should aim to establish a system that avoids bias as far as possible using a practical user-friendly system. While it has been suggested that an enormous amount of work would have to be undertaken to change the current ME system into an NME system the additional changes may not be as great as anticipated. The key issues are the extent to which the underlying physiological considerations are sound, the extent to which they should drive food-labelling policy and the extent to which food energy system(s) should become consistent within and between regional jurisdictions.

The role of carbohydrate as a regulator of appetite and energy expenditure is a subject for intensive study, propelled by the rise in obesity in many countries. Carbohydrate is generally more satiating than fat, but less satiating than protein. However, studies of eating behaviour indicate that appetite regulation does not unconditionally depend on the oxidation of one nutrient and argues against the operation of a simple carbohydrate oxidation or storage model of feeding behaviour to the exclusion of other macronutrients. The control of appetite operates through a system with many redundancies that does not rely overwhelmingly on one or two major factors, such as energy density or on a specific macronutrient. Rather it depends on multiple factors that can interact, compensate or override each other, depending on environmental exposures and their duration. These include sensory factors, diet composition and variety of available food items, eating environment and individual subject characteristics, such as age, habitual dietary intake and prior social conditioning. It has been difficult to establish the relative importance of these factors, which are likely to differ with the environmental setting. In the light of this evidence, the role of different types of carbohydrates on eating behaviour might not be expected to have large effects on long-term energy homoeostasis and intervention studies are generally consistent with this view.

Carbohydrates that reach the large bowel enter a very different type of metabolism, determined by the anaerobic microbiota of this organ and in so doing exert an important influence on its function. However, uncertainty remains regarding the exact amounts and types of carbohydrate that reach the caecum and are available for fermentation, largely because of the difficulties of studying this area of the gut and of variations in food processing, stage of maturity at which plant foods are eaten, post harvest changes, day to day fluctuations in food intake and individual differences in gut function. Current estimates of the amount of non-starch polysaccharide + resistant starch + non-α-glucan oligosaccharides + polysols + lactose that reach the large bowel are between 20 and 40 g/day in countries with ‘westernised’ diets, while they may reach 50 g/day where traditional staples are largely cereal or diets are high in fruit and/or vegetables.

Since the 1997 FAO/WHO Expert Consultation (FAO, 1998), there has been progress in understanding the role of these ‘unavailable’, but fermented, carbohydrates in the large bowel. Non-starch polysaccharide clearly affect bowel habit and so does resistant starch, but to a lesser extent. However, the non-α-glucan oligosaccharides or non-digestible oligosaccharides have little laxative role, if any, although they do affect the composition of the flora. This latter property has led to the invention of the term ‘prebiotic’, which designates the selective effect of these carbohydrates on the flora, in particular their capacity to increase numbers of Bifidobacteria and Lactobacilli without growth of other genera. This now well-established physiological property has not so far led through to clear health benefits. There is some evidence that use of prebiotic supplements increases absorption of calcium, but this has not been consistently observed. Prebiotics are incorporated into some brands of infant formulae, and a range of food for adults.

### Overweight and obesity

The prevalence of overweight and obesity has increased rapidly worldwide during recent decades reaching epidemic proportions in children and adults in both industrialized and developing countries, in particular those which are going through rapid economic transition. Carbohydrates are among the macronutrients that provide energy and can thus contribute to weight gain when consumed in excess of energy requirements. If energy intake is strictly controlled, macronutrient composition of the diet (energy percentages of fat and carbohydrates) does not substantially affect body weight or fat mass. However, an important issue is whether, among free-living individuals, the macronutrient composition of the diet affects the likelihood of passive overconsumption. There is no clear evidence that altering the proportion of total carbohydrate in the diet is an important determinant of energy intake. However, there is evidence that sugar-sweetened beverages do not induce satiety to the same extent as solid forms of carbohydrate and that increases in consumption of sugar-sweetened soft drinks are associated with weight gain (van Dam and Seidell, 2007). Thus, there is justification for the recommendation to restrict the consumption of beverages high in free sugars to reduce the risk of excessive weight gain. Solid foods high in free sugars tend to be energy dense and there is some evidence from intervention studies that reduction of solid foods high in free sugars can contribute to weight loss. Thus, the outcomes of the Scientific Update support the population nutrient intake goals on free sugars (that is, <10% of total energy) that were recommended by the 2002 WHO/FAO Expert Consultation (WHO, 2003). A high content of dietary fibre in whole-grain, vegetables, legumes and fruits is associated with relatively low energy density, promotion of satiety and in observational studies a lesser degree of weight gain than among those with lower intakes. Although it is difficult to establish with certainty that dietary fibre rather than other dietary attributes are responsible, it is considered appropriate to recommend that whole-grain cereals, vegetables, legumes and fruits are the most appropriate sources of dietary carbohydrate. The available evidence is considered
insufficient for the use of glycaemic index (GI) of carbohydrate-containing foods to predict the likelihood of their ability to reduce the risk of obesity in normal weight individuals or promote weight loss in those who are overweight or obese.

