

Insoluble cereal fiber reduces appetite and short-term food intake and glycemic response to food consumed 75 min later by healthy men^{1–3}

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ABSTRACT

Background: Insoluble fiber consumption is associated with reduced risk of obesity and diabetes, but its mechanisms of action are unknown.

Objective: The objective was to describe the effect of insoluble fiber on appetite, short-term food intake, and blood glucose (BG) before and after a meal 75 min later in healthy men.

Design: In a crossover design, high-fiber (HF; 33 g insoluble fiber) cereal, low-fiber (LF) cereal, white bread (WB), and water control were administered to young men after an overnight fast. Caloric treatments had similar energy, macronutrient content, volume, and weight. In the first experiment, subjective appetite and BG were measured at 15-min intervals before and after an ad libitum meal at 75 min. In the second experiment, a preset pizza meal (850 kcal) was consumed at 75 min. Appetite and blood glucose were measured for 150 min at fasting and at 15-min intervals before and after the fixed meal.

Results: In experiment 1, ad libitum food intake was lower after the HF cereal and WB than after the LF cereal and water (937 ± 86 , 970 ± 65 , 1109 ± 90 , 1224 ± 89 kcal, respectively; $P < 0.001$). Appetite was lower ($P < 0.05$) after the HF cereal than after the WB but not different from the LF cereal. The BG area under the curve (AUC) did not differ among the HF cereal, WB, and LF cereal from 0 to 75 min, but the postmeal BG increased after the WB and LF cereal but not after the HF cereal. In experiment 2, the HF cereal, but not the LF cereal or WB, increased fullness before and prevented an increase in the BG AUC after the preset meal ($P < 0.05$).

Conclusion: A serving of 33 g insoluble fiber reduced appetite, lowered food intake, and reduced glycemic response to a meal consumed 75 min later. *Am J Clin Nutr* 2007;86:972–9.

KEY WORDS Insoluble fiber, satiety, glycemic response, food intake, second meal

INTRODUCTION

Cereal fiber consumption associates with protection from obesity and type 2 diabetes, but it is unclear whether this is a direct effect of the fiber component (1–4). Reviews have concluded that fiber consumption is associated with increased satiety and decreased energy intake (5, 6). However, most studies of this relation have focused on soluble fiber or on mixtures of fiber types and not on insoluble fiber (7–11). The beneficial effect of fiber is presumed to be due to its reduction of the glycemic response by forming gels and delaying gastric emptying, but this is an attribute of soluble, not insoluble fibers (12). Insoluble

fibers are nonviscous, with negligible effects on gastric emptying and postprandial glucose response (13). A few studies have investigated the role of insoluble fiber in modulating satiety, but primarily indirectly as a component of fruit, vegetables, and unrefined whole grains, which are highly complex substances, containing both soluble and insoluble dietary fibers as well as other biologically active substances (14–17). The possibility, however, that insoluble fiber suppresses appetite is supported by observations of reduced hunger after supplements of predominantly insoluble fiber ($\approx 90\%$) (18–20).

Insoluble cereal fibers are associated with a reduction in the risk of type 2 diabetes attributed to a decreased insulin demand and a lower glycemic response (1, 2). However, insoluble fibers have a minimal effect on postprandial glucose response (13); therefore, mechanisms responsible for the protective effect of insoluble cereal fiber on type 2 diabetes remain unclear. The aim of this study was to determine the effect of insoluble fiber in a high-fiber breakfast cereal on short-term satiety and food intake and on glycemic response after a later meal.

MATERIALS AND METHODS

Subjects

Healthy men aged 20–35 y with a body mass index (in kg/m^2) of 20–27 were recruited to participate in 2 experiments through advertisements posted across the University of Toronto campus. Subjects were excluded if they had diabetes, did not eat breakfast, were on a diet, or were taking medication. Those who scored ≥ 11 on a questionnaire on eating habits were identified as restrained eaters and were excluded (21).

Sixteen subjects were recruited for experiment 1 and another 15 different subjects participated in experiment 2. Sample size was based on a power analysis for a within-subject design from the results of previous studies that had investigated the effect of carbohydrate and cereal fiber on subjective appetite and food

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TABLE 1
Composition of treatments¹

	Treatments			
	HF	LF	WB	Water
Ingredients				
Fiber One cereal (g)	71	—	—	—
Corn flakes cereal (g)	—	30	—	—
White bread (g)	—	—	76	—
Glucose (g)	13.1	13.1	—	—
Butter (g)	—	—	1.25	—
Water (mL)	140	200	160	500
Whey (g)	—	4.5	—	—
1% Milk (mL)	250	250	250	—
Nutrients				
Energy (kcal)	298	283	287	—
Dietary fiber (g)	33	1	0	—
Available carbohydrate (g)	49	49	50	—
Protein (g)	15.5	14.5	13.5	—
Fat (g)	3.8	3.1	3.6	—
Weight (g)	474.1	497.6	487.2	500
Volume (mL)	500	500	500	500

¹ HF, high-fiber cereal; LF, low-fiber cereal; WB, white bread.

intake (14, 22). In a repeated-measures crossover design the treatments were randomly assigned to each subject. All procedures were reviewed and approved by the Human Subjects Review Committee, Ethics Review Office of the University of Toronto, and all subjects gave informed consent.

