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Noncaloric Benefits of Carbohydrates

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Abstract

Noncaloric benefits of carbohydrates are due to the presence of dietary fibers, which are a heterogeneous group of natural food sources and form an important component of a healthy diet. They differ in physiochemical properties such as solubility, fermentability and viscosity. They have a wide range of physiological effects resulting in gastrointestinal and systemic benefits. These include appetite, satiety, bowel transit time and function, production of short-chain fatty acids and certain vitamins, and effects on gut microbiota, immunity and inflammation, as well as mineral absorption. They also help to control the glycemic status and serum lipid levels, resulting in reduced incidence rates of atherosclerosis, hypertension, stroke and cardiovascular diseases.

Introduction

Carbohydrates (CH) are a major source of nutrients for human beings. The average daily consumption is about 300 g (range from 250 to 800 g). Most of the digestible CH are converted to carbon dioxide, water and energy. CH provide more than 50% of the daily calories. However, the diet also contains low-digestible or nondigestible CH, which are mainly derived from plant sources and constitute the dietary fiber; they are capable of undergoing partial or complete fermentation in the large intestine [1]. There are various types of dietary fibers

which have varying physiological effects. Clinical studies have shown that fibers have a wide range of benefits, depending on their physical and chemical characteristics, e.g. solubility, fermentability and viscosity [2]. This article gives an overview of the noncaloric benefits of such low-digestible and nondigestible CH, which constitute the dietary fiber.

Definition of Dietary Fibers

Eben H. Hipsley used the term 'fiber' for the first time in 1953, when he reported an increased incidence of pregnancy-related toxemia in Indians living in Fiji Islands who were on a low-fiber diet, compared to a low incidence seen in indigenous Fijians who were on a high-fiber diet [3]. Consequently, a number of diseases were postulated to develop as a result of lack of fiber in the diet, and the term 'dietary fiber' was adopted, in keeping with the then 'dietary fiber hypothesis' [4]. However, a scientifically sound definition was lacking. In the year 2000, the American Association of Cereal Chemists (AACC) modified the definition based on years of research and inputs from food scientists worldwide [5, 6]. *'Dietary fiber (DF) is the remnants of the edible part of plants and analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the human large intestine'*. It includes various substances, such as polysaccharides, oligosaccharides and lignins.

The AACC further classified DF based on their solubility (table 1) [4]. A more practical way of classification is the one that is based on all the physiochemical properties, solubility, fermentability and viscosity (table 2) [2]. The definition was further refined by the Food and Nutrition Board of the Institute of Medicine based on an approach to distinguish between intrinsic and intact components of plants, which is the 'dietary fiber' and 'added fiber'. Together they are called 'total fiber' [6]. This last definition is more flexible, as it includes nondigestible CH from animal origin. Therefore, DF is the CH, either of plant or animal source, which is not completely digested in the small intestine and exerts physiological effects which are beneficial.

Carbohydrates and the Digestive System

Most of the CH are digested in the small intestine and provide calories. The undigested CH, by their complex effects on the large intestine, provide many noncaloric benefits. They increase the fecal bulk, prevent constipation and undergo

Table 1. DF constituents according to AACC [4]

NSP and resistant oligosaccharides
Cellulose
Hemicellulose
Arabinoxylans
Arabinogalactans
Polyfructoses
Inulin
Oligofructans
Galactooligosaccharides
Gums
Mucilages
Pectins
Analogous CH
Indigestible dextrins
Resistant maltodextrins
Synthesized CH compounds
Polydextrose
Methyl cellulose
Hydroxypropylmethyl cellulose
Indigestible ('resistant') starch
Lignin substances associated with NSP and the lignin complex in plants
Waxes
Phytate
Cutin
Saponins
Suberin
Tannins

fermentation to provide short-chain fatty acids (SCFA). In addition, they are a source of antioxidants, trace minerals, phenolic compounds and phytoestrogens. They also reduce the risk of diverticulitis, obesity, type 2 diabetes and cardiovascular diseases, and lower serum cholesterol levels [7].

Carbohydrates in the Small Intestine

Most of the carbohydrate intake is in the form of polysaccharides followed by oligosaccharides. These complex saccharides cannot be absorbed and need to broken down to monosaccharides, which undergo further enzymatic hydrolysis in the small intestine, resulting in the production of glucose, galactose and fructose. These simple molecules are absorbed via specific transport (sodium-dependent active transport and facilitated diffusion) and nonspecific transport (passive diffusion) systems within the small intestine [1].

