Original Article

The place of carbohydrates in newer food formulations: Opportunities for nutritional advancement and their safety

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Carbohydrates, from food, have a high degree of acceptability in the human diet as safe and are usually associated with other important nutrients, notably protein and various micronutrients (vitamins and minerals), but also biologically advantageous phytochemicals, although there is a wide spectrum of nutrient (or food component) densities between grains, root and other vegetables and fruits. As the human diet has evolved, less nutritious forms of edible carbohydrate have been in evidence, because of refining and co-presentation with fat (e.g. a sugary pastry). These are nutritional safety issues in their own right. But, as newer food formulations develop, greater attention can be paid to the chemical (which simple sugars, oligosaccharides or polysaccharides), physical (the food structure retained or conferred) or functional properties (glycaemic, digestible, fermentable) of the carbohydrate, along with the presence or absence of companion compounds (macro-, micro- and phyto-nutrients). These developments present opportunities and limitations in altering physiology and health outcomes and create new risk–benefit relationships. More now needs to be understood by food and nutrition policy makers, manufacturers and health-care professionals about the future of such foods, how they will influence food choice, what the regulatory arrangements will be, and how their use will be monitored for safety, sustainability and health.

Key words: carbohydrate, food intake indices, glycaemic index, intact food, novel foods, oligosaccharides, plant foods, polysaccharides, risk analysis, risk communication, satiety index, simple sugars, starch, sustainability.

Historical perspective

The biological advantage of the human species has almost certainly been conferred through its omnivorous eating habits and its migratory capacity, which have allowed and enabled it to live in a vast array of climatic and geographical situations with relative success. Primate ancestors that were tree-dwelling and/or at the water's edge obtained fruit, nuts, seeds and vegetables and aquatic foods to sustain them. The consumption of other creatures well up the food chain meant that concentrated and presynthesized forms of nutrients could be used efficiently and, ultimately, in a way more dependent on other forms of life and the ecosystem around them. By the palaeolithic period it is argued that we ate a variety of plant-food stuffs with a good deal of non-glycaemic carbohydrate (dietary fibre) and glycaemic carbohydrate (from fruits and starchy roots), along with eggs, lean meat (game), fish, shell-fish and crustaceans.[1] With settlement and subsistence agriculture, vegetables, grains and fruit became more important.[2,3]

We progressively depended on 'staples' for most of our energy (calories) when still fairly physically active; these were grains (e.g. rice, wheat, rye, barley, maize) and root crops (potatoes, sweet potatoes, taro). The coingestion of legumes provided nutrient complementarity, notably for amino acids, and therefore protein effectively of high quality. Some legumes, such as soy, in China, were quite exceptional for their protein quality and other constituents and probably provided biological advantage.

There is probably not only one optimal way of eating. Because of some 150–200 000 years of wandering and adaptation, *Homo sapiens sapiens* has been able to work out comparably successful food cultures: Indigenous, Oriental, Andean, Mediterranean, Scandinavian and others. The recent Food Habits in Later Life (FHILL) studies of the International Union of Nutritional Sciences (IUNS) demonstrate how, even beyond the age of 70, humans can live well and long in different locations, with different diets.[4] But a plant food orientation, with fish, provides advantage; and legumes are a cross-culturally robust predictor of longevity (Table 1).

But food alone is not enough for a favourable disability adjusted life expectancy (DALE)[5] as might be expected, with other lifestyle dimensions, especially activities of daily living (ADL) and smoking, playing a concerted role. When

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health indices (memory and a total health score) are included in the cross-cultural model, food remains important. Carbohydrate foods are part of the biological success of the human species, but not in isolation (Table 2).

FAO/World Health Organization recommendations: Nomenclature and assessment (1997)

Because of the increased understanding of carbohydrate chemistry and function, FAO and World Health Organization (WHO) sought to revise their 1979 report in 1997[6] with an expert consultation. Terms like 'complex carbohydrate' and 'dietary fibre' have taken on various meanings and have not been as measurable in agreed ways as many nutrition scientists and healthcare professionals would like. Thus the major dietary carbohydrates are now classified as:

This combines a chemical criterion and a principle functional characteristic of food carbohydrate classification. Further, the glycaemic index[7] is supported as an approach to food carbohydrate choice in relation to various health outcomes, especially diabetes.