Glycaemic index and glycaemic load

The 1997 FAO/WHO Expert Consultation suggested that the concept of GI might provide a useful means of helping to select the most appropriate carbohydrate-containing foods for the maintenance of health and the treatment of several diseases (FAO, 1998). It is acknowledged that choice of carbohydrate-containing foods should not be based solely on GI since low-GI foods may be energy dense and contain substantial amounts of sugars, fat or undesirable fatty acids that contribute to the diminished glycaemic response but not necessarily to good health outcomes. The inter-individual variation in glycaemic responses to foods is a further limitation of the GI concept and underlines the need to study a larger number of subjects under standard conditions than have been investigated previously to obtain more precise estimates of the GI of individual foods. In addition to the inter-individual variation, responses in a single individual are not necessarily consistent. Despite these reservations it does appear that distinguishing between foods with appreciable differences in the indices may produce some benefit in terms of glycaemic control in diabetes and lipid management. The benefits demonstrated in randomized-controlled trials are smaller than those conferred by other dietary and lifestyle changes especially those which facilitate weight loss in the overweight and obese (Venn and Green, 2007). Although some data suggest that the dietary fibre content of the foods does not explain the low-GI effect it remains conceivable that food structure or composition explain some of the health benefits.

The limitation of the GI concept may apply especially to some of the manufactured products that have been GI tested and are available in many countries. Given that most of the studies which have demonstrated a health benefit of low GI involved the use of naturally occurring and minimally processed foods, it would seem to be appropriate for manufactured foods to be further examined rather than to assume health benefits only on the basis of their functionality (that is, a low-glycaemic response).

GI is perhaps most appropriately used to guide food choices when considering similar carbohydrate-containing foods, for example bread with a low GI may be preferable to a higher GI bread, with a resultant lower glycaemic load (GL). Ideally, GI should be measured in a relatively larger group of individuals, but even then should be interpreted in the knowledge of the inter- and intra-individual variation. Furthermore, GI and GL should always be considered in the context of other nutritional indicators.

Carbohydrates in the aetiology of diabetes and cardiovascular disease

The Scientific Update also considered the relationship between dietary carbohydrate and cardiovascular disease, disorders of carbohydrate metabolism and cancer. A wide range of intakes of carbohydrate-containing foods is acceptable in the context of dietary patterns, which are protective against cardiovascular disease, diabetes and prediabetic states. The nature of carbohydrate eaten is important. Whole-grains, legumes, vegetables and intact fruits are the most appropriate sources of carbohydrate. There is impressive evidence that they are associated with a reduced risk of cardiovascular disease, although inconsistencies with regard to the definition of whole-grain explain why the cardiovascular effect of fruits and vegetables was described by the 2002 WHO/FAO Expert Consultation (WHO, 2003) as ‘convincing’ whereas the protective effect of whole-grains was graded as ‘probable’. These carbohydrate-containing foods are rich sources of dietary fibre (defined as non-starch polysaccharide in the 2002 WHO/FAO Expert Consultation), which protects against type II diabetes, and other cardioprotective components. However, there is no good evidence of protection against cardiovascular disease and diabetes when various oligosaccharides or polysaccharides or other isolated components of whole-grains, fruits, vegetables and legumes are added to functional and manufactured foods. This provides further justification for defining dietary fibre as ‘intrinsic plant cell wall polysaccharide’ as developed through this Scientific Update. Both the 1997 FAO/WHO Expert Consultation and the 2002 WHO/FAO Expert Consultation recommended that total carbohydrate should provide 55–75% total energy and that intake of fruits and vegetables (excluding tubers, for example, potatoes and cassava) should be 400 g/day or more. Precise amounts of dietary fibre as non-starch polysaccharide were not recommended by the 2002 WHO/FAO Expert Consultation (WHO, 2003). It was considered that the recommended intakes of fruit, vegetables, legumes and regular consumption of whole-grain cereals would provide adequate intakes of total dietary fibre. These recommendations of the 2002 WHO/FAO Expert Consultation are compatible with the outcomes of the Scientific Update, although some caveats are suggested. Given that a wide range of carbohydrate intakes is compatible with cardioprotection and that many western countries have average intakes that are below 55% of total energy intakes, the conclusion of the Scientific Update was that a lower limit of around 50% total energy was acceptable. Several national guidelines suggest a lower limit of 50%. It is more important to be prescriptive with regard to the nature of dietary carbohydrate, especially when total carbohydrate intakes are at the upper end of the recommended range. Failure to emphasize the need for carbohydrates to be derived principally from whole-grain cereals, fruits, vegetables and legumes may result in increased lipoprotein-mediated risk of coronary heart disease, especially with an
increase in the ratio of total low-density lipoprotein cholesterol to high-density lipoprotein cholesterol and an increase in triglycerides. This may apply particularly to overweight and obese individuals who are insulin-resistant. A low-dietary GI may reduce the risk of type II diabetes and cardiovascular disease but similar caveats to those described for GI apply when interpreting such observations.

