Whole Grains and Digestive Health

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ABSTRACT

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Whole grains contain all parts of the grain: the endosperm, germ, and bran. Whole grains are rich in fermentable carbohydrates that reach the gut: dietary fiber, resistant starch, and oligosaccharides. Most research that supports the importance of grains to gut health was conducted with isolated fiber fractions, rather than whole grains. Whole grains are an important source of dietary fiber and grain fibers such as wheat, oats, barley, and rye increase stool weight, speed intestinal transit, get fermented to short chain fatty acids, and modify the gut microflora. Wheat bran is particularly effective in increasing stool weight; wheat bran increases stool weight by a ratio of 5:1. In contrast, many novel fibers that are easily incorporated into beverages and foods increase stool weight only on a ratio of l:l. In vitro fermentation studies with whole grains have been published. Carbohydrates of oat bran (rich in β-glucan) were consumed by bacteria faster than those of rye and wheat brans (rich in arabinoxylan). Grain fibers were fermented more slowly than inulin, causing less gas production. Wheat is particularly high in fructo-oligosaccharides, while wheat germ is high in raffinose oligosaccharides. Some in vivo studies show the prebiotic potential of whole grains. Whole grain breakfast cereal was more effective than wheat bran breakfast cereal as a prebiotic, increasing fecal bifidobacteria and lactobacilli in human subjects. Wheat bran consumption increased stool frequency. Thus, the gut enhancing effects of cereal fibers are well known. Limited data exist that whole grains alter gut health.

DIGESTIVE HEALTH

The term laxation describes a wide range of gastrointestinal effects, including stool weight, transit time, bloating, and distention, flatus, constipation, and diarrhea. Fiber increases stool weight and promotes normal laxation (Grabitske and Slavin 2008). Constipation is a prevalent, chronic condition in Western society, a common clinical complaint but a poorly studied condition. It has been defined as less than three bowel movements per week, although most people define constipation as less than one bowel movement per day. Frequency of defecation is only one aspect of constipation. Ease of passage of stools or lack of straining are other components of normal laxation.

Bowel habit is affected by variables including medications, stress, physical activity, volume of food, the type of food, fluid intake, hormones, and other environmental factors. Although the subjective measures of bowel function are important variables to collect, objective measures such as wet and dry stool weight, gastrointestinal transit time, and frequency of defecation are useful biomarkers to study. Increased volume of bulk, softness, or pliability of colonic contents, and increased intestinal motility may protect against constipation. Stool weight increases as fiber intake increases, but the additional fiber tends to normalize defecation frequency to once daily and gastrointestinal transit time to between two and four days. The increase in stool weight and volume is caused by the presence of the fiber, by the water that the fiber holds and by partial fermentation of the fiber, which increases the amount of bacteria in stool.

Diarrhea is an unpleasant digestive disorder that can affect anybody at any time. Normally when food is consumed, it remains in a liquid form during most of the digestive process; when the unabsorbed food residue passes through the large intestine, most of the fluids are absorbed and what remains is a semisolid stool. However, in diarrhea, the food and fluid ingested pass too quickly or in too large an amount (or both) through the large intestine. The fluids are not sufficiently absorbed and the result is a watery bowel movement. Commonly accepted criteria for clinical diarrhea are elevated stool output (>200 g/day); watery, difficult to control bowel movements; and frequency of bowel movements exceeding three per day (Bliss et al 1992). The colonic fermentation of dietary fiber may help to improve gastrointestinal tolerance and decrease diarrhea. Dietary fiber seems to reduce diarrhea by protecting from harmful bacterial overgrowth in intestine. A meta-analysis of randomized, controlled trials found no evidence that dietary fiber is effective in treating diarrhea (Homann et al 1994).

Irritable bowel syndrome (IBS) is a functional gastrointestinal disorder defined as "a group of functional bowel disorders" and is characterized by chronic or recurrent abdominal pain or discomfort, usually in the lower abdomen, which is associated with disturbed bowel function (i.e., diarrhea or constipation alone or alternating) and feeling of abdominal distention and bloating (Drossman et al 2002). Due to its persisting symptoms, IBS has a significant negative effect on health-related quality of life. The prevalence of IBS is estimated at 10–20% among adults in the United States and Europe (Drossman et al 1993); however, this is an underestimate of prevalence indicated by the fact that 70% of symptomatic adults do not seek medical evaluation. Women with IBS report more symptoms of constipation and abdominal discomfort while men with IBS report more diarrhea. Psychological disturbances, such as anxiety and depression, are more common in individuals with IBS who seek medical consultation for their symptoms than in those who do not seek care for them, which suggests that psychological disturbance may amplify IBS symptoms and affect health-care-seeking behavior.

