



## CIMMYT Series on Carbohydrates, Wheat, Grains, and Health

# Carbohydrates, Grains, and Wheat in Nutrition and Health: An Overview Part I. Role of Carbohydrates in Health<sup>1,2</sup>

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### Cereal Grains and Carbohydrates as Global Food Staples

#### History of Grains in the Human Diet.

Cereal grains and other carbohydrate-rich staple foods form the basis of most diets, both ancient and modern, around the world. Despite claims to the contrary, records from pottery shards show that grains were likely eaten prior to the advent of agriculture during the Paleolithic Period. Carbon dating shows evidence of domestication of rice as far back as 16,000 years ago in the Yunan Province of China and of wheat 10,000 years ago in the Fertile Crescent (1,2). DNA from wheat strands has also been found in a hunter-gatherer site that predates the advent of agriculture in the United Kingdom (3).

Cereal grains and carbohydrates (CHOs) have been central components of human diets since the beginning of agriculture due to several factors. First, they are reliable, storable, sustainable, and readily available sources of energy and nutrients. All of these are key in averting malnutrition and promoting health. Second, as a ready source of energy grains and other staples spare proteins. As a result, proteins, which are a more expensive dietary component, are not used for energy. Third, grains are embedded in a variety

of cultural, religious, and linguistic traditions around the globe. In fact, eating patterns and national dishes in most regions combine grain(s) and other protein sources. Such dishes have become traditions within various cultures because they nourish and support the population. Modern nutrition science has documented that when combined and eaten in the right amounts cereals and other plant foods such as legumes or seeds, each of which contains an incomplete protein, work together to form complete proteins.

CHOs and grain-based staple foods played a key role in the development of agriculture, which in turn was vital for the development of human civilization, because a reliable supply of calories and nutrients enabled the specialization necessary for the advancement of humanity. Thus, cereal grains and other CHO sources form a nutritional base that supports life and are associated with other dietary components that enable optimal health and well-being for the world's human population.

**Processing and Refining Grains.** Nearly all CHO-rich staples must be processed in some way prior to human consumption. Egyptian hieroglyphs and biblical texts document the separation of the wheat grain from the chaff and the making of breads and other grain-based foods. Archeological sites around the world provide ancient evidence of grinding stones used for crushing grains. Some sites even contain evidence of sifting methods and separation of various parts of the grain.

The debate over use of refined flour or whole grains in bread was documented as early as the fourth century B.C.E. Plato advocated good health and longevity through eating locally grown, whole grain breads (4), whereas Socrates deemed Plato's whole grain bread "pig-food"! The debate contin-

ued into Roman times, when the Roman historian and scientist Pliny wrote in A.D. 70 about the consumer preference for whiter breads, noting that "The wheat of Cyprus is swarthy and produces a dark bread, for which reason it is usually mixed with the white wheat of Alexandria." Since Roman times highly refined grains were chosen by those who could afford them. Heartier breads, even today, are often referred to as peasant breads. However, Galen, a prominent Greek physician in Roman times, noted that white bread is the stickiest and slowest to pass and that brown bread is good for the bowels (5). Roman records show that whole grain meals were given to warriors and gladiators for strength. In fact, gladiators were called *hordearii*—literally, "barley men" (6).

The debate continues nearly 2,000 years later with those who champion whole grains and avoid refined grains. Although a large body of evidence, which is summarized in a paper from a recent Grains for Health Foundation Whole Grains Summit, shows that whole grains are important for health (7), there are data showing that refined and enriched grains make important contributions to the diet as well (8). At the same time, however, data also show that overconsumption of certain foods from the grain food group, particularly grain-based snacks and desserts, provides nearly as many calories in the diets of U.S. adolescents as do sugar-sweetened beverages (9,10). Both the benefits of cereal grain consumption and the risks of overconsumption will be discussed in this review.

**Debate Concerning the Effects of CHOs and Grains on Health.** While debates concerning grains and processing are not new, recent debates charge that wheat and all grains, even whole grains and CHO-rich staples, contribute to chronic diseases and

<sup>1</sup> Funded by a grant to CIMMYT from GrupoBimbo.

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<http://dx.doi.org/10.1094/CFW-60-5-0224>

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## Series of Reviews on Carbohydrates, Wheat, and Cereal Grains and Their Impact on Health

To address many claims now occurring that disparage and discourage the ingestion of carbohydrates (CHOs), wheat, and cereal grains, even whole grains, as well as to celebrate the versatility, nutritional and health benefits, and contribution of these foods to the world food supply, we felt compelled to defend their role in the diet and write this series of reviews. Where data exist, cereal grains and wheat as a source of CHOs and other important nutrients will be the focus.