Carbohydrates in the treatment of diabetes and cardiovascular risk factors

Similar issues to those described above relating to dietary carbohydrate and disease prevention apply to the management of people with diabetes and to those with risk factors for cardiovascular disease, especially to those with abnormal lipid profiles. While legumes, pulses and certain fruits, vegetables and cereal grains appear to confer particular benefit in terms of reducing glycaemia and lowering low-density lipoprotein cholesterol, difficulties of measurement and the possibility that other constituents of plant foods may be involved preclude the definitive conclusion that the content of ‘soluble’ dietary fibre is the determinant of this effect (Mann, 2007). Low-GI foods may confer benefits in terms of improving glycaemic control in people with diabetes. However, it is not clear whether these benefits are fully independent of the effects of dietary fibre or the fact that foods with intact plant cell walls tend to have low GI. Furthermore, it is uncertain whether functional and manufactured foods with a low GI confer the same long-term benefits as low GI predominantly plant-based foods.

Cancer

The review relating to cancer concluded that the most frequently observed association with carbohydrates was that between low intakes of dietary fibre and increased risk for colorectal cancer. However, it was noted that the data were not entirely consistent. The possible links between high intakes of sucrose and colorectal cancer and high intakes of lactose and ovarian cancer were considered to be rather more tenuous. The link between obesity and several cancers was considered to be convincing (Key and Spencer, 2007), thus, nutritional determinants of obesity may be regarded as causally related to all obesity-related cancers. Key and Spencer (2007) noted that the World Cancer Research Fund Report (WCRF) on Diet and Cancer to be published in November 2007 was likely to generate more definitive data on nutritional determinants of cancer than had previously been available.

Discussion

The Scientific Update has enabled us to draw a number of important conclusions. The importance of improving the definition of dietary fibre was discussed and it was agreed that the definition should be based on well-established health benefits and the ability to fulfill regulatory requirements. We, therefore, proposed that dietary fibre should be defined as intrinsic plant cell wall polysaccharides. Thus the method(s), which enable the measuring of the component polysaccharides would be appropriate for determining dietary fibre as defined above. The three food energy systems currently used in food tables and for labelling continue to create confusion for the consumer. There is an urgent need for an internationally agreed readily understood system, and further consideration of the net metabolizable energy approach is suggested. Review of the recent literature endorses the recommendations of the 2002 WHO/FAO Expert Consultation concerning the restriction of beverages high in free sugars and the limitation of total intake of free sugars to reduce the risk of overweight and obesity. The positive messages of that consultation are also endorsed, notably the potential of whole-grains, legumes, vegetables and intact fruits to protect against diabetes and cardiovascular disease. Many of these foods, high in dietary fibre, help to improve glycaemic control in people with diabetes and to reduce cardiovascular risk factors. However, while foods with a low GI may also confer benefit in some of these contexts, the Scientific Update suggested caution regarding the use of the GI as the sole determinant of the quality of carbohydrate-containing foods. Given the association between obesity and cancer at several sites and the possibility that dietary fibre may reduce the risk of colorectal cancer, the dietary messages aimed at reducing the risk of obesity, diabetes and cardiovascular disease have the potential to also reduce cancer risk.

Finally, the need to review the current recommended range for dietary carbohydrate intake (55–75% total energy) was identified. There appeared to be insufficient justification for the recommended lower limit, therefore a possible revision to 50% was suggested. A wide range of intakes, as a proportion of total energy intake, is compatible with low risk of chronic diseases although excess intake of any macronutrient is likely to lead to obesity. The nature of dietary carbohydrate appears to be a more important determinant of health outcomes than the proportion of total energy derived from carbohydrate intake. It is hoped that these papers will stimulate discussion among the scientific community and relevant health professions and inform the formal Expert Consultation on Carbohydrate to be convened in the foreseeable future.

Conflict of interest

During the preparation and peer-review of this paper in 2006, the authors and peer-reviewers declared the following interests.

Experts

Professor John Cummings: Chairman, Biotherapeutics Committee, Danone; Member, Working Group on Foods with Health Benefits, Danone; funding for research work at the University of Dundee, ORAFTI (2004).
Dr Hans Englyst: Director and share-holder of Englyst Carbohydrates Ltd—a small research-oriented company working on dietary carbohydrates and health within the Medical Research Council. The UK Food Standards Agency is the main research partner and sponsor. In addition, Englyst Carbohydrates provide analytical assistance and reagents to universities and food industry worldwide, albeit on a small scale. The complete independence of Englyst Carbohydrates is maintained by not entering into any consultancy agreement.

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