REVIEWS

Dietary fibre and satiety

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Summary

Dietary fibres have different physiological effects and provide a variety of health benefits, including satiety. They are thought to impact on satiation (the satisfaction of appetite during feeding that marks the end of eating and satiety (inhibition of hunger as a result of having eaten), because of their properties of adding bulk (satiation) and producing viscosity (satiety). Pre-absorptive factors, such as gastric distention, and the work and time required for chewing are important for satiation. For this reason, the bulking and textural properties of fibre make it an attractive ingredient for enhancing satiation. Adding bulk to the diet with fibre will also reduce the energy density of the diet. Satiety signals are generated both pre- and post-absorptively. Viscous soluble fibres may be useful because they prolong the intestinal phase of nutrient digestion and absorption. This means that there is a longer time over which the macronutrients can interact with the pre-absorptive mechanisms of satiation and satiety, as well as prolong the time course of post-absorptive signals. Diets low in energy and fat, such as those typically recommended for obese people, are poorly satiating. Adding fibre to low-calorie/low-fat foods may enhance satiety, but because weight-loss meals are low in energy and fat, satiety is likely to be short lasting. Not all dietary fibre has an impact on satiety. We review types of dietary fibre, whole foods that contain dietary fibre, and published studies on the effect of these fibres on satiety.

Keywords: appetite, fibre, satiation, satiety

Dietary fibre and health

Dietary fibre is supplied by plant foods in the diet (Slavin 1987). Different cultures prefer different foods, so sources of dietary fibre vary among countries. In North America and Europe, generally grains supply the most fibre in the diet. Starchy vegetables, fruits and legumes are also good fibre sources and, in different cultures, are consumed as dietary staples. In general, most foods are low in dietary fibre, supplying 1–3 g of fibre per serving (Table 1).

In 2002, new definitions for dietary fibre and recommendations for fibre intake were published in the Dietary Reference Intakes, the accepted nutrient standards for the United States and Canada (Institute of Medicine 2002). Dietary fibre consists of non-digestible carbohydrates and lignin that are intrinsic and intact in plants. Functional fibre consists of isolated, non-digestible carbohydrates that have beneficial physiolog-

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Table 1 Dietary fibre content of foods in commonly served portions (Slavin 1987)

Food group	<1 g	1–1.9 g	2–2.9 g	3–3.9 g	4–4.9 g	5–5.9 g	>6 g
Breads (1 slice)	Bagel White French	Whole wheat	Bran muffin	NA	NA	NA	NA
Cereals (1 oz)	Rice Krispies Special K Cornflakes	Oatmeal Cheerios	Wheaties Shredded Wheat	Honey bran	Bran Chex 40% Bran Flakes Raisin bran	Corn bran	All-bran Bran buds 100% Bran
Pasta (1 cup)	NA	Macaroni Spaghetti	NA	Whole wheat Spaghetti	NA	NA	NA
Rice (1/2 cup)	White	Brown	NA	NA	NA	NA	NA
Legumes (1/2 cup cooked)	NA	NA	NA	Lentils	Lima beans Dried peas	NA	Kidney beans Baked beans Navy beans
Vegetables (1/2 cup unless stated)	Cucumber Lettuce (1 cup) Green pepper	Asparagus Green beans Cabbage Cauliflower Potato without skin (1) Celery	Broccoli Brussels sprouts Carrots Corn Potato with skin (1)	Peas	NA	NA	NA
Fruits (1 medium unless stated)	Grapes (20) Watermelon (1 cup)	Apricots (3) Grapefruit (1/2) Peach with skin Pineapple (1/2 cup)	Apple, without skin Banana Orange	Apple, with skin Pear, with skin Raspberries (1/2 cup)	NA	NA	NA

NA, not applicable.

ical effects in humans. Total fibre is the sum of dietary fibre and functional fibre.

The benefits of fibre-containing foods, such as wholegrains, vegetables, fruits and legumes, are not disputed. Additionally, there are accepted health claims for oats, barley and psyllium because of their proven effectiveness in lowering blood lipids. By definition, all dietary fibres are presumed to have physiological effects; yet many isolated fibres have shown minimal physiological effects when given in clinical studies. Thus, physiological effects must be shown for functional fibre, and specific measurable physiological effects of fibre to establish functionality must be defined. Accepted biomarkers of fibre functionality related to satiety and weight management are not available, making it difficult to compare fibres for their role in satiety. Clearly, there are functional fibres that have little or no effect on satiety, while other functional fibres, mostly viscous fibres, increase satiety, even when small doses of the fibre are consumed.