The first grouping of review articles in the series will give some history showing that CHOs and grain-based foods have nourished the world population for millennia. The difference between and nutritional importance of glycemic CHOs and non-glycemic CHOs (e.g., dietary fiber) in nourishing the population will be emphasized. In the first review, the dietary recommendations for CHO and cereal grain consumption published in different countries and by health promotion bodies around the world will not only show striking concordance, but also will showcase their importance in the diet. The recommendations will show that CHO-rich staples, especially grains and whole grains, provide a low cost, versatile dietary base and deserve their important role in providing 45–65% of the calories in the health-promoting diets of most individuals. Further, these worldwide affirmations of the important role of CHOs, grains, and wheat in the diet will derail the arguments of authors and books that suggest otherwise. The second review will outline and discuss terminology associated with grains and whole grains and their processing, including definitions of whole grain, dietary fiber, and resistant starch and the characterization of a whole grain food. This discussion is important because the terms used often create consumer confusion and vary from country to country. The energy, protein, and critical vitamins and minerals contributed by grains as builders of a balanced diet for most healthy individuals around the world will be discussed. The nutritional contribution and bioavailability of nutrients and phytonutrients from grain-based foods will also be discussed.

The second grouping of reviews will include a paper that provides an overview of the physical health impacts of CHO-rich staple foods, including those that are wheat- and grain-based. It will address the impacts of these foods on basic health, including aspects such as blood glucose, inflammation and immunity, and composition and metabolic activity of the microbiome. As part of this discussion, the review will describe how these foods are digested and how their digestion impacts health outcomes in healthy people.

Further, the review will provide data regarding the small segment of the population who have medical conditions that preclude their eating wheat and other gluten-containing grains. This is especially important because many are attributing digestive problems and exacerbation of conditions such as irritable bowel to gluten and wheat. Caveats concern-

ing grain and wheat consumption discussed in the literature will also be reviewed.

The other articles in the second grouping of reviews will discuss the effects of CHO, grain, and wheat consumption on body weight maintenance and loss, blood pressure, metabolic syndrome, diabetes, stroke, cardiovascular disease, cancer, immunity, and longevity. Because inflammation, glycemic response, and insulin resistance all are associated with these chronic diseases, information from the first article in this grouping will be referred to for basic mechanisms.

The third group of review articles will assess the role of CHOs, grains, and wheat in neurological and brain functioning. The first of these will provide an overview of CHOs and other nutrients in brain functioning. It will include an introduction to specific terms and measures used in neuroanatomy and neurophysiology, such as cognition, working memory, attention, and executive functioning. The contribution of nutrients and phytonutrients from CHO-rich staples, with a focus on grains and wheat, in promoting normal brain functioning and fighting ill effects caused by inflammation will also be discussed. This article will also include an overview of dietary patterns, such as the dietary approaches to stop hypertension (DASH) and Mediterranean diets, that are associated with optimal brain health and neurological functioning.

The next set of articles will describe the relationship between CHOs, grains, and wheat and various dementias, such as mild cognitive impairment and Alzheimer's, and degenerative disorders, such as Parkinson's. The articles will include a look at the relationship between diabetes, insulin resistance, and abnormal glucose tolerance and various dementias. The last article in this group will review the scientific literature on the role of nutrition, CHOs, grains, and wheat in autism, attention deficit hyperactivity disorder (ADHD), major depression disorder, epilepsy, foggy brain, headache, multiple sclerosis, and schizophrenia.

The last two articles in the series will deal with the nutritional contributions of wheat and wheat-based foods in the diet and address the role of cereal grains and their global importance in providing a sustainable supply of calories and nutrients for the general population. The final article will have a global focus on wheat and its cultivation and processing and will assess similarities and differences in practices and uses. It will look at how wheat has evolved and continues to evolve and will describe how increases in yield and other factors have impacted different cultures and health. The cultural and nutritional contributions of wheat products in various regions will be compared and contrasted. The role of grains and wheat as part of a sustainable strategy for feeding the global population in 2050 and beyond will also be considered.

that consumption should be curtailed or completely eliminated from the diet.

Epidemiological studies showing that people who overconsume CHOs and grain-based foods have higher risks of developing obesity (11) and type 2 diabetes mellitus are used to support these arguments (12,13). Some suggest that consumption of CHO-rich foods impairs the ability to manage weight and type 2 diabetes. Although such arguments are based on associations found in epidemiological data, they frequently have been promulgated as causal rather than associational (14). Further, although some intervention studies have shown that the reduction or

elimination of CHO-rich foods in the diet, including wheat and grains, may result in short-term success in weight reduction and improvement in blood lipids (15), others show that for most individuals sustained weight loss and dietary adherence are not experienced or are lacking (16).

