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The importance of dietary carbohydrates

Claudia P. Sánchez-Castillo, Geoffrey J. Hudson, Hans N. Englyst, Peter Dewey and W. Philip T. James

Instituto Nacional de Ciencias Médicas y Nutrición Salvador Zubirán, Mexico D.F., MRC Dunn Clinical Nutrition Centre, Cambridge UK, The Rowett Research Institute, UK

SUMMARY. Forty years ago carbohydrates (CHO) were regarded as a simple energy source whereas they are now recognized as important food components. The human diet contains a wide range of CHO, the vast majority of which are of plant origin. Modern techniques based on chemical classification of dietary CHO replaced the traditional "by difference" measurement. They provide a logical basis for grouping into categories of specific nutritional importance. The physiological effects of dietary CHO are highly dependent on the rate and extent of digestion and absorption in the small intestine and fermentation in the large intestine, interactions which promote human health. Current knowledge of the fate of dietary CHO means that the potentially undesirable properties of many modern foods could be altered by using processing techniques that yield foods with more intact plant cell wall structures. Such products would more closely resemble the foods in the pre-agriculture diet with respect to the rate of digestion and absorption of CHO in the small intestine. The potentially detrimental physiological consequences of eating sugars and starch that are rapidly digested and absorbed in the small intestine suggest that, as fibre, the form, as well as the amount of starch should be considered. Increasing consumer awareness of the relationship between diet and health has led to demands for more widespread nutrition labelling. The entry "carbohydrate" is required in most countries, and the value is usually obtained "by difference" and used in the calculation of energy content. However, the value provides no nutritional information *per se*. Food labels should provide values that aid consumers in selecting a healthy diet.

Key words: Carbohydrates, classification, health, food labelling.

RESUMEN. Importancia de los hidratos de carbono. Hace 40 años los hidratos de carbono (HC) eran considerados como simple fuente de energía. Ahora se reconocen como componentes importantes de alimentos. La dieta humana contiene una amplia variedad de HC de los cuales la gran mayoría proviene de plantas. Las técnicas modernas basadas en clasificación química de HC han sustituido la medición tradicional «por diferencia» y proporcionan una base lógica para agrupar en categorías específicas de importancia nutricia. Los efectos fisiológicos de los HC de la dieta dependen en gran medida de la tasa y grado de digestión y absorción en el intestino delgado, así como de su fermentación en el intestino grueso. Estas interacciones promueven la salud. El conocimiento actual del destino de los HC de la dieta significa que los propiedades potencialmente indeseables de muchos alimentos modernos pudieran ser alteradas utilizando técnicas de procesamiento que den lugar a alimentos con estructuras de paredes celulares mas intactas. Estos productos se asemejarían mas, con respecto a las tasas de digestión y absorción de los HC en el intestino delgado, a los alimentos que se utilizaban antes que surgiera la agricultura. Las consecuencias fisiológicas potencialmente nocivas de ingerir azúcares y almidones que son digeridos y absorbidos rápidamente en el intestino delgado, sugiere que, de manera similar a la fibra, deben considerarse tanto su forma como la cantidad de almidón. La conciencia cada vez mayor del consumidor de la relación entre dieta y salud, ha motivado una demanda cada vez mas insistente de información nutricia en el etiquetado de alimentos. En la mayoría de los países se introduce en la etiqueta el término «carbohidratos», y este valor usualmente se obtiene «por diferencia» y se utiliza en el cálculo del contenido de energía. Este valor, sin embargo, no proporciona información nutricia *per se*. Las etiquetas en alimentos deben proporcionar valores que ayuden a los consumidores a seleccionar una dieta saludable.

Palabras clave: Hidratos de carbono, clasificación, salud, etiquetado alimentos.

INTRODUCTION

Starchy foods are the world's most abundant staples and the nutritional value of these foods is of great importance to health. The human digestive system is evolutionarily adapted to cope with the Hunter-Gatherer diet that prevailed until about 10,000 years ago. In comparison with the modern 'Western' diet, the Hunter-Gatherer diet contained far less fat and far more plant cell walls (dietary fiber). Starch in the Hunter-Gatherer diet was derived mainly from roots, beans, fruits and tubers; cereal grains were not a major component of this diet. The natural encapsulation of starch and sugars within undamaged plant cell walls in the raw or lightly processed foods typical of the Hunter-Gatherer diet slows the rate of digestion, resulting in a sustained release of glucose. Modern starchy food products are, however, mainly cereal-based and often finely milled, so that the plant cell walls are disrupted; furthermore the starch is often fully

gelatinized during processing. Thus the release of starch from within the cell walls, which may be removed during refining, and the gelatinization of the starch leads to rapid digestion and absorption of the starch in the small intestine, contrary to the fate of the starch in the Hunter-Gatherer diet. There are strong indications that the large amounts of rapidly available glucose derived from starch and free sugars in the modern diet, in combination with the consumption of discrete meals, lead to periodic elevated levels of plasma glucose and insulin. These could prove to be detrimental to health and enhance the risk of such diseases as diabetes, coronary heart disease and cancer.

The time-scale of dietary change is too short for there to have been any significant evolutionary adaptation of the human gut to the cereal-based diets introduced during the Agricultural Revolution 8-10,000 years ago and certainly not to the highly processed foods in the modern diet. However, current knowledge of the fate of dietary starch means that the potentially undesirable properties of many modern starchy foods can be changed by altering the food processing techniques to yield foods with a reduced rate of starch digestion in the small intestine. Such products would then more closely resemble the foods in the Hunter-Gatherer diet with respect to the rate of digestion of starch.

National dietary guidelines for 'Western' countries are consistent in their recommendations to increase intakes of dietary fiber and starch, and to decrease intakes of salt, fat and sugar with a moderation in red meat consumption becoming a commoner feature of recommendations. The advice to "Eat more dietary fiber in the form of fruits, vegetables, legumes, seeds and whole-grain cereals and not as fiber supplements" is based on the evidence (largely epidemiological) that a high-fiber, high-carbohydrate, low-fat diet is associated with lower prevalences of the so-called 'Western diseases' or the 'diseases of affluence', which constitute an ever-growing list and include obesity, type II diabetes, coronary heart disease, hypertension, hyperlipidemia, constipation, diverticulitis and a range of cancers. The advice to increase consumption of carbohydrates such as starch is widely accepted, but an issue arises as to whether all carbohydrates are of equivalent value and whether there are specific benefits of particular carbohydrates in addition to their acting as a source of energy and as a safer alternative to fat. Viewing carbohydrates as simply a reasonable substitute for fat has been favored by many physicians and nutritionists, especially in the United States, where the carbohydrate content of foods is still expressed as the calculated difference in weight of ingredients once fats, proteins and minerals have been subtracted from the dry weight of a food.