Study design

The objective of experiment 1 was to describe the effect of a breakfast high in insoluble fiber on appetite, food intake at an ad libitum meal consumed 75 min later, and postprandial plasma glucose. Four treatments were tested, including high-fiber (HF) cereal (71g, 33 g insoluble fiber; Fiber One; General Mills Inc, Minneapolis, MN), low-fiber (LF) cereal (30 g, 1 g fiber; Country Cornflakes; General Mills Inc), white bread (WB), and 500 mL water as control. Caloric treatments were given with 250 mL milk and had equal calories (≈ 300 kcal), macronutrient content (≈ 50 g available carbohydrate, 15 g protein), volume, and weight (Table 1). The HF and LF cereals were served in milk, whereas the WB treatment was served with milk on the side.

The objective of experiment 2 was to describe the effect of the high insoluble fiber cereal on blood glucose response to a preset pizza meal of fixed quantity (850 kcal) consumed 75 min later. The 3 treatments were similar to those of experiment 1 and included HF cereal (33 g insoluble fiber; Fiber One; General Mills Inc), LF cereal (1 g fiber; Country Cornflakes; General Mills Inc), and WB but excluded the water control treatment. All treatments were given with 250 mL milk and had equal calories (≈ 300 kcal), macronutrient content (≈ 50 g available carbohydrate, 15 g protein), volume, and weight (Table 1). In this experiment, the WB treatment was served cut into 2-cm³ pieces and dipped in the milk to be eaten with a spoon in manner similar to the cereals.

Protocol

The present study protocol is similar to protocols previously reported in other studies (22–24). Subjects chose a time between

0700 and 1000 to participate in the sessions and arrived at the same time at weekly intervals for each of the sessions. Subjects arrived at the study room in the Department of Nutritional Sciences at the University of Toronto for each session after an overnight fast (10–14 h). Water was allowed up to 1 h before the start of each session. On arrival, those subjects whose answers on a questionnaire on sleep habits and stress factors indicated feelings of illness, atypical fatigue, or stress were asked to reschedule.

In experiment 1, the ad libitum meal experiment, a baseline blood sample was taken, and subjects completed baseline visual analog scale (VAS) questionnaires that measured their motivation to eat. Then they proceeded to the taste panel room where they consumed 1 of the 4 treatments within 15 min. At that time, they returned to a study room where they completed VAS questions assessing the palatability of the treatment and measuring their motivation to eat and their physical comfort and provided a blood sample. Measurements continued at 30, 45, 60, and 75 min after the start of the session and immediately after termination of the test meal (≈ 90 min). Finger-prick blood samples were obtained with the use of a Monojector Lancet Device (Sherwood Medical, St Louis, MO). One drop of blood was placed on an Accu-Chek test strip for immediate reading of glucose concentration with the Accu-Chek monitor (Accu-Chek Compact and Compact-Plus; Roche Diagnostics Canada, Laval, QC). Accuracy and variance of the monitors and test strips were monitored before and after each experimental session for each subject by comparison against a commercial human serum standard (6.3 mmol/L; Assayed Human Multi-Sera; Randox Laboratories Canada Ltd, Mississauga, ON). Physical comfort VAS questionnaires were also administered at 75 min, immediately before the test meal. Each page of the questionnaire was folded out of view after each rating. The subjects remained seated throughout the experimental session.

At 75 min after the start of the session and 60 min after finishing consumption of the preloads, subjects returned to the taste panel room and were given bottled spring water (1.5 L; Crystal Springs; Aquaterra Corp, St-Laurent, Canada) and an ad libitum pizza meal and were instructed to eat until comfortably full. Before the sessions, the subjects ranked the pizza according to their preference. The participants were served 2 pizzas of their first choice and 1 each of their second and third choices per tray, consistent at each session. Each pizza was cut into quarters. The subjects were told that additional identical hot tray replacements would be presented in 6–7-min intervals. Three varieties of small round (5-inch diameter, ≈ 200 kcal each) pizzas (deluxe, pepperoni, and 3 cheese; McCain Foods Ltd, Florenceville, Canada) purchased from local retailers were available. An advantage of using these pizzas was the lack of an outer crust, which results in a pizza with uniform energy content and eliminates the possibility that the subject will eat the energy-denser filling and leave the outside crust of the pizza.