Dietary fibre and obesity

The 'fibre hypothesis' suggests that consumption of unrefined, high-fibre carbohydrate-based foods protects against diseases, including diabetes, cancer, heart disease and obesity. These traditional diets are both high in dietary fibre and low in dietary fat, making it difficult to separate out these effects.

Heaton (1973) proposed that fibre acts as a physiological obstacle to energy intake by at least three mechanisms:

(1) fibre displaces available calories and nutrients from the diet;
(2) fibre increases chewing, which limits intake by promoting the secretion of saliva and gastric juice, resulting in an expansion of the stomach and increased satiety; and
(3) fibre reduces the absorption efficiency of the small intestine.

Diets high in energy density elevate food consumption when compared with diets lower in energy density. Humans may consume a constant weight of food and, as such, a constant weight of lower energy (*i.e.* high-fibre) food per unit weight may promote a reduction in weight (Rolls 2000). High-fibre foods have a much lower energy density compared with high-fat foods. Thus, high-fibre foods can displace energy (calories). The bulking and viscosity properties of dietary fibre are predominantly responsible for influencing satiation and satiety. Fibre-rich foods usually are accompanied by increased efforts and/or time of mastication, which leads to increased satiety through a reduction in rate of ingestion.

Traditionally, high-fibre foods have been solid foods. Some of the newer functional fibres, such as resistant starches (RS) and oligosaccharides, are easily added to drinks and may not alter viscosity. Few studies on the satiating effects of drinks supplemented with these soluble, non-viscous fibres have been published, but we suspect they would have limited satiating effects.

Intrinsic, hormonal and colonic effects of dietary fibre decrease food intake by promoting satiation and/or satiety (Slavin 2005). Satiation is defined as the satisfaction of appetite that develops during the course of eating and eventually results in the cessation of eating. Satiety refers to the state in which further eating is inhibited and occurs as a consequence of having eaten. Dietary fibre also decreases gastric emptying and/or slows energy and nutrient absorption, leading to lower postprandial glucose and lipid levels. Dietary fibre may also influence fat oxidation and fat storage.

The effects of dietary fibre on hunger, satiety, energy intake and bodyweight have been reviewed (Howarth *et al.* 2001). The majority of studies with controlled energy intake reported an increase in post-meal satiety and a decrease in subsequent hunger with increased dietary fibre. With *ad libitum* energy intake, the average effect of increasing dietary fibre across all the studies indicated that an additional 14 g of fibre per day resulted in a 10% decrease in energy intake and a weight loss of over 1.9 kg through about 3.8 months of intervention. Additionally, the effects of increasing dietary fibre were reported to be even more impressive in obese individuals. This group concluded that increasing the population mean dietary fibre intake from the current average of about 15 g to 25–30 g/day would be beneficial and may help reduce the prevalence of obesity.

More recently, Maskarinec *et al.* (2006) reported that plant-based foods and dietary fibre were most protective against excess bodyweight in a large, ethnically diverse population. Howarth *et al.* (2005) examined the association of dietary composition variables with body mass index among US adults aged 20–59 years in the Continuing Survey of Food Intakes by Individuals 1994–1996. For women, a low-fibre, high-fat diet was associated with the greatest increase in risk of overweight or obesity compared with a high-fibre, low-fat diet.

Fibre and satiety

We will first review the data on whole foods and satiety and then isolated fibres. This discussion becomes complex because many foods, such as breakfast cereals, are whole foods that have been supplemented with isolated fibres. This trend has escalated recently with the addition of fibres to dairy products, drinks, snack foods and sweets. There are no standardised protocols for conducting studies on dietary fibre and food intake, which makes it difficult to compare studies and summarise results. Although many studies on this topic were conducted in the 1980s, recent interest in the prevention of obesity has rekindled interest in this area.

Whole foods and satiety

High-fibre foods contain other protective components. Dietary fibre mainly occurs in cell walls, brans (whole cereals) or hulls (legumes). Cell walls have complex structures in which the carbohydrates are intimately associated with non-carbohydrate substances, including vitamins, minerals, trace elements, and bioactive compounds, such as polyphenols and phytosterols. Current dietary recommendations emphasise increased consumption of fibre-rich foods, such as wholegrains, vegetables and fruits, based on observational evidence that consumption of these foods protects health (Slavin 2004).