This paper focuses on the importance of dietary carbohydrates, including their classification, measurement, absorbability, the links to health-promoting effects and the implications for national and international dietary guidelines. The effects of food processing on dietary carbohydrates and their documentation in food tables are also considered, together with labeling issues.

Classification of food carbohydrates

The wide range of carbohydrates, mostly of plant origin, in the human diet has very varied physiological effects and it is therefore essential to know both the amounts and the types of carbohydrates in foods if we are to understand the food-related mechanisms that link dietary carbohydrates and health.

We advocate a scheme in which dietary carbohydrates are divided into the three major categories of free sugars, short-chain carbohydrates and polysaccharides. The polysaccharides may then be divided into starch and non-starch polysaccharides, and further divided to reflect nutritional properties (Table 1). Division of the carbohydrates into the three main groups relates to their degree of polymerization (DP), i.e. the number of monosaccharide units joined together: (i) the monosaccharides; (ii) the oligosaccharides, with DP values of two to about ten; (iii) the polysaccharides, i.e. those carbohydrates with DP values greater than about ten (1,2).

I. Free Sugars

Monosaccharides

Free glucose occurs in small amounts in fruits and vegetables, particularly grapes and onions, and, with fructose, is one of the main constituents of honey. Glucose is also manufactured from starch and sold commercially in a number of proprietary preparations. These have no advantage over sucrose as a routine source of energy for normal people, but may be useful in special high-energy drinks consumed by athletes during competitions.

Fructose is present as a free sugar in fruits, vegetables and honey. Fructose is present in invert sugar, a syrup made from sucrose, and is used extensively in the food industry. Other monosaccharides, including arabinose, xylose, mannose and glucose are present as free sugars in many plant foods but are quantitatively insignificant.

Disaccharides

Sucrose, a disaccharide of glucose and fructose (1-*O*-α-D-glucopyranosyl-β-D-fructofuranoside) is extracted commercially from sugar beet and sugar cane. Table sugar is 99% sucrose and is the major dietary source of this disaccharide, although it is present naturally in many fruits and vegetables. Sucrose is readily hydrolyzed by acids and by the enzyme sucrase in the brush border of the human small intestine into glucose and fructose.

TABLE 1
Classification of the carbohydrates in plant foods

Class/Components	Comments
Free Sugars	
Mono- and disaccharides and their alcohols	Physiological response depends on identity and rate of release. Free glucose + glucose from sucrose = FSG[1]
Short-Chain Carbohydrates	
Maltodextrins	Measured as rapidly digestible starch (RDS[2])
Resistant short-chain carbohydrates (Non-digestible oligosaccharides)	Fermented in the large bowel and may stimulate growth of bifidobacteria
Starch	
Rapidly digestible starch (RDS)	RDS + rapidly released FSG = RAG[3]
Slowly digestible starch (SDS[4])	SDS + slowly released FSG = SAG[5]
Resistant starch (RS[6])	Escapes digestion in the small intestine.
Non-Starch Polysaccharides (NSP[7])	
Plant cell-wall NSP	Encapsulate and slow absorption of other nutrients. Marker for naturally high-fibre diets for which health benefits have been shown Fermented in the large bowel to different extents
Other NSP	Food additives. Minor components of the human diet Fermented in the large bowel to different extents

[1] FSG, free-sugar glucose; [2] RDS, rapidly digestible starch; [3] RAG, rapidly available glucose; [4] SDS, slowly digestible starch; [5] SAG, slowly available glucose; [6] RS, resistant starch; [7] NSP, non-starch polysaccharides. (1,2).

Lactose is a disaccharide of glucose and galactose (4-*O*-β-D-galactopyranosyl-D-glucopyranose) that is found naturally only in milk and milk products. During childhood, lactose is hydrolyzed readily by the enzyme lactase; however, many ethnic groups lose the ability to produce lactase in adulthood, a condition known as lactose intolerance.

Maltose, a disaccharide of glucose (4-*O*-α-D-glucopyranosyl-D-glucopyranose), is a product of the hydrolysis of starch. It is present in malted (sprouted) wheat and barley, from which malt extract is produced commercially for use in brewing and the manufacture of malted foods.

Trehalose, a disaccharide of glucose (1-*O*-α-D-glucopyranosyl-D-glucopyranose), is known also as the mushroom sugar, since it constitutes up to 15% of the dry matter of mushrooms. Trehalose is also present in insects. The fact that humans possess the enzyme trehalase suggests that fungi and insects were much more important foods for our ancestors than they are for us now.

Sugar alcohols

Sugar alcohols, or polyols, occur naturally and are prepared commercially. They are used in large quantities by the food industry as sweeteners. Unlike sucrose, the sugar alcohols are not digested by oral bacteria and are therefore non-cariogenic. Sugar alcohols are not digested or absorbed in the human small intestine but are fermented by the microflora in the large intestine.

D-Glucitol is known also as sorbitol, since it occurs in fruits, such as cherries, of the genus Sorbus. The large quantities used in food manufacturing are produced by the hydrogenation of glucose. Sorbitol is used as a sweetener and as a humectant in many types of products. Sorbitol is very stable, can withstand high temperature and does not participate in Maillard (browning) reactions.

Xylitol, the sweetest polyol known, occurs naturally in many fruits and vegetables and is prepared commercially from hardwood trees. Xylitol is widely used as a non-

cariogenic bulking agent and sweetener in chewing gum, pharmaceuticals and oral health products.

Lactitol is produced by reducing the glucose part of the disaccharide lactose. It is used commercially as a bulking agent and sweetener in a variety of low-calorie, low-fat foods such as ice cream, chocolate, chewing gum and baked goods.

Isomalt, a derivative of sucrose, is used as a non-cariogenic, low-calorie alternative to sucrose in many products, e.g. ice cream, chewing gum, baked goods, fruit spreads and beverages.

II. Short-Chain Carbohydrates (SCC)

Short-chain carbohydrates (SCC) is a category that has been introduced to include the dietary carbohydrates other than free sugars that are soluble in 80% ethanol under prescribed conditions. This diverse category includes: (i) naturally occurring oligosaccharides, such as raffinose, stachyose and verbascose; (ii) small polysaccharides, such as inulin and other fructans. The fructans consist of chains of fructose residues, often terminating in a single glucose molecule, with DP ranging from 3 to 50, depending on the source. Shorter fructans predominate in cereals, whereas Jerusalem artichokes contain a larger proportion of inulin, a fructan with DP of about 35–50. Other sources of inulin are onions, garlic and asparagus.