Table 2. Classification based on physiochemical properties [2]

Soluble	*Insoluble*
Acacia gum	Cellulose
PHGG	Soy polysaccharide
FOS	Resistant starch
Pectin	Hemicellulose B
Hemicellulose A	
Oat fiber	
Fermentable	*Nonfermentable*
Acacia gum	Cellulose
PHGG	Outer pea fiber
Inulin	
FOS	
Soy polysaccharide	
Resistant starch	
Pectin	
Viscous	*Nonviscous*
Pectin	Cellulose
Some gums (e.g. guar gum)	Outer pea fiber
	Soy polysaccharide
	Resistant starch
	PHGG
	Inulin
	FOS

PHGG = Partially hydrolyzed guar gum.

Carbohydrates in the Large Intestine

About 85% of CH are absorbed before entering the large intestine. Ten to 30% of the CH remain undigested and enter the colon. These include polymers such as nonstarch polysaccharides (NSP), resistant starches and polysaccharides in structure forms, for example. Bacterial hydrolases convert these complex polymers into smaller molecules, which are further broken down by bacterial amylases into monosaccharides. These monosaccharides undergo anaerobic fermentation by colonic bacteria and are converted to SCFA (acetate, propionate and butyrate), which are a source of energy, and noncaloric substances such as hydrogen, carbon dioxide and methane (fig. 1). This bacterial degradation of nondigestible CH yields an energy salvage of about 62%. The bacteria in the large intestine (there are about 300–500 bacterial species which contain nearly 2 million genes) thus salvage significant energy from the low-digestible and nondigestible CH [8].

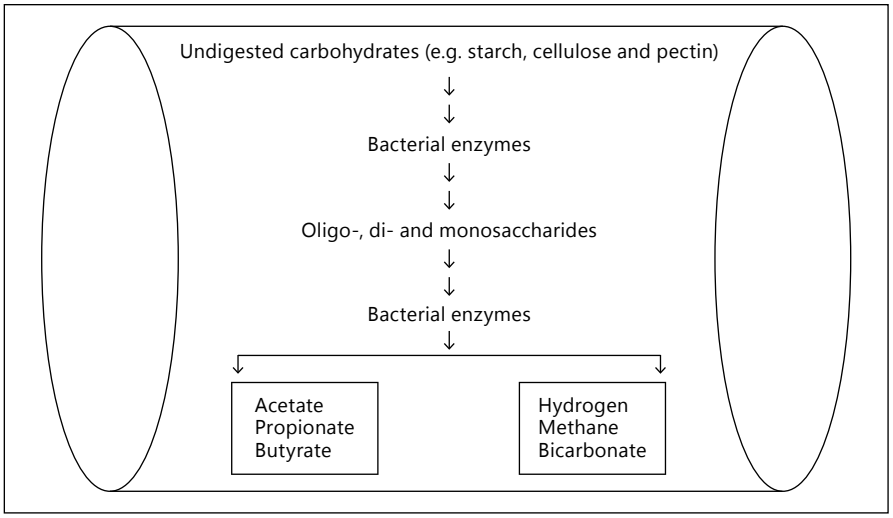

Fig. 1. Fate of CH in the large intestine.

Mechanisms of Noncaloric Benefits of Carbohydrates

The components of the low-digestible and nondigestible CH have a variety of actions, which result in various benefits. Most of them slow the gastric emptying time, increase satiety and have a variable mouth-to-fecal transit time. They inhibit the action of pancreatic and other digestive enzymes and reduce the rate of absorption. By their hydrophilic action, they increase the stool weight and volume by 40–100%. They act as nutrients (prebiotics) on the colonic bacteria, which in turn ferment the undigested CH residue, resulting in SCFA production [8]. Soluble fibers are more fermented than insoluble fibers (10 times more) by the huge population of colonic bacteria. SCFA are rapidly absorbed by colonic epithelium, in exchange for bicarbonate, and hydrogen is excreted as a result, which is exchanged for sodium along with water (fig. 2) [9]. The concentration of SCFA is negligible in the jejunum, but progressively increases and is about 10 times higher in the colon. Acetate and propionate control cholesterol to a certain extent [10]. Propionate also acts as a substrate for gluconeogenesis in hepatocytes. Butyrate is the most important SCFA and is the preferred fuel for colonocytes; it accounts for 80% of the energy for colonocytes. It has an immunostimulatory effect and also aids in the growth of jejunal and ileal epithelial cells [11]. An important action of butyrate is its anti-inflammatory effect, which is due to a decreased production of TNF-α, and inhibition of NF-κB activation and cytokine messenger RNA expression [12].