Finally, some authors and media spokespeople allege that the obesity epidemic and a myriad of other health problems are caused by wheat and/or gluten in the diet (17). Some even recommend the avoidance of all grains (18). The result is that there are many voices advocating the elimination of wheat and grains from the diet. Proponents of low-CHO and paleo-type

diets have questioned dietary advice that suggests 45–65% of daily calories from CHOs is an acceptable macronutrient distribution range. Some claim that in Paleolithic times humans did not eat grains (19) and, therefore, posit that humans have not evolved to include them in their diet (20). Additionally, some social media sources and diet books are claiming that modern wheat and grains, through breeding and other processes, have morphed and no longer deserve to be called the “staff of life.” They further allege that genetic modification has created grains that are not only addictive, but also destructive to many aspects of neurological functioning and mental health (17,18). Some sources even state that grains and CHOs are “chronic poisons.”

**Table I. Cereals and pseudocereals<sup>a</sup>**

Common Name	Scientific Name
<b>True cereals</b>	
Wheat (including spelt, emmer, farro, einkorn, kamut, durum)	<i>Triticum</i> spp.
Rice, African rice	<i>Oryza</i> spp.
Barley	<i>Hordeum</i> spp.
Corn (maize, popcorn)	<i>Zea mays</i>
Rye	<i>Secale cereale</i>
Oats	<i>Avena</i> spp.
Millet	<i>Brachiaria</i> spp., <i>Pennisetum</i> spp., <i>Panicum</i> spp., <i>Setaria</i> spp., <i>Paspalum</i> spp., <i>Eleusine</i> spp., <i>Echinochloa</i> spp.
Sorghum	<i>Sorghum</i> spp.
Teff (tef)	<i>Eragrostis</i> spp.
Triticale	<i>Triticale</i>
Canary seed	<i>Phalaris canariensis</i>
Job's tears	<i>Coix lacryma-jobi</i>
Fonio, black fonio, Aslan millet	<i>Digitaria</i> spp.
Wild rice	<i>Zizania aquatic</i>
<b>Pseudocereals</b>	
Amaranth	<i>Amaranthus caudatus</i>
Buckwheat, tartar buckwheat	<i>Fagopyrum</i> spp.
Quinoa	<i>Chenopodium quinoa</i> , generally considered a single species within the <i>Chenopodiaceae</i>

<sup>a</sup> Source: AACC International Whole Grain Task Force (21).

### Nutritional Contributions of CHO-rich Staples, with a Focus on Grains and Wheat

Major CHO-rich staples include seeds from cereal grass heads or rice, wheat, maize (corn), oats, rye, barley, sorghum, millet, and teff; roots and tubers such as potato, taro, and cassava; and seeds from pseudocereals such as buckwheat, amaranth, and quinoa. In 2006 the AACC International (AACCI) Whole Grains Task Force compiled the list of cereal grains and pseudocereals found in Table I (21). The proximate composition of a sampling of CHO-rich staples is provided in Table II (22,23).

**CHOs as Fuel.** CHOs are recognized by national and international authorities such as the World Health Organization/Food and Agriculture Organization (WHO/FAO) (22) as the macronutrient

**Table II. Major components of many cereal and root crops (per 100 g edible portion)<sup>a,b</sup>**

Crop	Energy (kJ)	Moisture (%)	Protein (g)	Fat (g)	CHO (g)	TDF (g)	Starch (g)	Sugars (g)
<b>Cereal</b>								
Wheat	1,318	14.0	12.7	2.2	63.9	12.6	61.8	2.1
Maize	1,515	12.0	8.7	0.8	77.7	11.0	71	1.6
Rice	1,531	11.8	6.4	0.8	80.1	3.5	80.1	1.0
Barley	1,282	11.7	10.6	2.1	64.0	17.3	62.2	1.8
Sorghum	1,610	14.0	8.3	3.9	57.4	13.8	(50)	1.3
Millet	1,481	13.3	5.8	1.7	75.4	8.5	60	4
Rye	1,428	15.0	8.2	2.0	75.9	14.6	75.9	NA
Oats	1,698	8.9	12.4	8.7	72.8	10.3	72.8	1.2
<b>Root</b>								
Potato	318	79.0	2.1	0.2	17.2	1.8	16.6	0.6
Cassava	607	64.5	0.6	0.2	36.8	NA	35.3	1.5
Sweet potato	372	73.7	1.2	0.3	21.3	3.0	15.6	5.7
Yam	488	67.2	3.0	0.3	28.2	3.3	27.5	0.7
Taro	451	68.3	1.4	0.2	26.2	2.9	25.1	1.1
Potato	318	79.0	2.1	0.2	17.2	1.8	16.6	0.6
Cassava	607	64.5	0.6	0.2	36.8	NA	35.3	1.5

<sup>a</sup> Source: FAO (22).

<sup>b</sup> CHO = carbohydrate; TDF = total dietary fiber.

that humans need to consume in the largest quantity. A main function of CHOs is as a source of readily available fuel—glucose. Glucose can be carried in the bloodstream to tissues and delivered to cells, where it can be readily utilized (provided that glucose tolerance is normal), or delivered to the liver for storage as glycogen. The liver has a limited capacity for storing glucose as glycogen, however, so excess glucose is used to make fat. Proper utilization of fat in the body requires CHOs to be present.