Austin et al (2009) found that a very-low-carbohydrate diet improved symptoms and quality of life in patients with diarrhea-predominant IBS. A systematic review of dietary interventions for children with IBS concluded that there is a lack of high-quality evidence on the effectiveness of dietary interventions and there is no evidence that fiber supplements, lactose-free diets, or lactobacillus supplements are effective in children with recurrent abdominal pain (Huertas-Ceballo et al 2009). Bijkerk et al (2004) con-

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ducted a systematic review of fiber in the management of IBS. They determined the outcome measures as the proportion of patients reporting clinical relief (global irritable bowel syndrome symptom improvements); the proportion of patients reporting improved irritable bowel syndrome-related abdominal pain; and the proportion of patients reporting an improvement in irritable bowel syndrome-related constipation.

A meta-analysis showed that general fiber supplementation alleviates IBS symptoms globally, but there is no benefit in the relief of abdominal pain, which is the most important feature capable of distinguishing IBS from functional constipation or functional diarrhea (Longstreth et al 2006). Bijkerk et al (2004) reported that most psyllium studies showed improvement of global IBS symptoms compared with the placebo. Improvement in global symptoms was shown in only two of the six insoluble wheat fiber trials, while miller bran treatment did not improve symptoms. Overall, bran was no better than placebo in regards to improvement of global symptoms, but improvement was shown in IBS patients with constipation. Neither probiotics nor prebiotics are effective in the treatment of IBS (Spiller 2008).

Thus, dietary fiber and whole grains may play a role in digestive health (Slavin 2008), but few studies have been conducted on selected grains and their effects on gut health. Most studies are in diseased populations and even in these studies the role of dietary fiber on gut health remains inconsistent.

Short Chain Fatty Acids (SCFA)

Fiber is fermented by anaerobic intestinal bacteria that generate SCFA, which serve as energy sources for colonic mucosal cells (Slavin 2008). Fermentable dietary fibers alter the gut environment, not only by inducing the production of SCFA, but also by altering the gut microflora. Indeed, fermentable dietary fibers have a significant prebiotic effect by altering the intestinal microflora composition toward a more beneficial distribution by leading to selective stimulation of microbial growth, which eventually helps to increase the water-holding capacity of the colonic content and fecal moisture.

Acetate, propionate, and butyrate are the SCFA produced in the highest concentrations (Topping et al 2001). Acetate is a fuel for skeletal and cardiac muscle, kidney, and the brain. Butyrate is the preferred fuel of the colonic epithelium, in particular, the distal colon and rectum. Propionate is metabolized by the liver and may play a role in cholesterol lowering. Fibers produce varying proportions of individual SCFA and thus differing concentrations of total SCFA. Physiological status may be improved by consuming fermentable fiber, so it is important to understand the fermentability of each type of fiber.

Fiber fermentability is difficult to study in vivo due to the invasiveness of colon studies and the dynamic nature of the colon. Fiber fermentation can be estimated by measuring fiber consumed in the diet and then collecting fecal samples and measuring fiber left in feces. This is tedious and difficult because feces contain bacterial cell walls that are also isolated in fiber methods. No easy biomarkers exist to measure fiber fermentation in vivo, so generally in vitro models are used.

Particle size, solubility, surface area, and other factors affect the extent of fermentation and the nature of the SCFA. In living systems, SCFA are absorbed from the colonic lumen shortly after they are produced. No method has been developed to accurately measure SCFA absorption in vivo, and measuring SCFA excreted in the feces is the best estimate of SCFA being produced in the colon. However, 95–99% of SCFA are absorbed from the lumen, so excreted SCFA concentration represent a very small portion of SCFA produced. Therefore, studying the amount of SCFA in the feces of human volunteers would provide only a partial picture.

In vitro models to study fiber fermentability are currently the best models to assess SCFA production in humans. A closed laboratory system can provide an estimate of fiber fermentability without losing SCFA to colonic absorption and, therefore, in vitro fermentation with representative human colonic microflora is a proven, noninvasive, time-efficient means to estimate fiber fermentability. Indeed, batch fermentation degrades nonstarch polysaccharides (NSP) to an extent similar to the human colon, based on residual NSP in fecal samples and fermentation flasks (Wisker et al 1998).