Table 1. The Cross-cultural Food Habits in Later Life Studies of Longevity: the plant-based and fish food pattern in the same model as social and physical activity†

Variables	Risk ratio‡ (95% CI)	*P*
Plant-based and fish diet score‡	0.855 (0.743–0.983)	0.028
Activities of daily living score§	0.950 (0.922–0.978)	0.001
Social network score¶	0.974 (0.934–1.016)	0.222
Social activity score††	0.995 (0.975–1.014)	0.591
Exercise score‡‡	1.039 (0.881–1.226)	0.647
Smoking status§§	1.517 (0.978–2.353)	0.062

†Mortality risk-ratio estimates (and 95% CI) derived from the Cox's model with modifiable variables including terms of age at enrolment (5-year interval); gender (0 = female; 1 = male); and ethnicity/locality (0 = Japan, 1 = Sweden, 2 = Anglo-celtic, 3 = Greeks in Melbourne, 4 = Greeks in Greece).

‡Plant-based and fish diet score (PBD) based on gender and combined cohorts median cut-offs; a 9-point score with the risk shift related to 1 point.

§Point score (15–62); ¶point score (12–46); ††point score (22–176); ‡‡point score (1–7).

§§0 = non-smoker; 1 = smoker.

Table 2. Traditional and novel carbohydrate foods

Traditional	Novel	Function
Basic commodities	Cultivars with enhanced level of nutritional components	As for G and NG carbohydrates, together with properties of nutritional components
(Unrefined carbohydrate)		
(1) Cereal (grain)		
(2) Fruit		
(3) Sugar crops		
(4) Vegetables		
Root		
Leafy		
Legumes		
(5) Sea plants and algae		
(6) Other seeds		
Rapeseed		
Flaxseed		
Sunflower (carbohydrate and oil)		
Certain nuts (e.g. chestnut)		
(7) Milk and dairy		
Non-fermented		
Fermented		
Combination of CF	Creation of variety in recipes	Convenient combinations for added nutrition security and enhanced function
(1) Soups		
(2) Dishes		
(3) Baked goods		
Combination of CF with animal-derived foods	Creation of variety in recipes	Convenient combinations for added nutrition security and enhanced function

*Based on Chapter 1 FAO/WHO 'Availability and Consumption'[6]

CF, carbohydrate foods; G, glycaemic; NG, non-glycaemic.

The overall recommendations about goals and guidelines for carbohydrate in the food chain (WHO/FAO) are given as the following.

Rationale and framework

Although the scientific basis for dietary guidelines requires an understanding of physiology and health relationships, the guidance most helpful to consumers uses food-based terms.[8] In preparing such guidelines, food traditions and beliefs must be taken into account and the total food intake should reflect practical issues, such as meal patterns, food status, celebratory or usual role, seasonal availability, affordability and sustainability. These, including the health priorities, are matters for national policy makers.

Principles of carbohydrate food choice

The principles are the following.

(1) To acknowledge the sociocultural context, lifestyle and stage of life cycle, in food carbohydrate choice.

(2) To give preference to food choices rather than to nutrient goals in carbohydrate food choices, and in so doing: (i) use food categories as a guide to chemically defined carbohydrate type; (ii) use numbers of portions (serving sizes) of foods from designated food categories in order to provide semiquantitative food-based advice. This may imply that meal frequency would need to increase in some cultures because the accommodation of enough carbohydrate food in the course of the day, without an excessive amount on any one occasion, requires more frequent servings and consumption.

(3) To appreciate that many of the world's health problems are associated with inadequate carbohydrate intake, and potentially also associated with inappropriate carbohydrate intake.

(4) To ensure the acceptability and practicality of any recommended change in carbohydrate food intake.

(5) To acknowledge that there may be unintended consequences involved in carbohydrate food intake change, and also to ensure that risks involved in dietary changes from traditional diets are considered.

(6) To monitor the intake of carbohydrate foods and, wherever possible, of chemically defined carbohydrate components of those foods in relation to health issues.

(7) To ascertain whether food carbohydrate choices encourage biodiversity and are sustainable.

Carbohydrate nutrient and food goals

Nutrient goals. The minimum amount of carbohydrate in the human diet that is needed to avoid ketosis is of the order of 50 g/day in adults. Beyond this, additional energy needs are best met by nutrient-dense carbohydrate foods. There must, of course, be adequate intakes of protein (with essential amino acids) and essential fatty acids from fat. Moderate intake of sugar-rich foods can also provide for a palatable and nutritious diet.