Previous work has identified food refinement as a predictor of satiety. A carbohydrate investigation with apples reported that an increase in carbohydrate refinement was associated with increased hunger and appetite (Haber *et al.* 1977). Juice was significantly less satisfying than purée, and purée less than apples, while rate of ingestion was kept constant. Bolton *et al.* (1981) found that satiety, assessed by two subjective scoring systems, was greater after whole fruit than after juice, and return of appetite was delayed. They studied both oranges and grapes.

In a study of spinach in mixed meals, 250 g spinach portions augmented satiety and reduced the postprandial glucose response (Gustafsson *et al.* 1995). The total satiety scores were correlated positively with the dietary fibre and water content of the vegetables. Changes in spinach structure, cutting or mincing, had no influence on satiety scores. After controlling for fibre content (4.4 g/serving), there were no differences in satiety among carrots, peas, Brussels sprouts and spinach in ten healthy male volunteers (Gustafsson *et al.* 1993). A dose–response experiment was performed with carrots at 100, 200 and 300 g/serving. The larger the carrot portion and fibre intake, the higher the satiety scores (Gustafsson *et al.* 1994).

Similarly, an assessment of wholemeal and white bread found that refinement was related to an increased energy intake (Grimes & Gordon 1978). Specifically, healthy volunteers were asked to consume wholemeal and white bread in a randomised manner to a point of comfortable fullness. Approximately 83% of the study participants consumed more white bread than wholemeal.

Oats and barley are concentrated in β-glucan (a viscous, soluble fibre), and fractions of oats and barley have been tested for satiety response. Satiety response was compared among boiled intact kernels (rice extender) and milled kernels (porridge) from four barley genotypes (Granfeldt *et al.* 1994). All barley products gave higher satiety scores when compared with white wheat bread. Different wheat-based breads were compared for their satiety score immediately after a test meal (Holm & Bjorck 1992). Breads fortified with soluble fibre and coarse-wheat breads were more satiating than white breads, supporting the premise that particle size and soluble fibres enhance satiety response. The satiety responses from buckwheat flour or groats were measured (Skrabanja *et al.* 2001). Reference white bread was compared with buckwheat groats and wheat bread made with 50% buckwheat flour. The highest satiety score was found with boiled buckwheat groats.

Satiety from rice-based and wheat-based preparations and rice-pulse combinations was compared (Pai *et al.* 2005). Neither fat nor carbohydrate content showed any correlation with satiety scores, suggesting that isoenergetic portions of various foods influence satiety to different extents. Most effective in delaying the return of hunger were high-protein and high-fibre foods, and foods with greater water-volume, leading to low energy density.

Particle size of refined-grain foods is often less, compared with wholegrain foods, although few studies exist in this area. Holt and Miller (1994) examined satiety ratings for four test meals of equivalent nutritional composition based on four different grades of wheat: wholegrains, cracked grains, coarse and fine wholemeal flour. The fine-flour meal gave the lowest satiety response, while the wholegrain meal was most satiating. The authors concluded that the processing of cereals is a major determinant of postprandial satiety.

Although dietary fibre has an important role in satiety, studies with whole foods show that other variables besides fibre are important for satiety. Holt *et al.* (2001) determined the effects of equal-energy portions of different breads on blood glucose levels, feelings of fullness, and subsequent food intake in ten healthy subjects. The strongest predictor of the breads' satiety index scores was their portion size and thus energy density. The breads' glycaemic responses were not significantly associated with fullness responses. Other studies have found that the volume of food that is consumed has a greater influence on perceptions of a food's pleasantness compared with its energy content (Norton *et al.* 2006). Dietary fibre is one variable affecting volume, but water-holding capacity of a food is also important.

For some satiety and hunger studies, fibre is baked into bread. Also, some studies have compared the effects of different cereals, ranging from very low to very high in fibre. Despite the investigator's best efforts, it is not possible to disguise large amounts of fibre. So subjects may not be told that the study is about fibre and satiety, but it is unlikely that they will not see and taste the differences among the products.

Grimes and Gordon (1978) offered wholemeal and white bread, in a randomised sequence, to 12 healthy volunteers, and asked them to eat to a point of 'comfortable fullness'. Ten of the 12 ate significantly more white bread than wholemeal, using a non-parametric ranking test.