Large Bowel Effects of Whole Grains

Whole grains are rich sources of fermentable carbohydrates including dietary fiber, resistant starch, and oligosaccharides (Slavin 2004). Undigested carbohydrate that reaches the colon is fermented by intestinal microflora to short chain fatty acids and gases. Short chain fatty acids include acetate, butyrate, and propionate, with butyrate being a preferred fuel for the colonic mucosa cells. Short chain fatty acid production has been related to lowered serum cholesterol and decreased risk of cancer. Undigested carbohydrates increase fecal wet and dry weight and speed intestinal transit.

Comparing dietary fiber content of various whole grains, oats, rye, and barley contain about one-third soluble fiber and the rest is insoluble fiber. Soluble fiber is associated with cholesterol-lowering and improved glucose response, while insoluble fiber is associated with improved laxation. Wheat is lower in soluble fiber than most grains, while rice contains virtually no soluble fiber. Refining of grains removes proportionally more of the insoluble fiber than soluble fiber, although refined grains are low in total dietary fiber.

Disruption of cell walls can increase fermentability of dietary fiber. Coarse wheat bran has a greater fecal bulking effect than finely ground wheat bran when fed at the same dosage (Heaton et al 1988), suggesting that the particle size of the whole grain is an important factor in determining physiological effect. Coarse bran delayed gastric emptying and accelerated small bowel transit. The effect seen with coarse bran was similar to the effect of inert plastic particles, suggesting that the coarse nature of whole grains as compared with refined grains has a unique physiological effect beyond composition differences between whole and refined grains (McIntyre et al 1997).

McIntosh et al (2003) fed rye and wheat foods to overweight middle-aged men and measured markers of bowel health. The men were fed low-fiber cereal grains foods providing 5 g of dietary fiber for the refined grain diet and 18 g of dietary fiber for the whole grain diet, either high in rye or wheat. This was in addition to a baseline diet that contained 14 g of dietary fiber. Both the high-fiber rye and high-fiber wheat foods increased fecal output by 33–36% and reduced fecal β-glucuronidase activity by 29%. Postprandial plasma insulin decreased by 46–49% and postprandial plasma glucose decreased by 16–19%. Rye foods were associated with significantly increased plasma enterolactone and fecal butyrate, relative to wheat and low-fiber diets. Rye appears more effective than wheat in overall improvement of biomarkers of bowel health.

Whole grain foods made from a novel high-amylose barley cultivar were compared with whole grain wheat in 17 volunteers (Bird et al 2008). Compared with the refined diet, consumption of the barley increased fecal weight by 33% and significantly lower fecal pH. Total fecal concentrations of short chain fatty acids was increased, with 91% higher excretion of butyrate. Grasten et al (2000) compared bowel function in middle-aged women and men. Whole-meal rye bread significantly increased fecal output and fecal frequency and shortened mean intestinal transit time when compared with wheat bread.

Prebiotics and Whole Grains

A prebiotic is defined as “a nondigestible food ingredient that beneficially affects the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon and thus improves host health” (Gibson and Roberfroid 1995).

The stimulated bacteria should be beneficial, with bifidobacteria and lactobacilli generally considered beneficial. The definition was recently updated and is described as "a prebiotic is a selectively fermented ingredient that allows specific changes, both in the composition and/or activity in the gastrointestinal microbiota that confers benefits upon host well-being and health" (Gibson et al 2004). The main candidates for prebiotic status include inulin, fructo-oligosaccharides, galacto-oligosaccharides, soly-oligosaccharides, xylo-oligosaccharides, pyrodextrins, and isomalto-oligosaccharides (Macfarlane et al 2006).

All nondigestible carbohydrates that reach the gut may alter the microflora, but the selective properties of prebiotics support an increase in bifidobacteria and lactobacilli at the expense of other bacteria in the gut, including *Bacteroides*, clostridia, eubacteria, enterobacteria, and enterococci. There are currently no standards that allow a substance to be called a prebiotic. The candidates described above have supportive clinical data that they alter colonic microflora in a beneficial manner. Yet wide ranges are found in microbial growth responses in healthy human subjects and the microflora are altered by diet, drugs, antibiotics, and age, etc.

Not all fermentable carbohydrates in the gut come from nondigestible carbohydrates. The mucus lay of the gut provides oligosaccharides that are also fermented and alter bacterial growth. Most studies have measured changes in fecal content of microbiota, although bacteria that grow adjacent to the colonic mucosa may be particularly important in immune function for the host. Langlands et al (2004) found that bifidobacteria numbers could be increased >10-fold in the mucosa of the proximal and distal colon in patients fed 15 g of a prebiotic mixture containing 7.5 g of inulin and 7.5 g of FOS/day for two weeks before colonoscopy.