(iii) Semi-synthetic and synthetic species. The latter includes Polydextrose (3) and a range of fructo-oligosaccharides. The resistant SCC (RSCC), are the SCC other than the maltodextrins, which are not susceptible to hydrolysis by endogenous enzymes but may be fermented by the microflora in the large intestine. Fructo-oligosaccharides, inulin and some other RSCC have been shown to stimulate selectively the growth of bifidobacteria; this is potentially beneficial to health.

III: Starch

Starch is the main storage polysaccharide of plants and is found in considerable amounts in dietary staples, such as cereal grains, potatoes and plantains. Starch is quantitatively the major carbohydrate in the human diet. Starch consists of two types of polysaccharide; amylose has a molecular mass of 10^3 to 5 x 10^5 Da and is a long, virtually unbranched chain of glucose units with $\alpha(1\rightarrow4)$ linkages. Amylopectin is much larger (up to 10^6 Da) and is a highly branched polymer with 15 to 30 $\alpha(1\rightarrow4)$ linked glucose units in each branch, the branches being joined by $\alpha(1\rightarrow6)$ linkages. The majority of starches contain between 15 and 35% amylose but the relative amounts of amylose and amylopectin vary widely among different plant sources, from 2% amylose in waxy corn starch to 80% amylose in high-amylose corn starch.

Starch is stored within the plant cells in the form of water-insoluble granules, which have shapes characteristic of each species. The amylose and amylopectin chains in the granules have a semi-crystalline structure, which retards their digestion by pancreatic amylase. When starch granules are heated in the presence of water, the crystalline structure is disrupted and the polysaccharide chains take up a random conformation, causing swelling of the starch granules (gelatinization). The starch is then readily accessible to digestive enzymes. On cooling, the gelatinized starch begins a process of recrystallization known as retrogradation. This occurs very rapidly for amylose, while the retrogradation of amylopectin, known to be responsible for the staling of bread, takes place over several days.

Because of the nature of the linkages between the glucose units, all dietary starch (including maltodextrins) is potentially degradable by the action of α-amylase. However, certain factors can reduce the rate at which starch is hydrolyzed and absorbed *in vivo*, thus delaying the appearance of glucose in blood after a meal. The magnitude of the rise in blood glucose after feeding one of these carbohydrate fractions is termed the glycemic response. For some foods, hydrolysis is hindered to such an extent that some starch passes into the colon.

Rapidly Digestible Starch (RDS)

As the name suggests, RDS is rapidly and completely digested and absorbed in the small intestine. RDS consists mainly of amorphous and dispersed starch and occurs typically in starchy foods that have been cooked by moist heat, e.g. bread and potatoes, where the starch is fully gelatinized.

Slowly Digestible Starch (SDS)

SDS, like RDS, is completely digested in the small intestine, but more slowly. This category includes starch that is poorly accessible to enzymes, such as a portion of that in milled grains and seeds, and in foods with a dense structure, e.g. pasta, and a high proportion of the granular starch in raw foods.

Resistant Starch (RS)

RS is defined as the starch (and starch degradation products) that escapes digestion in the small intestine and becomes available for fermentation by the microflora in the small intestine (4-6). RS may be measured as a single fraction of starch or subdivided into RS_1, RS_2 and RS_3. Physically inaccessible starch, which may be found in whole or partly milled grains and seeds, and in some very dense types of processed starchy foods, e.g. pasta, is termed RS_1. Starch that escapes digestion in the small intestine because the granules in, for example, raw potato and banana, are intrinsically highly resistant to hydrolysis by pancreatic amylase is termed RS_2. The third category, RS_3, is mainly retrograded amylose formed during the cooling and retrogradation of gelatinized starch. Most moist-heated,

starchy foods will therefore contain some RS_3 after cooling. The proportion of RDS, SDS and RS varies between foods (Table 2), depending partly on the source of starch, but largely on the type and extent of processing the food has undergone. The amounts and type of starch in foods are of great importance to health (see later).

TABLE 2
Starch fractions and RAG content of some starchy foods (g/100g as eaten)

Food	TS	RDS	SDS	RS	RAG
Cereals					
Pearled barley	17.1	8.0	7.0	2.1	9
Sweetcorn	17.1	15.4	1.4	0.3	18
Bread					
Wheat white	41.7	37.4	3.7	0.6	42
Wheat wholemeal	35.0	32.1	1.4	1.5	36
Biscuits					
Digestive	46.5	32.0	12.6	1.9	44
Oatmeal	55.9	48.8	6.2	0.9	55
Breakfast cereals					
All Bran	22.2	20.6	0.5	1.1	35
Oat bran	45.8	31.2	13.6	1.0	36
Porridge Oats	13.0	9.9	3.1	0.1	11
Rice Krispies	69.8	65.6	1.7	2.5	80
Weetabix	57.0	56.8	1.0	0.0	65
Rice					
Brown - long grain	23.8	14.6	9.2	0.0	16
White - long grain	23.0	17.4	5.6	0.0	19
Pasta					
Macaroni	26.2	13.4	12.0	0.8	15
White spaghetti	23.5	13.5	9.0	1.0	15
Legumes					
Butter beans	11.4	9.4	0.8	1.2	11
Chickpea	16.4	5.1	8.8	2.5	6
Frozen peas	7.2	4.1	1.0	2.1	6
Haricot beans	18.2	4.1	5.8	8.3	5
Red lentils	15.8	7.3	6.1	2.4	8
Tubers					
Instant potato	12.7	10.9	1.1	0.8	12
Potato	16.0	15.2	0.7	0.1	17
Potato crisps	50.0	42.7	2.8	4.5	48
Sweet potato	9.3	7.5	0.8	1.1	11
Yam	16.8	14.3	0.4	2.1	18

TS, total starch; RDS, rapidly digestible starch; SDS, slowly digestible starch; RS, resistant starch; RAG, rapidly available glucose. (21).

IV. Rapidly Available Glucose (RAG)

RAG is defined and measured as the sum of free sugar glucose and RDS. The considerable amounts of RAG in many modern processed foods result in periodic high blood glucose and insulin levels, which are both associated with a range of chronic diseases, including diabetes, coronary heart disease and cancer. The *in vitro* measured RAG and the *in vivo* assessed glycemic index (GI) (7) are highly correlated so these two measures are complementary tools which now can be suggested as potentially important indices of the carbohydrate links with human health.