Bryson *et al.* (1980) repeated and extended this work and came to a different conclusion. Ten normal volunteers were offered unlimited amounts of bread, butter and jam for lunch: 2 days with white bread and 2 days with wholemeal bread. Food records were kept from the morning of the test lunch until the following day's lunch. There was no significant difference in energy intake during the test meal or for 24 hours thereafter.

Mickelsen *et al.* (1979) added 24 g of cellulose to the bread that they fed daily to overweight college-aged men for 1 month and compared with a control bread. Subjects lost weight on both diets. However, none of the subjects were hungry on the cellulose bread, while four of the six subjects were hungry on the control bread. With a different design, subjects were instructed to consume roast-beef sandwich halves made from low- or high-fibre bread (Porikos & Hagamen 1986). During the eating episode, subjects were intentionally interrupted and taken away from the sandwiches. Subjects were allowed to finish eating the sandwiches 30–45 minutes later (test meal). Results showed that consumption of sandwiches made with high-fibre bread 30–45 minutes prior to the test meal resulted in a significant reduction in subsequent energy intakes. However, this reduction in energy intake was only seen in the obese participants.

The acute effect of high-fibre cereals has also been investigated (Levine *et al.* 1989). Healthy individuals were randomly assigned to either a very-high-fibre (VHF) cereal or a very-low-fibre (VLF) cereal. A significant inverse correlation was observed between fibre content of the cereals and energy intake at lunch. In fact, ingestion of the VHF cereal at breakfast resulted in decreased energy intake at both breakfast and lunch. Additionally, individuals consumed less food during lunch after the VHF cereal at breakfast, in comparison with the VLF cereal. Participants also reported feeling less hungry after consuming the VHF cereal than after consuming the VLF cereal.

Low- and high-fibre diets and satiety

Some investigators have designed fibre and satiety studies where a low-fibre diet is compared with a high-fibre diet. Silberbauer *et al.* (1996) compared four equicaloric breakfasts with different fibre and macronutrient contents on hunger and satiety ratings and subsequent lunch intake. The range of fibre contents consumed with breakfast did not differentially affect hunger and satiety ratings and the size of the subsequent lunch. The authors suggest that energy content of a meal is the major determinant of subsequent energy intake.

Burley *et al.* (1987) also compared the effects of high- and low-fibre breakfasts on hunger, satiety and food intake in a subsequent meal. The fibre content of the two breakfasts was: 3 and 12 g of fibre. They found no differences in energy intake at lunch. There was no difference between the diets on desire to eat, although the high-fibre breakfast did cause greater fullness.

The effects of diets low in energy density and high in energy density were examined for satiety, energy intake and eating time among 20 obese and non-obese subjects (Duncan *et al.* 1983). Each diet was served over a 5-day period, and subjects were allowed to eat to satiety. With equal acceptance ratings of the diets, satiety was reached on the diet low in energy density at a mean daily energy intake one-half that of the diet high in energy density (1570 *vs.* 3000 kcal). Eating time was significantly longer on the diet low in energy density by an average of 33% per day. There were no differences between obese and non-obese subjects.

Isolated fibres and satiety

As understanding and definitions of dietary fibre have evolved, so has the design of these studies. Because of early interest in soluble and insoluble fibres as the primary chemical difference between fibre sources, many of the early studies compared soluble and insoluble fibres. The results of these studies were often unclear and suggested that the solubility of the fibre source did not determine satiety response (Delargy *et al.* 1997).

Sugar-beet fibre

Sugar-beet fibre, which has both soluble (40%) and insoluble (60%) fibres, was used to assess appetite in non-obese, healthy men and women (Burley *et al.* 1993a). Four and a half hours after breakfast, participants were provided with an *ad libitum* lunch. The results showed no significant differences in motivation to eat between the low- and high-fibre breakfasts immediately after breakfast consumption and 4.5 hours later. However, significant differences were observed with energy intakes. After the ingestion of the high-fibre breakfast, energy, protein and fat intakes were significantly decreased in comparison with the control breakfast. At lunch, 14% less energy was consumed after the sugar-beet fibre breakfast. Participants who consumed the high-fibre breakfast ate for 18.5 minutes at lunch, while individuals who consumed the control breakfast ate for 21.3 minutes.