Food goals. There are a number of approaches to translating nutrient recommendations to food goals.

(1) Recommending the total weight of food groups to be consumed. Various national food guides have suggested quantities of specific foods to be consumed, such as fruits and vegetables, and pulses, nuts and seeds.

(2) Examining sources of carbohydrate foods in various diets, particularly diets that have desirable total carbohydrate intakes or from countries where the incidence of lifestyle diseases is low. Recommendations can then be made on the basis of intakes.

(3) Examining major food groups that contain carbohydrate foods and recommending numbers of servings of those food groups. Numerous countries around the world, both developed and developing, have produced food guides with such groupings and, considering the level of agreement that exists for carbohydrate as a percent energy, these food guides are remarkably consistent in their advice.

(4) Examining indices that exist to describe various physiological properties of carbohydrate-containing foods, such as glycaemic index values and values from other indices that are presently being developed.

On the basis of these approaches, and taking into account the principles for carbohydrate food choice, the following recommendations can be made.

(1) A variety of foods should provide the carbohydrate in the diet, not a single or small number of sources.

(2) Cereals, roots, pulses, fruit and vegetables are all components of a healthy diet throughout the world.

(3) Cereal foods or root crops, where this is the main staple, should provide the major source of carbohydrate energy.

(4) Intake of fruits and vegetables (including potatoes in developed countries) should be high. As well as being a valuable source of carbohydrate, fruit and vegetables are an important source of anti-oxidant vitamins and other food components.

(5) Consumption of pulses, nuts and seeds should be encouraged. Although this group often represents only a small amount of carbohydrate energy, these foods are a good source of protein and micronutrients. They should be consumed with cereals to optimize protein quality.

(6) At least small quantities of milk products are desirable, even when low lactose activity exists, because these are a good source of protein and micronutrients.

These recommendations apply to all individuals over the age of two years, with adjustments as necessary for growth and the increased demand of pregnancy and lactation.

Nutritional significance

Carbohydrate is relevant and important for growth and development, energy balance and optimal health through life (Table 3). Food carbohydrates have several functions that range from its palatability to gut function, nutrient bioavailability, metabolic control and homeostasis, physical performance and behaviour (Table 4).

Table 3. Carbohydrate nutrition throughout the life cycle

	Carbohydrates	Role
Pregnancy and fetal life	Maternal intake of varied unrefined low-GI food carbohydrates	Avoid ketosis Reduce risk of gestational diabetes
Lactation	Breast milk (exclusive for 1 and 6 months wherever possible Lactose Oligosaccharides Formula foods (breast milk substitutes) Complementary feed	Growth and development
Infancy	Relatively more fat than after the age of 2 years, when carbohydrates can be at least 55% energy intake	Growth and development
Childhood	Amount and type of carbohydrate intake needs to allow for adequate energy and essential nutrition intake	Growth and development
Adulthood	High and varied food carbohydrate sources, accompanied by regular physical activity	Energy balance, optimal health
Ageing	As for adulthood with emphasis on legumes and low-GI foods	Optimize DALES

DALES, disability adjusted life expectancies; GI, glycaemic index.

Table 4. Functions of food carbohydrates

	Simple sugar		Oligosaccharides		Polysaccharides	
	G	NG	G	NG	G	NG
Palatability	+	+	+	++	++	++
Sweetness	+++	+	+	–	–	–
Satiety	?	?	?	+	++	+++
Food structure and food component bioavailability	–	–	+	++	+++	++++
Fermentable and large bowel function	–	+	–	+++	–	+++
Vehicle for nutritional food components	+	+	++	++	++	+++
Energy and anti-ketogenic	+	–	+	–	+	–
Metabolic control (glucose, insulin protein glycosylation, lipid, bile acid)	+++	++	++	++	+++	++
Physical performance	+	–	+	–	++	–
Behaviour (mood and sleep)	+	?	?	?	?	?

G, glycaemic; NG, non-glycaemic; ?, inadequate information to form any judgement.

Carbohydrate–food component interactions and cooperativity: 'Unrefined carbohydrate'

Because most carbohydrate derives from plant sources, either as energy storage carbohydrate (such as simple sugars or starch) or structural carbohydrates (such as non-starch polysaccharides), it is accompanied by other potentially nutritionally relevant food components, including essential macronutrients (protein and amino acids, polyunsaturated fatty acids), micronutrients (vitamins and minerals) and various other phytochemicals (especially polyphenolic substances). Food preparation and processing can make these components more palatable and ingestible, alter their nutritional significance (favourably or unfavourably), and influence their presence and their bioavailability. Therefore it is unusal to be able to consider a carbohydrate in isolation from its food origins and associated components, although there are degrees of refinement from fully 'unrefined'.