V. Slowly Available Glucose (SAG)

SAG can be measured *in vitro* as the increase in glucose between 20 and 120 minutes of incubation with an enzyme mixture of invertase (to hydrolyze sucrose), pancreatic alpha-amylase and amyloglucosidase (8). RAG and SAG together represent all the glucose in a food that is likely to be available for absorption in the small intestine. RAG values for starchy foods have been shown to be highly correlated with average glycemic response. By inference, SAG values are likely to reflect the amount of glucose that will be more slowly absorbed, although direct measurements of slow glucose absorption *in vivo* are technically difficult. In practice, SAG and SDS values are identical, because free-sugar (FSG) values are included in RAG values for pragmatic reasons. In principle, however, RAG and SAG values are independent of the source of glucose; e.g. sugars and starch trapped within cell walls or a dense food matrix may be released and thus absorbed slowly. They could both therefore, at least in theory, contribute to SAG values. However, *in vitro* measurement techniques are not yet sufficiently sophisticated to separate the contributions of FSG and starch to SAG values.

VI. Non-Starch Polysaccharides (NSP)

Non-starch polysaccharides (NSP) consist of the polysaccharides other than starch that are insoluble in 80% ethanol under prescribed conditions (Table 1). In relation to human nutrition, the principal NSP are those that comprise approximately 90% (9) of plant cell walls (dietary fiber; see later).

Plant NSP may be separated into cellulose (β(1-4) glucan) and non-cellulosic polysaccharides, which are a very heterogeneous group whose main constituent sugars are arabinose, xylose, mannose, galactose, glucose and uronic acids. Table 3 shows the NSP content and composition (10,11) of four different types of food. The spectrum of the constituent sugars is characteristic for various types of plant NSP and may indicate the origin of the NSP measured. The values for wholemeal bread are characterized by high levels of insoluble NSP in the form of cellulose (measured as insoluble NSP) and arabinoxylans. Wheat NSP are slowly and incompletely

fermented (12) and are able to bind considerable amounts of water, thus serving to increase fecal bulk. Compared to wheat products, oats contain a greater proportion of soluble NSP, the main fraction of which is a β-glucan measured as soluble NSP glucose. Apples and carrots are typical of fruits and vegetables in general in having high levels of soluble NSP. The main NSP fraction of these foods is pectin, which is measured as soluble NSP uronic acids. Cereal products usually contain more xylose than arabinose and this is mostly in the soluble fraction. High values for uronic acids in measured overall NSP intakes indicate a diet rich in fruits and vegetables.

TABLE 3
NSP constituent sugars (g/100g dry matter)

Sample	NSP	(% DM)	NSP constituent sugars Rha	Fuc	Ara	Xyl	Man	Gal	Glc	Uac
Wholemeal	Sol	2.3	–	–	0.7	0.8	0.1	0.2	0.4	0.1
bread	Ins	6.9	–	–	1.8	2.7	0.1	0.1	2.0	0.2
	Tot	9.2	–	–	2.5	3.5	0.2	0.3	2.4	0.3
Oats	Sol	4.0	–	–	0.2	0.2	–	0.1	3.4	0.1
	Ins	3.1	–	–	0.7	1.0	0.1	0.1	1.1	0.1
	Tot	7.1	–	–	0.9	1.2	0.1	0.2	4.5	0.2
Apple	Sol	5.8	0.2	0.1	1.2	0.1	–	0.3	0.1	3.8
	Ins	7.5	0.1	0.1	0.9	0.7	0.3	0.6	4.5	0.3
	Tot	13.3	0.3	0.2	2.1	0.8	0.3	0.9	4.6	4.1
Carrot	Sol	11.4	0.7	–	1.7	–	0.1	3.0	–	5.9
	Ins	8.1	–	–	0.3	0.3	0.3	0.4	6.5	0.3
	Tot	19.5	0.7	–	2.0	0.3	0.4	3.4	6.5	6.2

DM, dry matter; Rha, rhamnose; Fuc, fucose; Ara, arabinose; Xyl, xylose; Man, mannose; Gal, galactose; Glc, glucose, UAc, uronic acids. (10,11)

Plant cell walls are composed largely (~90%) of NSP, and measurement of NSP values in unrefined plant foods provides a reliable index of dietary fiber (13).

The NSP, such as the gum mucilages that are not part of the plant cell wall, occurs naturally in only small amounts in most plant foods. Isolated non-cell wall NSP are used in food additives for their structural properties.

Dietary fiber

National guidelines recommend that dietary fiber is obtained naturally in the form of fruits, vegetables and whole-grain cereal products, where the encapsulation of starch and sugars by plant cell walls ensures their slow digestion and absorption. The beneficial effects of a true high-fiber diet, which is naturally low in fat and rich in both minerals and antioxidants, are related to many properties. 'Fiber supplements', such as wheat bran or guar gum, cannot restore these properties to refined plant foods and their use is discouraged in most guidelines. Foods labeled with their fiber content, when this is based on the measurement of plant cell wall non-starch polysaccharides (NSP), aid the consumer in the choice of a true high fiber diet for which health benefits are many (14).

Methods of measurement of dietary carbohydrates

The measurement of chemically distinct categories of molecular species must be the cornerstone of all analyses (15). Values for a defined molecular species or class of species do not become obsolete and may be combined in various ways for different purposes. This demands a chemical classification, which at the first level may be related to atomic species and chemical bonds: this is the basis for the division of organic materials into fats, proteins, carbohydrates, etc. Subdivision of these major categories at the second level must take into account molecular species, chemical bonds and physical properties. Classification at a third level may then address nutritional and physiological properties.

Details of methods available for the specific measurement of carbohydrate fractions are provided in the Appendix.

I. Measurements of sugars, short-chain carbohydrates, starch and NSP

All the free monosaccharides and disaccharides in food may be measured directly by standard techniques.

The Cambridge group has developed *in vitro* methodology for the measurement of total SCC (unpublished)

and for the measurement of the RSCC, with the option to measure the fructans separately (16).