Soy polysaccharide

Effertz *et al.* (1991) conducted a double-blind, placebo-controlled study to assess the effects of soy polysaccharide (largely composed of insoluble fibre) on satiety and weight regulation over a 14-week period. Moderately obese subjects in the treatment group were fed soy crackers, providing 189 kcal and 20.3 g/day of dietary fibre compared with 0.7 g/day of fibre in the placebo cracker. Although there were small changes in bodyweight, hunger ratings on the higher fibre diet were lower at breakfast, although not for lunch and dinner.

Pea fibre

The effect of a low- and high-fibre meal on 6-hour postprandial thermogenesis and satiety was examined in ten healthy lean men (Raben *et al.* 1994a). The fibre portion of the pea cell membranes comprised 7.9% cellulose, 56.6% soluble non-cellulose polysaccharides (NCP), 33.6% insoluble NCP and 2% lignin. Subjects reported increased feelings of fullness, and food intake was significantly reduced after the high-fibre meal.

Purified cellulose fibre

Other investigations have provided further evidence for an effect of insoluble fibre on hunger and satiety. Astrup *et al*. (1990) examined the effects of added fibre on hunger and satiety in 22 obese individuals. They assigned participants for 2 weeks to either a very-low-calorie diet (VLCD) without fibre or a VLCD with fibre. The fibre diet provided 30 g/day of plant fibre from birch, which is high in cellulose (98.5% insoluble fibre). Weight loss did not differ between groups. Individuals consuming the VLCD without fibre reported increased feelings of hunger that were alleviated with the addition of fibre in the corresponding dietary treatment. In contrast, insoluble-fibre addition had no effect on satiety.

Mycoprotein

Mycoprotein is approximately one-third chitin and two-thirds insoluble β-glucan cell wall material. Eighteen subjects consumed two meals (mycoprotein *vs*. control) differing only in dietary fibre content (11 g *vs*. 3 g of fibre) (Burley *et al*. 1993b). The high-fibre meal decreased motivation to eat during the period of 4–4.5 hours after lunch. The high-fibre meal also caused an 18% reduction in energy intake at the evening test.

Turnbull *et al*. (1993) examined the effect of mycoprotein on appetite and energy intake in 13 female subjects. Two isocaloric meals were provided: either mycoprotein (16.8 g of dietary fibre) or a chicken-based diet without mycoprotein (10.1 g of dietary fibre). Desire to eat 3 hours after the mycoprotein meal was significantly lower, as was the prospective consumption rating when compared with the chicken meal. Furthermore, energy intake during the day of testing was reduced by 24% in the mycoprotein group. Additionally, energy intake was reduced by 16.5% the following day in the mycoprotein group. Mycoprotein and tofu pre-loads, in comparison with the chicken pre-load, were associated with lower food intake shortly after consuming the preload at lunch (Williamson *et al*. 2006). Food intake after consumption of mycoprotein and tofu did not differ, and subjects did not compensate for lower food intake at lunch by consuming more food at dinner.

Fermentable and non-fermentable fibres and satiety

Newer fibre definitions have categorised fibre into viscous and fermentable fibres. Fermentable fibre, a mixture of pectin and β-glucan, was compared with non-fermentable fibre, which was methylcellulose (Howarth *et al*. 2003). Daily satiety assessed with visual analogue scales was higher with the methylcellulose, compared with the fermentable fibre. Insoluble fibres that survive transit through the gut may alter satiety and hunger cues by different mechanisms compared with soluble fibres. Rather than changing gastric emptying, insoluble fibres may affect satiety in the small and large intestines, which may be linked to changes in gut hormones or intestinal transit.

Viscous fibres and satiety

Viscous fibres may increase satiety. Early trials focused on soluble fibre as the active ingredient in guar gum, pectin and psyllium. Often the insoluble fibre had as much, or more, impact on satiety as the soluble fibre. Many of the more recent trials using soluble fibres that are not viscous, such as RS and inulin, have found no effect on satiety or hunger, even when large amounts of the isolated fibre were fed.

As viscosity is a new concept in dietary fibre research, few data exist on viscous characteristics of individual fibre sources in relation to one another. Dikeman *et al*. (2006) measured viscosity of different fibre sources in solutions and in simulated human gastric and small intestinal digesta. Rice brans, soy hulls and wood cellulose had the lowest viscosities, whereas guar gum, psyllium and xanthan gum had the highest viscosities, regardless of concentration. During gastric simulation, viscosity was higher at 4 hours than at 0 hours for guar gum, psyllium, rice bran and wheat bran. During small intestinal simulation, viscosities were higher between 3 and 9 hours, compared with 18 hours, for guar gum, oat bran and rice bran. Guar gum, psyllium and oat bran were viscous throughout small intestinal simulation, while wheat bran, rice bran and wood cellulose were never viscous.