Prebiotics and Immunity

The immune system guards the body against foreign substances and protects from invasion by pathogenic organisms. The immune system of the gut scans and inhibits growth of harmful pathogens while promoting growth of beneficial organisms (Hooper 2004). The immune system is divided into the innate (nonspecific immune) system and the acquired (specific immune) system. Nondigestible carbohydrates can affect immunity by altering the number and composition of the intestinal microflora, but also may affect the gut-associated lymphoid tissue (GALT). The largest immune organ is situated in the gut, where continuous exposure to diverse antigens takes place. The GALT contains ≈60% of all lymphocytes in the body (Watzl et al 2005).

The gut is also an important organ of hormonal communications. It communicates with the brain to tell us what to eat and drink and when we have had enough (Badman and Flier 2005). The importance of the gut microflora in the prevention of obesity has only recently been considered. Reviews of the ability of prebiotics to improve acute disorders (Bruck 2006) and chronic disorders (Bullock and Jones 2006) support the importance of the gastrointestinal microflora in health and disease, but find little data from human studies of an immune effect of prebiotics distinct from the alteration in microflora caused by prebiotics. Bruck (2006) concludes that the success of prebiotics lies in the ability to improve resistance to pathogens by increasing bifidobacteria and lactobacilli, which lowers the gut pH to a level at which pathogens are no longer able to complete. But adverse effects of prebiotics have been found in vitro and in experimental animals and must be considered when designing prebiotics for human use.

Prebiotic Potential of Whole Grains

Cereal grains are important sources of dietary fiber in the food supply. The dietary fiber content of grains varies greatly, ranging from 15% in rye to 4% in rice (Charalampopoulos et al 2002). The majority of dietary fibers occur in decreasing amounts from the outer pericarp to the endosperm, except arabinoxylan, which is also a major component of endosperm cell wall materials. Processing of grains will alter the carbohydrate composition of the fractions.

Fructo-oligosaccharides (FOS) are known prebiotics. The FOS content of all grains has not been determined, but wheat is particularly high in FOS, containing 0.8–4.0% of FOS in fresh material (Vernazza et al 2006). At least two types of oligosaccharides exist in cereal grains, galactosyl derivatives of sucrose (stachyose and raffinose) and fructosyl derivatives of sucrose (fructooligosaccharides) (Henry and Saini 1989). Distributions of these polymers within the cereal grain have not been fully established. For wheat, oligosaccharides have been reported in the bran (Yamada et al 1993) and germ (Pomeranz 1988). Wheat germ is particularly high in raffinose oligosaccharides, 7.2% on a dry basis (Charalampopoulos et al 2002). Oligosaccharides can be isolated from cereal grains and purified, although extractions have not been fully developed due to complexities and connections with other molecules, including proteins. Cereal grains are also concentrated sources of resistant starch, which has been described as an emerging prebiotic, with supportive animal trials but limited human studies (Crittenden 2006).

Because whole grains are an important source of fermentable carbohydrate in the gut, there is interest in the prebiotic properties of whole grains. In cereals, β-glucans and arabinoxylans are the major dietary fibers fermented by bacteria in the human gastrointestinal tract (Crittenden 2006). In vitro bifidobacteria and lactobacilli cannot ferment cereal β-glucans well (Crittenden et al 2002), but they can utilize oligosaccharides resulting from partial hydrolysis. In vitro studies find that *Bifidobacterium longum* and *B. adolescentis* can ferment arabinoxylan from cereal sources as well as arabinoxylan oligosaccharides (Crittenden et al 2002). Potentially harmful bacteria such as *Escherichia coli*, *Clostridium perfringens,* or *C. diffcile* do not directly ferment these substrates. Rye bran rich in arabinoxylan was bifidogenic when fed to mice (Oikarinen et al 2003).

Screening methods to compare prebiotic effect of dietary oligosaccharides have been developed (Palframan et al 2003). Prebiotic index (PI) equation is based on the changes in key bacterial groups during fermentation. The bacterial groups incorporated into this PI equation include bifidobacteria, lactobacilli, clostridia, and bacteroides. The changes in these bacterial groups from previous studies were entered into the PI equation to determine a quantitative PI score. PI scores were then compared with the qualitative conclusions made in these publications. It is hoped that the PI equation could be used to quantify the in vitro prebiotic effect and screen potential prebiotic substances.