II. Measurement of starch, rapidly available glucose and slowly available glucose

The physical characteristics of starchy foods will influence the fate of the starch they contain; some starch may escape digestion and absorption in the human small intestine. The physical form of starch itself may influence the rate and extent to which it is digested. The starch in bananas and raw potatoes is present as granules that are largely resistant to enzymatic hydrolysis, but when this starch is gelatinized by cooking it is rapidly digestible. Starch that has been gelatinized during cooking may retrograde upon cooling to a form that is not hydrolyzed by α-amylase. The fate of starch in the gut is influenced also by a number of host factors in addition to the physical characteristics of the food or starch. These include the extent to which food is chewed, the amount of pancreatic amylase available and transit time through the small intestine. These factors are highly variable both within and between individuals, and any *in vitro* analytical scheme that attempts to produce an index of absorbability will, at best produce an estimate of the average fate of starch in the gut. The term resistant starch (RS) refers to the sum of starch and starch degradation products that pass into the large intestine (4,5), which makes the distinction between starch that is hydrolyzed and the products absorbed in the human small intestine (the sum of RDS and SDS) and starch that reaches the human large intestine either intact or partly hydrolyzed (RS). The term RS has become widely accepted and the *in vitro* measurement technique was tuned to yield the average of values obtained for individual foods in studies using ileostomy subjects (17-19). The method provides reliable values for mixed meals (20). The likely rate and extent of the starch digestion and absorption has been incorporated into a classification scheme for nutritionally important starch fractions (21-23), and an analytical scheme for the measurement *in vitro* has been developed (8).

Given their potential importance, an overview of the methodology for distinguishing these fractions is important. Foods that are normally eaten dry are analyzed as such. Foods that are normally eaten hot are cooked immediately before they are taken for analysis, thus avoiding the development of retrograded starch during cooling.

The various categories of starch are measured after incubation with an enzyme mixture that contains proteinase, lipase and α-amylase activities, and an amyloglucosidase. The incubation is done under standardized conditions in a shaking water-bath, and the tubes contain glass balls, which disrupt the food particles. Free-sugar glucose is measured in a separate sample as the sum of free glucose and the glucose from sucrose (after incubation with invertase).

Samples are removed after 20 and 120 min of incubation. The glucose released from starch within 20 min is used to specify RDS and that released between 20 and 120 min specifies the SDS fraction in starchy foods. The resistant starch fraction, i.e. the starch unhydrolysed after 120 min *in vitro* hydrolysis, need not be further subdivided except for research purposes.

Values for RAG, SAG and RS can be obtained by one simple procedure (21,22). The RAG measurement takes only 2 to 3 hours, and RS can be measured readily within a working day.

RDS is the fraction of starch that is likely to be digested rapidly in the human small intestine, and is measured as the starch digested between zero and 20 minutes of enzymatic hydrolysis in vitro. SDS is the fraction of starch that is likely to be digested completely in the human small intestine, but more slowly than RDS, and is measured as the starch digested between 20 and 120 minutes of enzymatic hydrolysis *in vitro*. RS is the starch likely to reach the human large intestine and is measured as the difference between starch hydrolyzed by 120 minutes and total starch. The RAG measurement takes only two to three hours, and RS can be measured well within a working day (8,21,22).

RAG is the amount of glucose measured after incubation of a food sample for 20 minutes with a mixture of invertase, pancreatin and amyloglucosidase. Values for RDS can be obtained by correcting RAG for FSG, which includes the glucose released from sucrose. Both RAG and RDS are highly correlated with the glycemic index (23).

The identification of specific health benefits related to ingestion of the various starch fractions will be possible only if separate measurements of these are available. The proportions of RAG, SAG, RDS, SDS and RS in foods, and thus the expected rate and extent of digestion in the human small intestine can be controlled by food processing, which could be developed appropriately to the benefit of both the consumer and the food industry.

Values of free sugar and starch content of Mexican foods are available in the literature (24,25). Table 2 shows the proportion of the various fractions of starch and the rapidly available glucose (RAG) values for a range of foods. The RAG fraction includes the free-sugar content of the food and the glucose released from starch within 20 min of starting the hydrolysis procedure. The legumes have the lowest RAG values, because they have low levels of both free sugars and RDS. The cause of the slow and incomplete digestion of legume starch is probably a combination of starch granule encapsulation by cell walls (dietary fiber) and the incomplete gelatinization of the starch. Spaghetti, macaroni and pearled barley are examples of foods with moderate RAG values. Although pasta is made from a highly processed cereal

(durum wheat), the dense structure of the food hinders the access of amylolytic enzymes (23).

It is important to recognize the concept of RAG. The analytical RAG values are expressed in terms of grams of RAG per 100 g of food "as eaten", and therefore can range only between zero and 100. If the dry matter of a food consisted entirely of rapidly available glucose, the RAG value for the food will depend on the water content of the food as eaten. For example, although a considerable proportion of the starch in digestive biscuits is measured as SDS, reflecting the low water content, the biscuits have a higher RAG value than that for white bread, in which nearly all the starch is measured as RDS. Similarly, the low RAG value for cooked potato reflects the low dry matter content of this food as eaten.

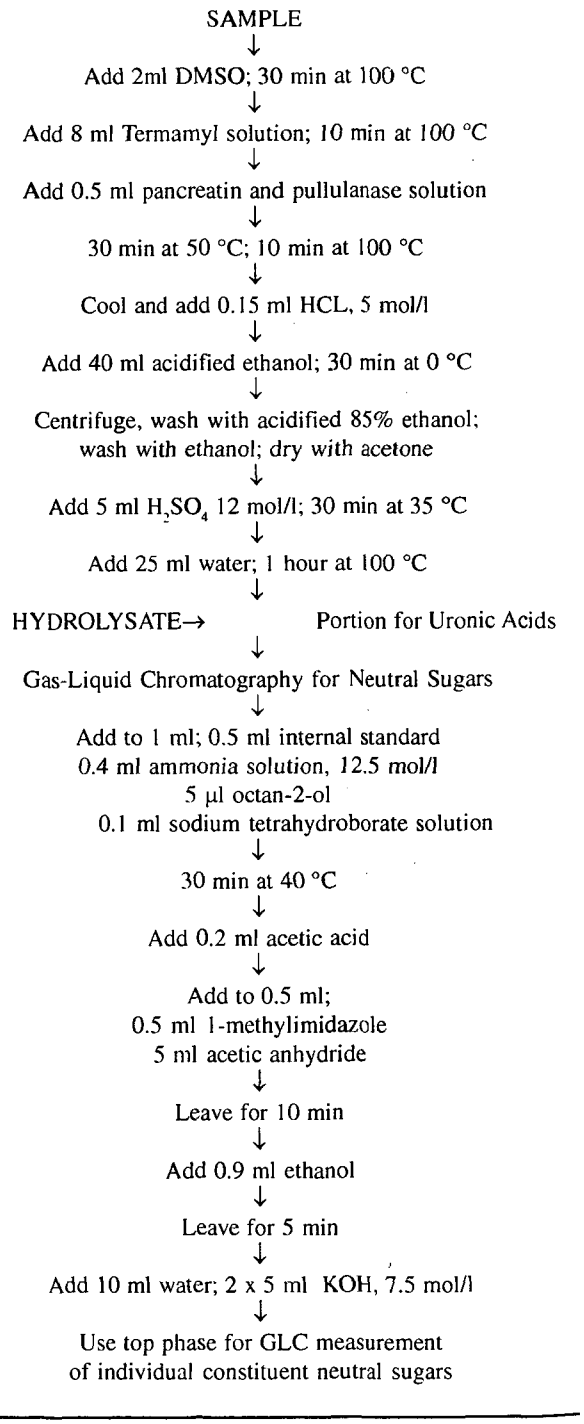
The RAG value of 80 for Rice Krispies is markedly higher than those of the other breakfast cereals in Table 2, presumably because of the processing effects as well as the paucity of water and high carbohydrate content of the food.