The viscosity of the liquid may be important in determining hunger response. Mattes and Rothacker (2001) reported significantly greater and more prolonged reductions in hunger with thicker shakes compared with thinner shakes. All other aspects of nutrient composition of the shakes were held constant in these studies. Marciani *et al*. (2001) compared solutions of different viscosity on satiety. Twelve healthy subjects ingested 500 ml of a low- or high-viscosity locust bean gum test meal, either containing energy/nutrients (olive oil and carbohydrate) or being a non-nutrient control, according to a four-way cross-over design. Subjects ingested the test meal within a 10-minute period and completed satiety questionnaires every 12 minutes, for up to 1.5 hours. Energy intake and viscosity had an additive effect on satiety, although viscosity had a greater effect. They found increased satiety for the same gastric volume with the viscous meal, which suggests an important mechanism beyond delayed gastric emptying.

Hoad *et al.* (2004) examined gastric emptying and satiety in human subjects. They compared alginates with different viscosities and guar gum, whose viscosity is not affected by acid. Gastric emptying did not vary among the fibre source, but satiety was greater with the more viscous fibre. They hypothesise that more viscous fibres exert their effect owing to distention in the gastric antrum and/or altered transport of nutrients to the small intestine.

Pectin

Pectin is a viscous fibre known to delay gastric emptying. DiLorenzo *et al.* (1988) compared the effects of 15-g pectin *vs.* 15-g methylcellulose on gastric emptying and satiety in nine adult obese patients. Pectin significantly increased subjects' sensation of satiety. Pectin in doses as small as 5 g added to orange juice increased satiety in US Army employees (Tiwary *et al.* 1997).

Psyllium

Psyllium is a viscous, soluble fibre isolated from the seed of a plant grown in India. Psyllium is unique as a viscous fibre as it survives transit throughout the gut, while other viscous fibres are extensively fermented (Fischer *et al.* 2004). It is widely used as a bulk laxative and has been shown to reduce blood lipids. Bergman *et al.* (1992) measured sensations of hunger and satiety in 12 healthy volunteers after consuming 10.8-g psyllium or placebo in a randomised, cross-over, double-blind trial. Psyllium significantly delayed gastric emptying from the third hour after a meal. It increased the sensation of satiety and decreased hunger at the sixth hour after the meal.

The satiating effectiveness of psyllium was measured when the fibre was consumed as part of a commercially available wafer (Cybulski *et al.* 1992). Non-obese subjects (*n* = 15) were given placebo wafers, and four different amounts of the fibre wafer with water, 30 minutes prior to a test meal of macaroni and beef. The two largest amounts of fibre wafer reduced intake of the test meal and hunger ratings.

Turnbull and Thomas (1995) compared three treatments: a psyllium supplement and 200 ml of water, a placebo and 200 ml of water, and 200 ml of water. Subjects were then given a test meal at lunchtime, 3 hours after the supplement. Psyllium treatment gave significantly more fullness at 1 hour than the other two treatments. On the day of the meal, total fat intake was significantly lower in grams per day and as a percentage of energy after the psyllium, compared with water alone.

Delargy *et al.* (1997) compared psyllium with wheat bran fibre in a 24-hour appetite study of two breakfasts containing 22 g of dietary fibre. There was a trend towards reduced hunger and voluntary energy consumption following the psyllium, compared with the wheat bran, much later in the day (9.5–13.5 hours after breakfast), although this was not significant. A smaller dose of psyllium (7.4 g) was given to normal volunteers in a double-blind study, and its effects on hunger and food intake were measured (Rigaud *et al.* 1998). After the meal, hunger feelings and energy intake were significantly lower following the psyllium treatment compared with the placebo. Not too surprisingly, a smaller dose of psyllium (1.7 g) added to pasta had no effect on hunger (Rigaud *et al.* 1998).

Guar gum

Although guar gum has positive physiological benefits, its high viscosity makes it difficult to incorporate into food products and drinks. Modified guar gums are now commercially available, in which the guar gum has been hydrolysed, making it less viscous. The chain length of hydrolysed guar gum can vary greatly, and this will affect the viscosity. Little research has directly compared the physiological differences between native guar gum and hydrolysed guar gum, but the large difference in viscosity would predict less effectiveness on satiety with the hydrolysed guar gum.