Moreover, almost all carbohydrate foods are eaten together with another food, dependent on recipe or cuisine.

One of the best examples of carbohydrate food component interaction and cooperativity is between glycaemic and non-glycaemic carbohydrate, where the glycaemic impact of the foodstuff can vary greatly from glucose alone to the low glycaemic impact of leguminous carbohydrate. Again, there is growing interest in how oligosaccharides might modulate divalent cation (Fe^{++}, Ca^{++}, Mg^{++}, Zn^{++}) bioavailaibility,[9] as has been known for non-starch polysaccharide which is non-glycaemic ('dietary fibre').

Snack, meal and cuisine: A food-based approach to risk and benefit

As with a forager or hunter–gatherer, carbohydrate foods may be ingested off and on throughout the day, depending on sleep and work patterns and social need. There may be several physiological advantages in a snacking pattern for carbohydrate foods, ranging from achieving food adequacy to maintenance of satiety, increasing variety, and decreasing insulin requirements on any one occasion (with associated advantage in coronary heart disease (CHD) risk profiles).[1,10,11]

However, a meal can provide for a relatively low glycaemic impact when high and low glycaemic index (GI) foods are consumed together.

A disadvantage in snacking can be the risk of dental caries if 'sticky' foods are ingested without properties that inhibit cariogenic bacteria such as *Streptococcus mutans*. (Some carbohydrate foods may contain antimicrobial compounds like peptides and polyphenols.)

Indices of intake

Carbohydate (and other) foods included in more global food indices can provide a useful way of evaluating not only their functionality, but also their relative contribution to a healthful diet.

Examples are the following.

(1) Mass and type of carbohydrate food: the digestive and metabolic response to food carbohydrate will depend in part on mass, and also on the monomeric components (glucose, fructose, galactose), type of carbohydrate (simple, oligo- or poly) and companion compounds.

(2) Traditionality scores: as with the Greek (Cretan) diet, used in the FHILL studies of the IUNS and WHO.[12]

(3) Food variety scores,[13] as used by (i) Kant *et al.* in the NHANES study;[14,15] Horwath *et al.* in studies of the elderly;[16–18] and (iii) Hardinsyah in an Indonesian nutrition survey.[19]

(4) Glycaemic index: now used extensively in diabetes education.[6,7,20,21]

(5) Satiety index: as developed by Susan Holt *et al.*[22–26] Satiety is by no means determined by carbohydrate alone, but carbohydrate food plays an important part in its determination, both in immediate and longer time frames after food ingestion. A satiety index may therefore be useful in the novel foods arena.

Sustainability and carbohydrate foods

Because plant food are the principal sources of carbohydrates, and because they can contribute to a varied food intake pattern, their use can also be contributory to biodiversity and sustainability.[27,28] These factors can be taken into account in novel food development and in food choice.

Development and risk management of novel carbohydrate foods

Opportunities

There is a broad range of opportunities for advancement of health at different stages of economic development by focusing on novel foods: their role, potential and safety.[29,30]

Communication about carbohydrate for consumers

The present nomenclature about carbohydrates in the marketplace and education system limits the capacity of consumers to make informed and healthful choices about the food that contains these. 'Sugar', 'starch', 'complex carbohydrate', and 'dietary fibre' have taken on meanings often remote from the science. The FAO/WHO report of 1997 merits communication to food producers, processors and consumers alike, and can form part of various curricula.

Process

A general scheme for the development of foods that might confer health advantage and minimize risk is shown in Table 2, focusing on novel foods: their role, potential and safety.[29,30]

Safety of carbohydrates

There is now broad consensus on the way in which carbohydrate intake can be high and safe, as reflected in the FAO/ WHO Report of 1998.

> Unlike fat and protein, high levels of dietary carbohydrate, provided it is obtained from a variety of sources, is not associated with adverse health effects.
>
> An optimum diet should consist of at least 55% of total energy coming from carbohydrate obtained from a variety of food sources.[6]

Conclusion

Information about the chemistry and functionality of carbohydrates, along with source, companion compounds, food technology process and palatability will all be important in the safe development of novel carbohydrate foods.

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