The proportions of RAG, SAG, SDS and RS in foods, and thus the expected rate and extent of digestion and absorption in the human small intestine, can be controlled by food processing. Once the benefits or otherwise of different fractions are clearly established, then the food industry can contribute to consumer welfare by adopting manufacturing techniques to adjust the proportions of the different carbohydrate fractions.

III. Measurement of non-starch polysaccharides

The Englyst procedure (10) for the measurement of dietary fiber as non-starch polysaccharides (NSP) has evolved from the principles laid down by McCance & Widdowson (26), and later by Southgate (27). The procedure involves the complete enzymatic hydrolysis of starch, the precipitation of NSP in ethanol, and the acid hydrolysis of the NSP. The released constituent sugars can be measured by one of three alternative techniques, GLC, HPLC or colorimetry (Figure1). The detailed information obtained from the chromatographic methods, which quantify the individual constituent sugars, is particularly useful in studies of the relation between intakes of NSP and health; values for the constituent NSP sugars have been published for a wide range of foods (12; 28-31). The simpler but non-specific colorimetric version can be completed within 8 working hours and is suitable for food labeling and for quality control. The Englyst procedure for the measurement of dietary fiber as NSP has been thoroughly tested in large international collaborative trials (32) and certificated reference materials are available (33). Values for dietary fiber measured as NSP by this technique are used in the UK (34-36) and Mexican food tables (37,38) among other countries.

FIGURE 1
Flow diagram for the measurement of dietary fibre as NSP



Certificated reference materials

As the result of a large international trial of methodology, following rigorous study of stability of the test materials, five BCR-certificated reference materials (CRMs) are available for the Englyst GLC and colorimetry NSP procedures. (from BCR, EU Community Bureau of Reference): (1) dried haricot bean powder, CRM 514; (2) dried carrot powder, CRM 515; (3) dried apple powder, CRM 516; (4) full fat soya flour, CRM 517; (5) dried powdered bran breakfast cereal, CRM 518. These CRMs can be used to check the performance of the analytical method and as quality control of analytical measurements for nutritional labeling.

Carbohydrates and health issues

The incidence of Western diseases is steadily increasing in Latin America, reflecting the transformation to a Western diet characterized as high in sugars and refined foods and low in fiber (39). Human physiology is evolutionarily adapted to a diet in which much of the sugars and starch is naturally encapsulated within the cell walls of unrefined plant foods. As well as the use of additives, often in inappropriate amounts, food processing has other, far-reaching effects on the nutritional value of foods. Modern food processing, especially milling, destroys the cell structure (dietary fiber) of plant foods and releases nutrients, including sugars and starch. The starch is often fully gelatinized during food processing and the sugars and starch may then be rapidly digested and absorbed (see later). The consequent rise in the levels of blood glucose and insulin have been associated with a range of diseases, including coronary heart disease (40) cancer (41-43) and diabetes (44-46).

Unrefined plant foods are a good source of antioxidants and minerals, many of which may be lost during processing. Tortillas and beans are staple foods for both rural and urban communities in many Latin American countries. The commercial preparation of these foods, however, has a major impact on the composition of these foods. Commercially prepared tortillas are of a lower dietary fiber content than rural tortillas and canned beans have a lower dietary fiber content than freshly cooked beans (29). Fat and salt are added to canned refried beans in large quantities, and commercially prepared wheat tortillas contain high levels of salt. As the result of access to and the power to purchase modern processed foods, dietary fiber intakes are lower (47) and sodium intakes are higher (48) in the urban communities. Low-fiber (non starch polysaccharides) diets have been positively correlated with an increased incidence of a range of cancers: breast (49,50), colorectal adenomas (51-53), gallbladder cancer (54), pancreatic cancer (55) and stomach cancer (56,57).

I. Rapidly available glucose, the glycemic response and disease

There has been a great deal of debate about the value of distinguishing the different forms of carbohydrate in relation to health. Traditionally there has been a concern to restrict sucrose intakes in diabetes because the rapid ingestion of sucrose in patients on standard insulin treatments leads to a rapid rise in blood glucose. A whole series of metabolic problems could be linked to recurrent hyperglycemia. These include increases in glycosylated proteins, demonstrable by measuring the level of hemoglobin A_{1c}, microvascular deterioration, the induction of polyol metabolic pathways leading to cataract formation and other changes, such as elevated circulating concentrations of the triacylglycerols. High triacylglycerols levels are predictors of cardiovascular disease independently of other risk factors such as elevated LDL cholesterol and low HDL cholesterol levels (58). The induction of greater insulin resistance by high intakes of RAG was considered very likely in NIDDM patients because of the further down-regulation of the insulin receptor system as a result of the demand for greater pancreatic insulin secretion when foods of a high RAG content were fed. This insulin resistance has also been involved in a promotional component for colon and breast cancer induction (41-43; 59). The original concern for restricting carbohydrate diets in diabetes led to low-carbohydrate, high-fat diets which, in practice, amplified the likelihood of cardiovascular disease. This recognition then stimulated a new approach to diabetic diets based on the use of abundant amounts of complex carbohydrates with restricted sugar intakes (60). More recently, the practical benefits of restricting sucrose intakes have been questioned, with many clinicians claiming that the use of modest amounts of sucrose does not materially affect the ability to maintain plasma glucose at reasonable levels, given the appropriate use and timing of exogenous insulin injections. Thus, there has been a swing towards viewing the sugar/starch distinctions as academic and not of clinical importance. This conclusion, of course, may well reflect the fact that some starches are as rapidly absorbed as glucose. Thus a simple starch substitution for sucrose might not yield any benefit thus leading to the inappropriate conclusions about the importance of rapid absorbability.