Guar gum (15.5 g) and methylcellulose (16 g) were given for 1 week each, and weighed food intakes were obtained over 4 weeks (Evans & Miller 1975). The fibre supplements were given with water, in two equal doses, 30 minutes before meals. Subjects lost weight, and there was a 10% reduction in energy intake with the fibre supplements. When seven overweight subjects consumed low-energy milky drinks, with and without the addition of 2 g of guar gum, time to maximal hunger was delayed by addition of the guar (Wilmshurst & Crawley 1980).

Ellis *et al.* (1981) compared bread alone and bread supplemented with guar gum, with the guar gum given at three levels. Satiety was measured at 30, 60 and 120 minutes. They found no differences with the guar treatment. Krotkiewski (1984) alternated weekly treatment with guar gum or wheat bran for an average of 10 weeks. Fibres (10 g) were given twice daily with

150 ml of water. Guar gum reduced hunger at both lunch and dinner.

Guar gum (12 g) was added to both low- and high-fat soups, and hunger and satiety were compared between the high- and low-fat soups, and with and without the addition of the guar gum (French & Read 1994). There was a large delay in time for hunger to return with the guar and high-fat soup. Thus, there appeared to be some interaction between the fibre and fat, making the fibre more effective in the high-fat version of the soup. Guar gum also reduced rating for hunger and desire to eat when it was added to a 30% glucose drink (Lavin & Read 1995). Ten healthy, male volunteers were given glucose drinks, with and without guar gum. The guar treatment also increased ratings for fullness and satiety.

Pasman *et al.* (1997a) gave guar gum to obese subjects who had lost weight on a VLCD. Twenty subjects were given 20 g of guar gum daily, and 11 subjects were untreated controls. The treatment was given for 14 months. No significant differences were found on suppression of energy intake with the fibre treatment. Pasman *et al.* (1997b) compared the effect of 1 week of supplementation with guar gum in obese women who had lost weight. Two doses of fibre were given: 40 g in study 1 and 20 g in study 2. They found reductions in energy intake and less hunger, and concluded that fibre might be useful in the treatment of obesity, by facilitating compliance to low energy intake.

Heini *et al.* (1998) published the first study on guar gum and satiety where a hydrolysed guar gum was used. This was a 5-week, prospective, randomised, double-blind study where subjects consumed 800 kcal/day diets, with and without 20-g hydrolysed guar gum. On days 1, 3 and 7, satiety ratings were measured. No changes were found in satiety ratings, suggesting that the loss of viscosity in this modified guar gum decreased its physiological effectiveness in enhancing satiety.

Overweight subjects consumed a solid meal, a semi-solid meal, and a semi-solid meal with added guar gum (Kovacs *et al.* 2001). Subjects were allowed to consume a free-choice meal for dinner. Appetite was increased with the semi-solid meal compared with the other two meals. There were no differences in weight loss, and the authors noted a strong order effect, suggesting that results decreased with later treatment.

The studies with viscous fibre suggest that even small amounts of viscous fibre may improve satiety. Unfortunately, no studies have been conducted comparing the satiety of a wide range of soluble fibres that have been chemically modified to present a range of viscosities within the same fibre source.

Non-viscous functional fibres and satiety

The new physiological definitions of functional fibre adopted in the USA have increased the number of compounds that are classed as functional fibres. These include oligosaccharides, polydextrose, RS, and an ever-expanding group of compounds. Some recent studies have been published on the effects of these highly processed, functional fibres and satiety. In general, these fibres can be added to foods and drinks in fairly large amounts, more than 10 g/serving, with little effect on the food properties or consumer acceptability of the product. Overall, these new fibres have shown little effect on satiety.

Resistant starch

The effect of RS on satiety was investigated in ten healthy men (Raben *et al.* 1994b). The test meals consisted of 50-g raw potato starch or 50-g pre-gelatinised potato starch (54% RS) mixed with 500 ml of diluted artificially-sweetened fruit syrup. The meal that consisted of digestible potato starch resulted in greater feelings of satiety and fullness, compared with the meal that comprised resistant and slowly digestible starch. Within 1–1.5 hours, with the meal that consisted of raw potato starch, subjective scores returned to fasting concentrations, while the satiating power of the digestible-starch meal lasted 2.5–3 hours postprandially.

de Roos *et al.* (1995) examined whether two types of RS were more satiating than glucose. During the 4-week study, subjects consumed their habitual diet plus a daily supplement, comprising either glucose or high-amylose corn starch (RS2) or extruded and retrograded high-amylose corn starch (RS3), in a cross-over, single-blind, randomised and balanced study design. The dose given was 30 g/day of RS. Consumption of 30 g/day of RS2 and RS3 had little influence on appetite and food intake.