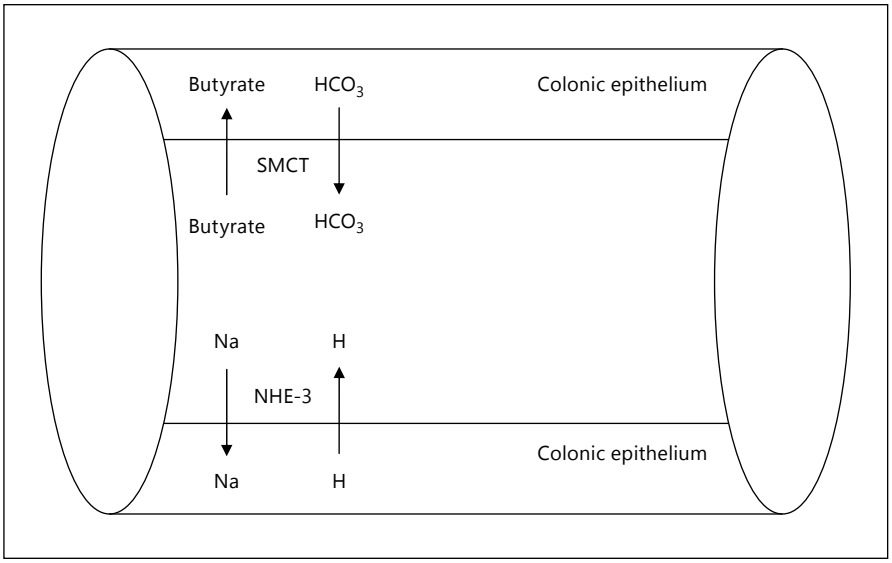

Fig. 2. SCFA stimulate Na and consequently water absorption in the large intestine [9]. SMCT = Sodium-coupled monocarboxylate transporter; NHE-3 = sodium hydrogen exchanger-3.

Certain components such as nonstarch fruits and vegetables have a low glycemic index, resulting in reductions in the glycemic load and, thereby, in the incidence of type 2 diabetes [13]. Viscous, soluble fibers (pectin, oat fiber and gums) have a lipid-lowering effect. They form a viscous gel and increase bile salt excretion by preventing their reabsorption in the small intestine. As a result, the liver converts more low-density lipoprotein (LDL) cholesterol to bile acids, resulting in a reduction in total and LDL cholesterol levels [14], and, consequently, exerts a beneficial effect on the incidence of atherosclerosis, cardiovascular diseases and stroke.

The nondigestible bulk, in addition to preventing constipation, also binds luminal carcinogens, thereby reducing their exposure. The presence of vitamins and various bioactive compounds inhibit the molecular pathways which promote carcinogenesis. In addition, butyrate also has an effect on cell differentiation, apoptosis and gene expression on the colonic epithelium [15].

Fermentable nondigestible CH ingredients such as inulin and fructooligosaccharides (FOS), which are present in edible fruits, onions, garlic and bananas, selectively stimulate the growth and activity of a limited number of species of bacteria in the colon, such as lactobacilli and bifidobacteria (called prebiotics) [16]. They have a low viscosity, are water soluble and cause a reduction in the pH of the colonic contents. They stimulate the growth of beneficial bacteria,

Table 3. Noncaloric benefits of CH

Gastrointestinal benefits	Systemic benefits
Transit time	Appetite and satiety
Constipation	Weight control
Diarrhea	Glycemic control
Prebiotics and microflora	Hyperlipidemia
SCFA	Cardiovascular disease
Inflammatory bowel disease	
Irritable bowel syndrome	
Gastrointestinal cancer	

which inhibit the growth of pathogenic bacteria (e.g. clostridia), are helpful in treating constipation and may be beneficial in inflammatory bowel diseases.

FOS have been shown to have a variety of beneficial properties. They help in the production of SCFA. By reducing the pH, they reduce the ammonium levels and the number of clostridia and other putrefactive bacteria, and also increase calcium and magnesium uptake. They may also reduce serum cholesterol levels, especially in diabetic persons [17].

The nondigestible CH have diverse effects, which can be divided into gastrointestinal benefits and systemic benefits (table 3).

Gastrointestinal Benefits

Transit Time. It depends on the source, type and structure of the dietary fiber, and the effects on the upper gastrointestinal tract can be different from the effects on the colon. Soluble fibers (e.g. pectin and oat fiber) and insoluble fibers (e.g. coarse bran and soy polysaccharides) reduce gastrin emptying time and increase satiety. Pectin, especially in its solid form, is more effective in reducing motility than in its liquid form. The presence of a fiber-rich meal in the ileum has an inhibitory feedback mechanism (ileal brake) and reduces gastric emptying. However, not all fibers have the same effect, as some (guar gum in semisolid form) have induced conflicting outcomes depending on the form of administration [18–20].