These views need to be set alongside those propounded by Jenkins and his colleagues (7), who developed the glycemic index (GI) as a measure of the rate and extent to which carbohydrates were hydrolyzed and absorbed in the small intestine. They refocussed the approach to carbohydrate absorption and metabolism by suggesting that diabetic patients had less glycosuria and lower blood glucose values if they ate slowly digestible carbohydrates. These foods were therefore of greater value. They have moved on to monitor the GI values of many foods, making these measurements in groups of healthy and diabetic volunteers.

The issue arises of whether the GI of individuals' diets is predictive of their likelihood of developing such metabolic complications as insulin resistance or hypertriglyceridemia, or eventually diabetes, cardiovascular disease or cancer. Clearly more needs to be done, but a practical difficulty arises because of the extensive human studies needed to document the impact of each type of food in terms of its GI measured in a group of volunteers. It is for this reason that complementary *in vitro* methods directly applicable to food were sought.

II. The relationship between the RAG and GI values of foods

The glycemic index (GI), proposed by David Jenkins and co-workers, ranks foods by the glycemic responses that are elicited *in vivo* by 50 g of 'available' carbohydrate from these foods (7). The GI is calculated as the incremental area of plasma glucose above fasting glucose levels for 120 minutes after a test meal. To account for within-subject variation, the glycemic response to each test food is measured on at least three occasions for each subject. To minimize between-subject variation, each subject's glycemic response data are normalized to the individual's response to 50 g of glucose derived from white bread (7, 61). RAG values determined *in vitro* for a range of starchy foods, when normalized to a standard amount of 'available' carbohydrate, are highly correlated with published GI values determined *in vivo* for similar foods (23).

The relation between RAG values (measured *in vitro*) and glycemic response values (measured *in vivo*) has been investigated in a study in which eight non-obese, healthy adult subjects ate a carbohydrate test meal on eight separate occasions under carefully controlled conditions. The eight test meals consisted of two portions sizes of each of four starchy test foods, for which RAG values were determined. Fingerprick blood samples were taken to follow the glycemic response of each subject to each test meal. The average of two blood samples taken before the test meal was consumed was used as the fasting value (8).

Figure 2 shows the change in blood glucose levels for eight test meals. Linear regression analysis was performed for the incremental area under the curve (the glycemic response) and the RAG content of the test meals in each subject. The slopes for different individuals are all significantly different from 0 ($p<0.05$) and range from 0.9 to 4.9, reflecting differences in glucose tolerance between subjects. When the glycemic response data are normalized in relation to the response to white bread for each subject (the relative glycemic response), the range of slope values is reduced to between 2.0 and 3.1, with a mean of 2.6. Regression analysis for individual subject's data ranged from $r = 0.73$ to 0.96 with no significant departure from proportionality for the influence of RAG on glycemic response up to an intake of 50 g of RAG. The correlation for RAG intake and the mean glycemic response over all subjects is $r = 0.97$ (8).

The finding that RAG intake, up to 50 g, is highly correlated with the average glycemic response, adds support to the use of the *in vitro* measured RAG as an expression of the glycemic load.

III. Food tables and food labeling

Artificial "Fiber" values can be misleading

Starch can be made resistant to digestion by heating and cooling, but this may or may not be desirable. Table 4 shows the massive increases in Prosky 'Fiber' values that can be achieved by simple heating and cooling of wheat flour. Resistant starch products are often now being advertised as a source of fiber. Indeed, some of these products measure as much as 35% 'Fiber' by the Prosky procedure (62) but contain no plant cell wall material and thus yield a value of zero for NSP. Apart from its fermentation in the large intestine, resistant starch is not known to share any of the other properties traditionally associated with dietary fiber. The use by the food industry of high-RS material in the production of snack foods or breakfast cereals can result in apparently dramatic increases in the supposed 'Fiber' content of the diet when the values are obtained by the Prosky procedure, but there are two important reasons why the marketing of such products as 'fiber-rich' should be viewed with caution:

(i) The consumer will be seriously misled in the choice of foods that comprise a truly high-fiber diet and will not enjoy the health benefits associated with a diet rich in unrefined plant foods, with its associated supply of micronutrients and other biologically active components.

(ii) The consumption of increased amounts of RS has been postulated to be of potential benefit to health but, as yet, there is no evidence to support this claim. In fact, recent results from some animal studies have suggested that high-level intakes of RS may actually be detrimental to health (63-67).

At present, the food tables of different countries include different values for dietary fiber because different methods have been used for the measurement of dietary fiber. These methods are designed to include different dietary components. The material included as 'fiber' by non-specific gravimetric procedures can be a mixture of NSP, starch and non-carbohydrate components in unspecified proportions, which may vary as the result of food processing. It is not possible to interpret these values in chemical terms and, therefore, they cannot be used in energy calculations.

FIGURE 2
Glycemic response to eight test meals containing different amounts of rapidly available glucose (RAG). The Figure shows mean (±SEM) increment in blood glucose above fasting concentration for all subjects after low-RAG (spaghetti and pearled barley) and high-RAG (corn flakes and white bread) test foods fed as portions containing 25g (continuous line) or 50g (broken line) of available glucose. (22).