Costabile et al (2008) conducted a double-blind, randomized, cross-over study of whole grain and wheat bran in 31 volunteers. Numbers of fecal bifidobacteria and lactobacilli were significantly higher with whole grain ingestion compared with wheat bran ingestion. There were no significant differences in fecal SCFA with ingestion of either cereal. No adverse intestinal symptoms were reported and wheat bran ingestion increased stool frequency.

Some in vitro studies have been conducted on prebiotic potential of grains. Karppinen et al (2000) compared in vitro fermentation of polysaccharides of rye, wheat, and oat brans and inulin. The brans were first digested enzymatically to remove starch and protein. The digested brans and inulin were then fermented with human fecal inoculum. The progress of fermentation was measured by following the consumption of carbohydrates and the production of short-chain fatty acids and gases. Inulin, a short fructose polymer, was consumed significantly faster than the more complex carbohydrates of cereal brans. Carbohydrates of oat bran (rich in β-glucan) were consumed faster than those of rye and wheat brans (rich in arabinoxylan). In all brans, glucose was consumed faster than the other main sugars, arabinose and xylose, and arabinose degraded only slightly. Formation of gases was fastest and greatest with inulin. Rye, wheat, and oat brans were fermented in a similar way, slower than inulin. Fermentation of rye bran enhanced the bioactivity and technological potential of the bran (Katina et al 2007). The presence of indigenous lactobacillus and enzymes concentrated on the outer layers of the grains and contributed to the changes seen in bran during the fermentation. The authors suggest that the extent of these changes can be modulated by changing the milling process during separation of the bran prior to fermentation.

Korakli et al (2002) measured the metabolism by bifidobacteria of exopolysaccharide (EPS) produced by *Lactobacillus sanfranciscensis* (sourdough). In addition to polyfructan (FOS) found in wheat and rye, these flours contain kestose, hystose, and other fructooligosaccharides similar to inulin (Campbell et al 1997). Arabinoxylan undergoes degradation by cereal enzymes during dough resting time, causing solubilization of arabinoxylan (Korakli et al 2002). In addition to the polysaccharides from wheat or rye, strains of *L. sanfranciscensis* produce exopolysacchaides in wheat and rye sourdough. This EPS is a high molecular weight fructan of the levan type. Few data are available on the metabolism of polysaccharides isolated from wheat and rye by bifidobacteria and lactobacilli. Korakli et al (2002) found that bifidobacteria metabolize fructan from *L. sanfranciscensis*. Polyfructan and the starch fractions from wheat and rye, which possess a bifidogenic effect, were degraded by cereal enzymes during dough fermentation, while the EPS were retained.

Some clinical studies have examined changes in gut microflora with consumption of grain fractions. Metteuzzi et al (2004) conducted a double blind, placebo-controlled study in 32 healthy subjects with a prebiotic wheat germ preparation. After 20 days of supplementation of the product, the coliform population and pH decreased significantly. The number of lactobacilli and bifidobacteria increased significantly only in subjects with low basal levels. No significant changes were found for other bacterial groups and total bacteria did not increase. An arabinoxylan-rich germinated barley product induced proliferation of bifidobacteria in the human intestine (Kanauchi et al 1999). The germinated barley product was also fed as treatment in experimental colitis in comparison with probiotic or antibiotic treatment. Modification of the intestinal microflora by prebiotics, including the germinated barley fiber, can be a useful adjunct in the treatment of ulcerative colitis (Fukuda et al 2002). Additional animal trials supporting the use of the germinated barley for nutraceutical treatment of ulcerative colitis are described by Bamba et al (2002).

CONCLUSIONS

Whole grains provide necessary dietary fiber, resistant starch, and oligosaccharides to the diet. Carbohydrates that escape digestion and absorption in the small intestine and are fermented in the large intestine may be prebiotics. Wheat, the most common whole grain consumed, is a rich source of fructo-oligosaccharide, an accepted prebiotic. Resistant starch and β-glucan, carbohydrate components of whole grains, have also shown promise as prebiotics. There is no accepted method to measure prebiotic performance, either in vivo or in vitro. Systematic studies that measure the fermentability of whole grains as consumed in human foods have not been published, nor have studies of the bifidogenic properties of whole grains in vitro. The development of a prebiotic index may prove beneficial as a way to screen compounds for prebiotic activity before a clinical trial measuring changes in fecal microflora with whole grain feeding is launched. Few clinical trials of whole grains have been published, so extensive work remains to define the role of whole grains in digestive health.

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