Glucose is required by all body tissues, including brain tissue. The brain is a CHO “gas guzzler.” While it comprises only 2% of the body mass, it uses 20% of the fuel (24). Further, more recently evolved brain structures, such as the frontal cortex, are particularly sensitive to falling glucose levels, whereas more primitive regions, such as the brain stem, are less affected (25). This explains why a drop in blood sugar is associated with confused thinking but has little impact on physiological functions such as breathing that are controlled by the brain stem.

The brain and nervous system run optimally on a constant supply of glucose, which either comes from CHOs supplied in recently eaten foods or from glycogen stores in muscles or the liver. Without glucose, the body catabolizes protein to supply it. Fat does provide energy to the muscles, but less efficiently than glucose. This may have advantages for those experiencing caloric surfeit, but not for those experiencing caloric deficit. Ketone bodies result when fat is metabolized without CHOs and can be used by the brain but are not considered an optimal fuel for most individuals (26).

**Excess CHOs.** Excess circulating blood glucose is an aspect of CHO metabolism that causes great concern for several reasons. First, excess glucose is known to contribute to the synthesis of triglycerides; second, it can trigger a cascade of inflammatory responses; and, third, it can lead to the development of insulin resistance and type 2 diabetes mellitus. The latter conditions can hinder glucose entry into the cell, lead to glycosylation of protein, and impair functioning of all tissues, including brain tissues (27).

While excess CHO may impair glucose tolerance and insulin function (in certain individuals under specific conditions), it is not unique in this ability. Excess intake of fat or calories, as well inadequate intake of nutrients, have all been shown to cause inflammation and can lead to insulin re-

sistance and numerous other adverse effects (28–30).

### Grains and Glycemic CHOs

A glycemic CHO is one that can be broken down and absorbed as glucose in the small intestine and deliver glucose to the bloodstream and body. In grains, the major source of glycemic CHOs is starch, a polymer of glucose with  $\alpha$ 1→4 and 1→6 linkages that is split by human amylases.

Nearly all starch in cereal grains is found in the endosperm, whereas the outer layers (bran, germ, and aleurone) contain almost none. In the endosperm, starch exists in granules, which vary by grain variety in size, shape, and properties such as crystallinity. Less than 1% of the CHOs in most grains are in the form of simple sugars, so these CHOs have little impact on the glycemic response caused by grains.

#### Digestion and Absorption of Glucose.

During digestion, starch is first broken down by amylases to shorter polymers and then to maltose. Starch is broken down to a minor degree by salivary amylase, but primarily by pancreatic amylases in the small intestine. Maltase in the brush border completes the breakdown by splitting the maltose into its two glucose monomers. How rapidly and completely this occurs depends on a number of factors, including the size and composition of the meal; type, size, and structure of the starch granule; particular starch moiety—amylose or amylopectin, with its chain length in the starch molecule and its degree and pattern of branching; ability of the chain to form helices or crystals (31); and degree of starch gelatinization.

**Amylose and Amylopectin.** In most grains starch is a mixture of two glucose polymers—linear amylose and branched-chain amylopectin—in a 1:3 ratio. Amylose is smaller (100–10,000 glucose units) and less branched than amylopectin. Amylopectin is larger (10,000–100,000 glucose units) and more highly branched. This branched structure provides free ends that allow amylase attachment and more rapid glucose release. The size and extensive branching of amylopectin contribute to lower gelatinization temperatures and a more porous structure. Both factors favor faster amylase action.

**Digestible and Resistant Starches.** The amylopectin/amylose ratios in grain varieties and cultivars differ widely. “Waxy” varieties contain mainly amylopectin, whereas some varieties, such as HiMaize or basmati rice, are higher in amylose. For

grains that are higher in amylose, delivery of glucose to the bloodstream is slowed, and starch digestion may be incomplete (32). When digestion is incomplete, the undigested starch fragments move from the small intestine into the large bowel where they become “resistant starch” (RS), which is a form of dietary fiber (33).

Starch crystallinity also affects digestion rate. Highly crystalline networks inhibit penetration by amylases and slow digestion. Repeated cooking and cooling remove some water held between the starch chains and promote crystalline bonding between the chains in a process called retrogradation. Retrograded starch chains also resist digestion and become a type of RS. In parts of Africa, such cooking procedures increase RS in staple grain porridges (34).

Four types of RS have been delineated by Brown (35). RS1 is starch that is embedded in a food or grain matrix, hindering its availability to amylases. Such starches are common in foods containing unbroken kernels or seeds. RS2 is starch in a native crystalline structure that is poorly degraded by amylase. RS3 results from retrogradation of starches. RS4 is derived from starches that have been chemically cross-linked. Some researchers suggest that amylose helices with an internal fat core should be classified as RS5 (36).