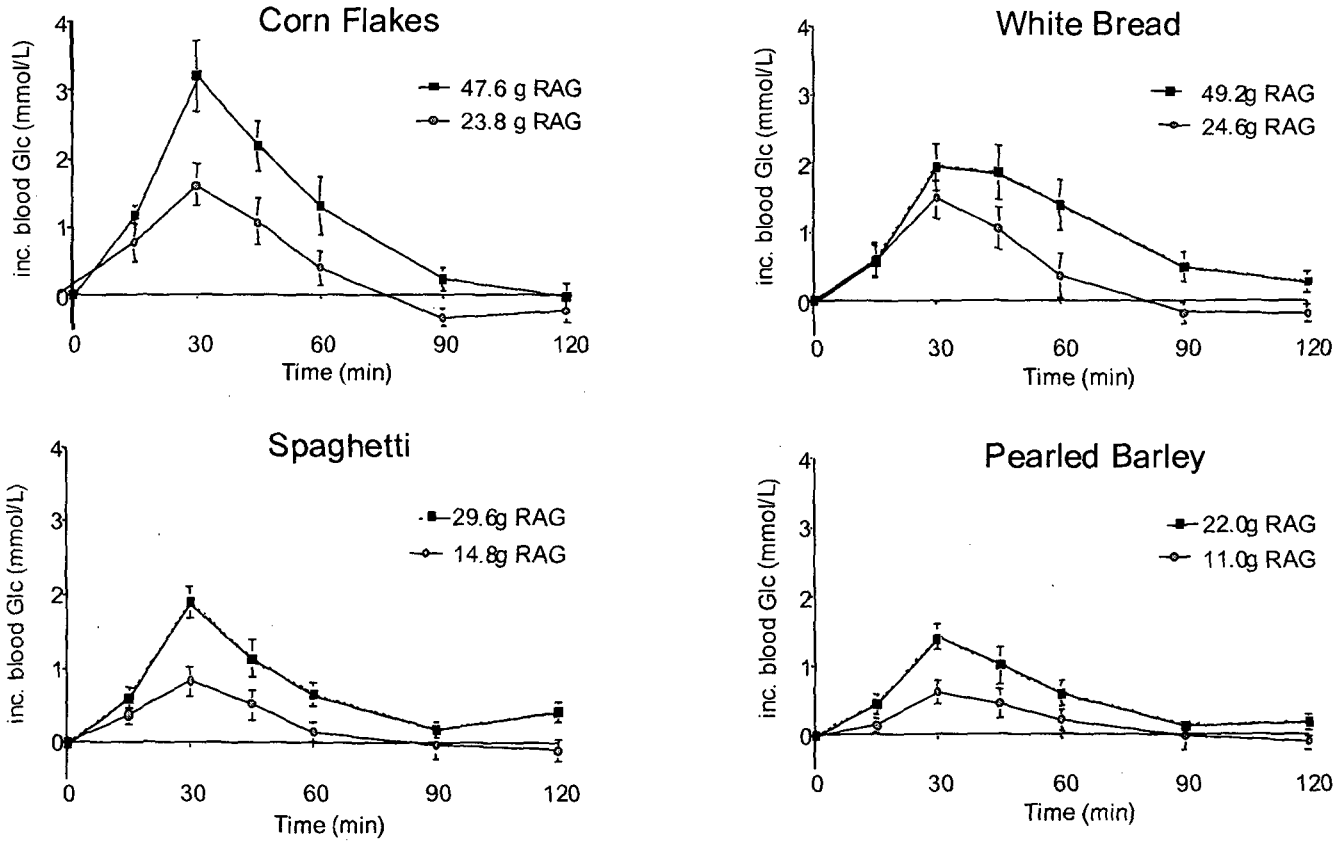


TABLE 4
Formation of "High-fiber White Flour" by repeated heating and cooling

	AOAC 'DF' (% DM)			
	Bread flours		Pastry flours	
Untreated	2.7	(0.1)	2.4	(0.1)
Heated/cooled	11.2	(0.6)	12.4	(1.3)

Data from Ranhotra *et al.*,(69); the values are mean (SD) for five bread flours and five pastry flours.

Food tables and databanks

Values in food tables for the foods and ingredients that are common to national Western diets should supply meaningful, reliable data that are suitable for use by dietitians, epidemiologists and the food industry. Most of the current food table values for minerals, fat, proteins and vitamins do meet these criteria adequately but values for carbohydrates in food tables represent a potential minefield, with ambiguities leading to anomalous calculations of the carbohydrate, fiber, starch and metabolizable energy content of foods. Furthermore, at present no food table provides values for oligosaccharides, or the different fractions of starch. Table 5 presents a suggested way of presenting the carbohydrate components of foods in food tables. When these are routinely used then for the first time it will become possible to undertake appropriate epidemiological analyses on dietary carbohydrates and health.

TABLE 5
Example of detailed carbohydrate component entries for food tables for a fictitious food, code A6497

Free sugars and short-chain carbohydrates could appear together

Food code	Free sugars (g/100g DM)								Short-chain carbohydrates (g/100g DM)					
	Glc	Gal	Fru	Man	Xyl	Sucrose	Maltose	Total	Raffinose	Stachyose	Verbascose	Maltodextrins	β-Fructans	Total
A6497	1.2	0.3	0.1	t	t	1.5	0.2	3.3	0.1	0.2	0.1	1.3	0.6	2.3

Values for starch (g/100g dry matter) could appear together with values for the glycaemic index (normalized values) and for slowly available glucose and rapidly available glucose (g/100g dry matter)

Food code	Starch				Glycaemic index (GI)	Slowly available glucose (SAG)	Rapidly available glucose (RAG)
	RDS	SDS	RS	Total			
A6497	12	3	1.0	13.3	89	3.3	15.3

Soluble, insoluble and total NSP values could appear together with values for their constituent sugars and separate values for the cellulose and non-cellulosic components (all as g/100g)

Food code	NSP	Total (%fresh)	Total (%DM)	Cellulose (%DM)	Non-cellulosic (%DM)							
					Rhamnose	Fucose	Arabinose	Xylose	Mannose	Galactose	Glucose	Uronic acids
A6497	Soluble	0.6	3.8	–	0.1	–	0.1	0.1	–	1.8	0.6	1.1
	Insoluble	0.6	3.6	2.8	t	–	0.4	0.1	–	0.2	t	0.1
	Total	1.2	7.4	2.8	0.1	–	0.5	0.2	–	2.0	0.6	1.2

Food labeling

If dietary fiber values are to be meaningful to the consumer who is concerned with health issues, then the values need to be based on the measurement of chemically identified components. This requirement has recently been recommended by FAO/WHO (68), and it is clear that no non-specific gravimetric methods for the measurement of "dietary fiber" could fulfill this criterion.

We suggest that for the purpose of food labeling, fiber values should be reported as a measure of naturally occurring plant-cell wall NSP, since this provides a reliable index of a naturally fiber-rich diet. For most foods, a value for plant cell wall NSP is obtained directly by the NSP procedure (10,11). If foods contain NSP in the form of additives, these have usually been extracted from different sources and are accompanied by few if any nutrients. The nutritionally meaningful fiber value therefore should be taken as the naturally occurring plant cell-wall NSP, i.e. with the additive value excluded. NSP values would aid the consumer in choosing the unfortified, naturally high-fiber diet recommended in national dietary guidelines and by WHO. Such a development would be beneficial to all concerned, including the food industry and the consumer.

The current Western practice of consuming large amounts of highly processed, energy-dense, rapidly digestible foods in combination with a sedentary life style has led to a soaring prevalence of obesity and its attendant complications. This link between diet and public health serves as a warning note to those countries where the impact of modern processed foods is just beginning to be felt. It is timely to examine the dietary status of the Latin American countries and to identify those facets of dietary practice that promote public health. Clearly new analyses of the impact of dietary carbohydrates must now be included in these new analyses.

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