Nutriose is a resistant wheat starch (Pasman *et al.* 2006). To determine long-term gastrointestinal tolerance, Nutriose was fed to healthy men in a parallel design with three arms: 30-g Nutriose, 45-g Nutriose, and 22.5-g maltodextrin (placebo). Diets were consumed for 6 weeks. Bodyweights were not changed by consumption of either dose of Nutriose, and there were no significant differences among the three treatment groups in hunger and satiety scores.

Oligosaccharides

Oligosaccharides include a wide range of fibre sources. Inulin is a long-chain carbohydrate, naturally occurring in wheat and onions, and isolated from chicory and Jerusalem artichokes. Inulin can be consumed as a long-chain carbohydrate or hydrolysed into shorter chain lengths, usually referred to as oligofructose or fructo-oligosaccharides. Archer *et al.* (2004) compared inulin with lupin-kernel fibre, both of which are used as fat replacers in products. Lupin-kernel fibre is made from the dehulled seeds of Australian sweet lupin, and has high water-binding and viscosity as compared with insoluble fibres. These two fibres were used as fat replacers in breakfast sausage patties and were fed to 33 healthy men to determine satiety. The authors found that lupin-kernel fibre provided greater satiety compared with a control or inulin patty. In contrast, the inulin sausage patty was associated with lower daily energy intake compared with control or lupin-kernel fibre. Both fibre-containing patties provided 24 g of either lupin-kernel fibre or inulin.

Cani *et al.* (2006) reported that oligofructose promotes satiety in human subjects. Subjects were given either 8 g of oligofructose or dextrin maltose twice a day. Supplements were consumed for 2 weeks. Energy intake, hunger, satiety, fullness and prospective food consumption were assessed with visual analogue scales at the end of each experimental phase. Providing oligofructose at breakfast significantly increased satiety, and total energy intake per day was 5% lower after oligofructose treatment as compared with control.

In a double-blind, randomised, cross-over design, ten healthy subjects consumed boiled white rice containing 50 g of digestible carbohydrate, to which 0 (control), 2, 5 or 10 g of alpha-cyclodextrin was added (Buckley *et al.* 2006). Alpha-cyclodextrin is a new dietary fibre, a cyclic oligosaccharide. Higher doses of alpha-cyclodextrin resulted in greater satiety, but were associated with reduced palatability and an increased incidence of gastrointestinal complaints.

Polydextrose

King *et al.* (2005) compared the independent and combined effects of xylitol (a sugar alcohol) and polydextrose (a functional fibre), given with yogurt, on hunger and energy intake. Four treatments were given: no carbohydrate, 25 g xylitol, 25 g polydextrose, and a mixture of 12.5 g xylitol and 12.5 g polydextrose. Despite large doses, pre-loads of these carbohydrates had small effects on satiety and suppression of energy intake, but only when the energy difference between the yogurt pre-loads was accounted for.

Conclusion

Many studies support the premise that increased dietary fibre intake promotes satiety, decreases hunger, and thus helps provide a feeling of fullness. Foods rich in dietary fibre tend to have a high volume and a low energy density, and should promote satiation and satiety, and play a role in the control of energy balance. However, research into the effects of different types of fibre on appetite, energy and food intake has been inconsistent. Results differ according to the type of fibre, and whether it is added as an isolated fibre supplement, rather than naturally occurring in food sources. Short-term studies in which fibre is fed to subjects and food and energy intakes assessed at subsequent meals suggest that large amounts of total fibre are most successful at reducing subsequent energy intake. Additionally, the more viscous fibres appear most successful in promoting satiety, while other soluble fibres, such as inulin, that are less viscous appear to have minimal effects on satiety, even if consumed in very large doses. Longer-term studies of fibre intake which examine the effects of both intrinsic and functional fibres on satiety are required. Yet, there is ample evidence that increasing consumption of high-fibre foods and the addition of viscous fibres to the diet may decrease feelings of hunger by inducing satiation and satiety.

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