Constipation. Nondigested CH increase the stool weight and volume by the physical presence of dietary fiber itself; the hydrophilic effect of the fibers; the increase in gel formation and absorption, and also by the increase in the bacterial mass by fermentation. A systemic review and meta-analysis showed that fiber-enriched diets reduce the incidence of constipation in healthy volunteers and in acute-care settings [2, 21].

Diarrhea. Soluble fiber has shown to reduce the incidence of diarrhea by slowing the intestinal transit time and also probably by increasing the

bioavailability and absorption of zinc (zinc is known to reduce the incidence and duration of diarrhea). An earlier meta-analysis did show a reduction in the incidence of diarrhea in hospitalized patients [21, 22].

Prebiotics and Microflora. Prebiotics (e.g. FOS, oligofructose and inulin) stimulate the growth of *Bifidobacterium* and *Lactobacillus* species. These bacterial species stimulate fermentation and production of SCFA in addition to inhibiting the growth of pathogenic bacteria (e.g. clostridia). They are also known to produce B vitamins (by bifidobacterial species) and improve bone health by increasing the absorption of minerals [23]. Whelan et al. [24] reported significant increases in bifidobacterial species and SCFA following fiber supplementation.

Inflammatory Bowel Disease. It has been proposed that a high-sugar diet and a low-fiber diet are associated with the development of inflammatory bowel disease, but this hypothesis has not been proven [25, 26]. However, a diet rich in hemicelluloses (30 g daily) and glutamine decreased the severity of mild-to-moderate active ulcerative colitis [27]. In a multicenter trial, butyrate enema was shown to reduce inflammation in the distal colon when combined with 5-amino salicylic acid in refractory ulcerative colitis [28].

Irritable Bowel Syndrome. The etiology of irritable bowel syndrome is still not clear. Prebiotics, which induce a selective change in microbial species [29] (with or without soluble fibers) may be beneficial in irritable bowel syndrome [30].

Gastrointestinal Cancer. DF have a preventive role. The mechanisms depend on the site. In the esophagus and stomach, DF reduce the cancer incidence by their scavenging actions [31]. In the colon, DF sequester potential carcinogens and bile acids, and also increase transit time [32].

Systemic Benefits

Appetite and Satiety. The presence of a fiber-rich meal in the stomach reduces its motility and induces a sense of satiation, and results in a reduction in the rate of macronutrient delivery to the small intestine. This may have an indirect effect on appetite [18].

Weight Control. Body weight results from a complex interplay of many factors. Low-digestible and nondigestible CH have a low density of energy and the potential to prevent weight gain. Previous studies have shown that a diet rich in fibers is associated with a low body weight [33].

Glycemic Control. The viscous and gelling nature of soluble fibers results in lower postprandial glucose levels. Insoluble fibers also have an effect on the glycemic status via enhanced insulin sensitivity. The exact mechanism is unclear but may be due to its effect on gut microbiota. A fiber-rich diet reduces

Gram-negative bacteria in the intestines, and experiments have been shown that insulin resistance develops following daily injections of Gram-negative bacterial lipopolysaccharide [34]. A meta-analysis showed a 21% reduction in the development of diabetes with whole-grain consumption [35].

Hyperlipidemia. Soluble fibers reduce total and LDL cholesterol by increasing the fecal loss of bile acids without any alteration in high-density lipoprotein or triglycerides [14]. A meta-analysis has shown a reduction in LDL of 6–15% by DF [36].

Cardiovascular Disease. DF have shown to be beneficial in the prevention and control of hypertension. Probable mechanisms include improvements in hyperinsulinemia and insulin resistance, and a beneficial effect on body weight. This has been confirmed in a meta-analysis [37]. DF also contain biologically active compounds such as phytochemicals and antioxidants, in addition to other natural constituents of fibers, which might contribute to an overall reduction in cardiovascular diseases [38, 39].

Concluding Remarks

Digestible CH are the major source of calories. However, CH also contain low-digestible and nondigestible constituents, which are part of a healthy diet. Physiological effects are varied and depend on the site of the gastrointestinal tract, as well as on the physical and chemical composition of the fiber. They reduce gastric emptying and small bowel transit time, and, by inhibiting the actions of pancreatic and other digestive enzymes, they have a positive effect on the metabolism. By their fermentation effect, they aid in the production of SCFA, which has numerous benefits, e.g. in the absorption of minerals. The various mechanisms of action result in numerous gastrointestinal benefits like managing constipation and diarrhea, and having a prebiotic effect, which results in a change in the composition of gut microflora. They are useful in managing inflammatory bowel disease and irritable bowel syndrome as well as in reducing the incidence of certain colon cancers. The systemic benefits include maintaining a healthy weight, helping in achieving glycemic control and reducing hyperlipidemia, which result in decreased incidence rates of atherosclerosis, stroke and cardiovascular diseases.

Disclosure Statement

None.

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