Bread and cereal products are the greatest contributors of RS in most diets, not because they are the best sources, but because they are frequently selected and eaten (37,38). Breads and cereals provide about one-third of the average daily intake of RS ( $\approx$ 4 g). Some countries with higher average intakes include China (14.9 g/day), Italy (8.7 g/day), and Spain (5.7 g/day) (39,40).

**Glycemic Response and Index.** Grains and other CHO-rich food sources of glycemic CHOs directly impact blood glucose. The glycemic impact of a meal or total diet is of great importance because excess circulating blood glucose or dramatic swings in blood glucose levels and attendant hormones, such as insulin, affect health. However, the precise effect varies due to a wide range of factors.

To measure glycemic impact, the glycemic index (GI) was proposed in 1981 by Jenkins et al. (41) as a means of quantifying the effect of a CHO-rich food on postprandial glycemia. Specifically, it measures the increase in blood glucose concentrations (the incremental area under the curve of blood glucose concentrations) after the ingestion of a portion of a

test food containing 50 g of available CHO compared to the area of the glucose curve measured after the ingestion of 50 g of a CHO reference food, usually glucose (sometimes white bread). If the CHO from the test food raises blood glucose the same amount as the reference food, then the ratio is represented as 100; if it raises it less, then the value is smaller than 100. Foods are typically classified as high GI if the GI value is between 70 and 100, medium if the GI value is between 56 and 69, or low if the GI value is  $\leq 55$ .



Canadian guidelines.

Many recent books and blogs charge that grain-based foods should be avoided because of their high GI. It is true that some grain-based foods have a high GI. However, for several reasons the GI is often misunderstood and misused. First, many assume that the index compares equal amounts of food or even equal amounts of CHO. In actuality, it compares equal amounts of available CHO. For instance, for both whole wheat bread and white bread the GI value is 70, but it takes 3.5 to 4 slices of whole grain bread and 3 slices of white bread to obtain 50 g of available CHO. Thus, eating a slice of whole grain bread will have a lower glycemic impact than a eating slice of white bread.

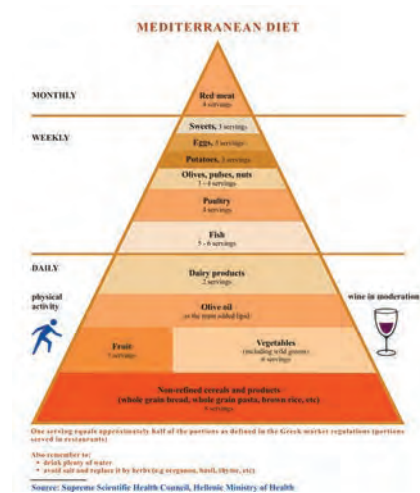
The GI is affected by many components in a food product (42). For example, fat interferes with the action of amylase, thereby lowering the GI. Dietary fibers, especially viscous ones, also impede the action of enzymes and slow the entry of glucose into the bloodstream. The extent and type of cooking or processing, particle size, ripeness, and numerous other factors affect the GI as well (43).

GI values in tables are derived using a single food under strictly controlled con-

ditions. The GI is measured for a single food using 10 subjects with normal glucose tolerance and following a strict protocol that includes an overnight fast and a prescribed dinner. Because foods are rarely eaten either alone or after following a strict protocol, the GI values listed in tables may be wholly inadequate to reflect the blood glucose impact of foods eaten in combination. For example, bread eaten with olive oil or butter has a lower GI value than bread eaten by itself, while bread dipped in vinegar or sushi rice (cooked and cooled with vinegar added) has a lower GI value because of the effects of pH on the enzyme amylase (42). The actual effect of a food on blood glucose depends on how much of the food is eaten, how frequently, and what other foods are eaten in the snack or meal (44).

Popular press publications point out that cereal foods such as whole wheat bread have a higher GI than certain candy bars, such as a Snickers bar (GI = 41) (17). Although the comparison between an indulgent snack and a staple grain is nutritionally ridiculous, it does demonstrate that the nuts, fat, and chocolate in the candy bar combine with the medium GI component sucrose (GI = 68) to slow the entry of glucose into the bloodstream and result in a food with a lower GI than bread. Further, such comparisons say nothing about the volume of food needed to obtain 50 g of available CHO or the nutrition delivered by the food.

Health promotion organizations vary concerning their acceptance of the GI. The American Diabetes Association notes that it may be used as an adjunct to CHO counting (45). The Australian Diabetes Association notes that the “GI is only a small part of the healthy eating plan for people with diabetes” (46). The American



Greek guidelines.

Heart Association (AHA) does not have a formal position on the GI, nor does it express strong support for the GI as an important tool in the evaluation of health risks, CHO quality, or diet planning. The AHA concludes that there are unresolved issues with the use of the GI as a research tool at this time (47).



Belgian guidelines.

### Non-glycemic CHOs in Grains: Dietary Fiber

Nearly all of the CHOs found in the bran and germ, as well as the CHOs comprising the cell walls in the endosperm, are non-glycemic. They are not digested in the small intestine, which is a key tenet in dietary fiber definitions. Thus, they meet the AACCI (48) and Codex Alimentarius Committee definitions of dietary fiber, i.e., polymers with a degree of polymerization  $\geq 3$  that are neither digested nor absorbed in the small intestine and are at least partially fermented in the large intestine and have beneficial physiological effects (49,50). (In some countries, these are referred to as nonstarch polysaccharides.)

**Dietary Fiber Functions.** Dietary fiber is a class of diverse molecules that have many functions. In 2010 an agreed upon list of core dietary fiber functions, which experts attending the international 9th Vahouny Dietary Fiber Symposium suggested had enough scientific evidence to support them, was created and dubbed the “Vahouny 9” (51):

- 1) Reduced blood total and/or LDL cholesterol levels
- 2) Attenuation of postprandial glycemia/insulinemia
- 3) Reduced blood pressure
- 4) Increased fecal bulk/laxation
- 5) Decreased transit time
- 6) Increased colonic fermentation/short-chain fatty acid (SCFA) production
- 7) Positive modulation of colonic microflora
- 8) Weight loss/reduction in adiposity
- 9) Increased satiety



Slovenian guidelines.

Because there are vast differences in the polymers due to different base sugars and attached molecules, as well as different branching structures and matrices, it makes sense that not all dietary fibers perform all physiological functions. However, to be deemed a dietary fiber when added to a food product, the polymer needs to demonstrate at least one of the physiological effects listed above.

Since the 2010 Vahouny meeting, stronger evidence has been gathered for some additional functions. These include bolstering immune functions and exerting anti-inflammatory effects (52).

**Dietary Fiber Types.** Cellulose is the predominant dietary fiber in many plant-based foods, including grains, because it forms the cell walls of all plants. It is composed of glucose monomers, but human enzymes are unable to split the  $\beta$ -linkage between the monomers. This primary component of many cereal brans is very insoluble and slightly fermentable. Therefore, it is very effective in aiding gut motility, increasing laxation and stool weight, and improving overall gut health.

The polymers that make up a “mortar-like mixture” between the cell walls formerly were called pentosans. More recently, they have been characterized and include  $\beta$ -glucan, fructans, arabinoxylans, pectins, and a variety of oligosaccharides (53). Many of these molecules are soluble, highly fermentable, and able to produce SCFAs. Some are viscous polymers, such as  $\beta$ -glucan found in oats and barley, which may slow absorption by entrapping various dietary components. Through such mechanisms they help maintain healthy serum cholesterol and blood glucose levels (54). The actual functionality is determined by the specifics of the molecule, e.g., branching pattern, molecular weight, concentration, and viscosity.

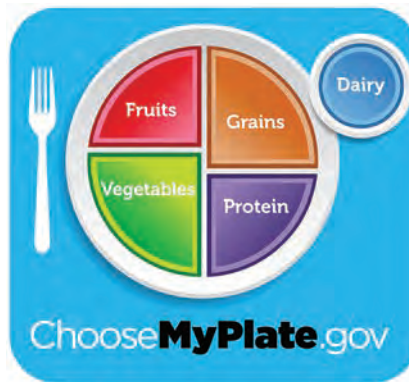
Fructans, polymers of fructose such as inulin, are soluble, nonviscous, and readily fermentable. They improve mineral absorption and can alter the bacterial

composition of the gut and act as prebiotics. Although they are present in a range of plant foods, wheat and rye are important sources in cereal-based foods (55). Inulin from wheat has been shown to stimulate the growth of bifidobacteria and inhibit growth of pathogenic bacteria such as *Escherichia coli*, *Salmonella*, and *Listeria* (56).

Arabinoxylans are polymers of arabinose and xylose. In grains such as wheat, they exist in both soluble and insoluble forms. They have been shown to act as prebiotics, improving gut health and having some systemic health effects (57). Arabinoxylan from rice bran has been shown to have positive effects on the immune system and gut (58).

**Dietary Fiber and SCFAs.** Many of the effects of dietary fiber stem from its role in modulating the type and amount of bacteria in the gut. Changing the composition of the gut microbiota can have a positive prebiotic effect on health in that these changes can promote the growth of beneficial bacteria (59).

The fermentation of various CHO polymers in the large bowel produces SCFAs such as acetate, propionate, and butyrate, which are the principal end-products that promote health benefits, both through local and systemic effects. In the colon, they not only lower the pH, which may be helpful in reducing the risk of colon cancer, they also provide energy, promote the growth and differentiation of healthy colonic cells, help repair damage to colonocyte DNA, and induce cell death (apoptosis) in nonrepairable aberrant cells (60–62). These properties provide a credible link between dietary fiber intake and protection against colorectal cancer (63,64).

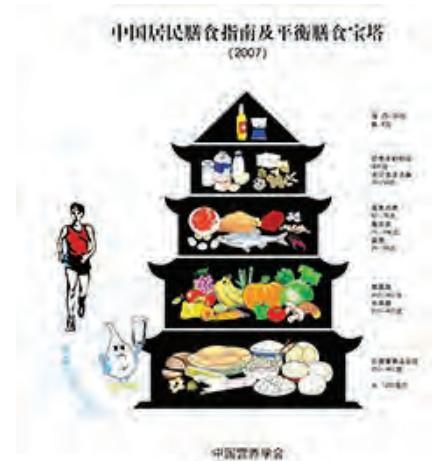


U.S. guidelines.

SCFAs also can affect lipid, glucose, and cholesterol metabolism in various tissues (64). They may help counter diet-induced obesity through their ability to increase fatty acid oxidation in muscle and other

tissues and decrease fat storage in adipose tissue.

**Dietary Fiber and Grain Processing.** The actual physiological benefits of the various dietary fibers, including RS in grain-based foods, depend on the type and extent of milling; resultant particle size; fiber type, solubility, viscosity, and molecular weight; linkage patterns; and compounds attached to the fiber complex. Thus, processing can both increase and decrease the effects of a dietary fiber by altering its molecular weight (65), viscosity, or the amount of available RS (66–68).



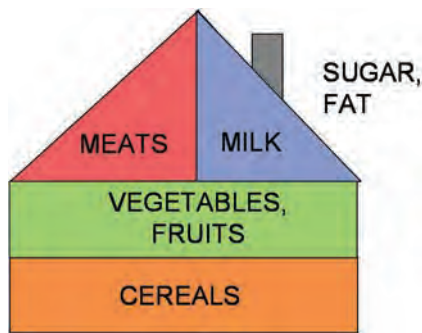
Chinese guidelines.

## Recommendations Regarding CHOs in the Diet

With the important nutritional contributions made by CHO-rich foods, it is no wonder that health and government organizations around the world, together with expert consultative committees, recommend that the bulk of calories consumed come from CHOs, particularly from CHO-rich staples, including grains. The WHO/FAO expert consultation on diet (69), U.S. Dietary Guidelines Advisory Committee (70), U.S. Department of Agriculture (USDA) series of systematic reviews on healthy dietary patterns (71), dietary reference intakes established by the U.S. National Institute of Medicine and Health Canada (72), European Food Safety Authority (73,74), Nordic Nutrition Recommendations (75), U.K. Scientific Advisory Committee on Nutrition (76), Singapore Health Promotion Board (77), and Australian Dietary Guidelines (78, 79), as a partial list, all support these recommendations. Most guidelines suggest that at least 45% of calories consumed come from CHOs, with suggested CHO intakes ranging from 45 to 65% of calories; the WHO report recommends as

much as 75% of energy come from CHO (80). Lower GI and higher protein intakes have been recommended by some for individuals with insulin resistance or who are trying to maintain weight (81), but controversy still swirls around this topic, and research continues to try to tease out the answers.

**Setting Upper Limit for CHO Intake.** The setting of an upper limit for CHO intake is based on two major concerns. The first is the concern that excess CHO intake will upset the dietary balance and impede intake of adequate protein, fat, and other essential nutrients. The second is the concern that excess calorie and CHO intakes can lead to excess circulating glucose and insulin in the bloodstream. Excess glucose in any tissue, including the brain, is known to trigger a cascade of inflammatory responses and insulin resistance that can impair the functioning of all tissues (27). However, the adverse effects of excess CHO intake are not unique to this nutrient; excess intakes of calories and other dietary components (28,29), as well as the lack of them, have also been shown to cause inflammation, insulin resistance, and other adverse effects (30). Although not a basis for setting an upper limit for CHO intake, some have alleged that excess consumption of readily available CHO-rich and grain-based desserts leads to overconsumption of calories.



Hungarian guidelines.

**Dietary Fiber Intake.** Around the world dietary fiber is included as part of general dietary recommendations. Its inclusion is based on evidence produced by epidemiologic and intervention studies indicating that adequate intakes, both in quantity and types, of dietary fiber are associated with improved gut health (82) and reduced risk of death and chronic disease from a number of disorders (83–85).

Despite recommendations, the daily intake of dietary fiber in most developed and developing countries is well below

recommended levels. For example, in North America less than 4% of the population meets the adequate intake recommendation for dietary fiber (86). Therefore, several U.S. Dietary Guidelines Advisory Committees have listed it as a “nutrient of concern.” Consumption of bran and grain-based foods is an important dietary strategy for meeting the dietary fiber requirement.



Japanese guidelines.

**Grains in CHO Recommendations.** Translating the recommended balance of calories into food-based dietary guidance is common practice around the globe, according to the European Food Information Council (87). Its compilation of guidelines found that most use verbal descriptions and/or graphic illustrations to assist people in selecting optimal proportions of recommended food groups. While the graphics used vary in form from pyramids and plates to temples and pagodas, the prominence of grain-based and CHO-rich foods in the various recommendations is strikingly similar. Guidance provided by countries around the world, such as the United Kingdom (88), South Africa (89), Singapore (90), France (91), and Australia and New Zealand (92), all urge that grains and starchy foods form the basis of most meals and that they be eaten daily to provide a primary source of energy. Most guidelines suggest that starchy foods



Irish guidelines.

should make up about one-quarter or one-third of the total foods eaten. Grain-based foods (e.g., breads and flat breads, cereals, pastas and noodles, and rice dishes) are included among the starchy foods listed. In some cases, specific amounts are recommended. For example, the U.S. Dietary Guidelines Advisory Committee (71) and USDA MyPlate (93) recommend that the average person ingesting 2,000 cal/day consume 6 servings of breads and cereals, with half of the servings as whole grain foods. Health Canada’s guidelines recommend adults consume 6–8 servings of grains/day (94).

Whole grains have been incorporated into dietary guidelines in many regions. Some specifically mention the need to consume high-fiber, whole grain foods. A recent review by Jonnalagadda (95) contains a compilation of guidelines on whole grain consumption from around the world.



Spanish guidelines.

Despite the general concordance worldwide regarding recommendations for CHO, dietary fiber, and whole grain intake, only a small part of the population consumes the suggested amounts. For example, the French Nutritional Guidelines recommend the consumption of starchy foods from a variety of sources at each meal. Yet, in a survey of more than 80,000 people in the French NutriNet-Santé cohort, only 43% had intakes of starchy food that were in line with the guidelines (96). The authors noted similar data from many Western European countries. Data from U.S. surveys show that 36% of all age and gender categories fail to meet the grain recommendation and 99% fail to meet the whole grain recommendation (9,97).

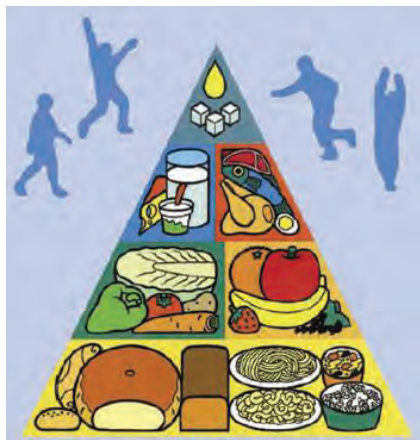
Worldwide agreement concerning the importance of CHOs and CHO-rich foods

in the diet does not mean that CHO are free from vigorous debates in both the scientific and popular press about the source and quality of CHO-rich foods. Some advocates argue that the type of CHO-rich foods chosen should be low glycemic, while others argue that only minimally refined or processed grains should be selected and no refined grains should be consumed.



French guidelines.

A few suggest that amounts of CHOs consumed should be decreased or even stripped to a bare minimum of 50 g (200 kcal) for optimal weight control, diabetes prevention, and brain health (17,18). Advocates of the paleo diet claim that grains and legumes should be severely limited because humans did not evolve to eat them. They further argue that adherence to such a diet will bring about weight loss and improve several chronic conditions (19,20). Such claims are appealing in some populations, such as the United States, where as much as two-thirds of the population is overweight or obese (98).



Czech guidelines.

The role of wheat and other gluten-containing grains as a cause of celiac disease and other disorders also has caused some to argue that everyone needs to avoid grains and foods that contain gluten. (Celiac and other gluten-related disorders will be addressed in a subsequent review.)

## Conclusions

CHO-rich staple foods, including those from a wide array of whole and refined grains, are inexpensive sources of energy, protein, and other nutrients. Grain-based staple ingredients have been incorporated into an enormous variety of foods, becoming cultural icons and national dishes that are readily accepted by various populations around the world and adapted to specific agricultural necessities and cultural preferences. In many cultures such foods have a long history as dietary cornerstones that continues today.

Dietary guidance by health promotion bodies around the world recommends that 45–65% of total calories be from CHOs and reinforces the message that grains play an important role in the diet. The important health benefits provided by grains argues for their incorporation in the everyday diets of healthy people. Whole grains in particular are associated with decreased risk of certain chronic diseases, and consumption of an optimal mix of whole and refined grains is associated with a number of health benefits.

Cereal grains provide a wide variety of nutrients, dietary fibers, and phytochemicals. This combination uniquely positions them as a source of nutrition to both sustain and nourish a global population.

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