Each variety of pizza was weighed separately, and the energy consumed was calculated by converting the net weight to kilocalories with information provided by the manufacturer (McCain). Water consumption was determined before and after the test meal by weighing the water bottle. At the end of the test meal, the subjects rated the palatability of the test meal and completed the postmeal motivation-to-eat questionnaire.

Procedures for experiment 2 were identical to experiment 1 until the 75-min meal. At 75 min the subjects were given a preset pizza meal of a fixed quantity and 250 mL water (850 kcal). The



pizza meal consisted of 2 deluxe pizzas, 1 pepperoni pizza, and 1 three-cheese pizza. The subjects consumed the meal within 15 min. The subjects then returned to the study room where they completed VAS questions assessing the palatability of the meal and measuring their motivation to eat and physical comfort. At meal completion (90 min) and at 15, 30, 45, and 60 min later, blood samples were obtained and the motivation-to-eat VAS questions were administered. Physical comfort VAS questionnaires were administered at 90 and 150 min after the start of the session.

The motivation-to-eat VAS questionnaire, used to assess appetite (22, 23, 25), was composed of 4 standardized questionnaires or scales: 1) How strong is your desire to eat? ("very weak" to "very strong"), 2) How hungry do you feel? ("not hungry at all" to "as hungry as I've ever felt"), 3) How full do you feel? ("not full at all" to "very full"), and 4) How much food do you think you could eat? ("nothing at all" to "a large amount"). Each VAS consisted of a 100-mm line anchored at the beginning and end by opposing statements. The subjects marked an "X" on the line to indicate their feelings at that given moment. Scores were determined by measuring the distance (in mm) from the left starting point of the line to the intersection of the "X." The palatability of the test meal was measured with a VAS. The question "how pleasant have you found the food?" could be answered by marking on a 100-mm line anchored at the beginning and end by the statements "not at all pleasant" and "very pleasant." (22, 23). Similarly, physical comfort was assessed by answers to the following questions: 1) Do you feel nauseous? 2) Does your stomach hurt? 3) How well do you feel? 4) Do you feel like you have gas? and 5) Do you feel like you have diarrhea? The answers ranged from "not at all" to "very much" (22, 23). The subjects remained seated throughout the experimental session.

Statistical analysis

Statistical analyses were conducted with SAS, version 8.1 (SAS Institute Inc. Cary, NC). One-factor repeated measures analysis of variance (ANOVA) was performed to test for the effect of the treatment on outcome variables, including area under the curve (AUC) (26) for blood glucose, and appetite, energy intake, water intake, palatability, and physical comfort.

PROC MIXED ANOVA was used to test for the effect of treatment and time on the mean blood concentrations for glucose and on the absolute scores and change from baseline scores for average appetite and the motivation-to-eat and physical comfort questions (27, 28). Fasting concentrations of blood glucose were included in the model as a covariate to control for between-subjects differences at baseline. Tukey's post hoc test was performed when the interaction between treatment and time was statistically significant. Student's paired *t* test was used to compare changes in blood glucose concentrations after consumption of the pizza meal.

An average appetite score was calculated at each time of measurement for each treatment as appetite score = [desire to eat + hunger + (100 – fullness) + prospective consumption]/4. The formula reflected the 4 questions on the motivation-to-eat questionnaire (22, 29). Average appetite was therefore used as a summary measure of subjective appetite for statistical analyses.

A composite physical comfort score, based on the 5 questions in the questionnaire, was calculated at each time of measurement for each treatment as [(100 – nausea) + (100 – stomach) + well + (100 – gas) + (100 – diarrhea)]/5 (22, 29). The composite

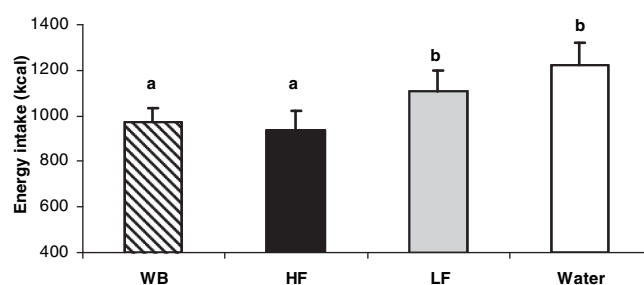


FIGURE 1. Energy intake at an ad libitum meal 75 min after white bread (WB), high-fiber cereal (HF), low-fiber cereal (LF), and water treatments in 16 healthy men. Data are presented as mean \pm SEM. Treatment affected energy intake ($P < 0.001$, 1-factor ANOVA). Bars with different superscript letters are significantly different, $P < 0.05$ (Tukey's test).

score was used as a summary of physical comfort for statistical analyses. The percentage of caloric compensation for the test treatment was calculated as compensation (%) = [control treatment (kcal) – test treatment (kcal)]/preload (kcal) \times 100.

All values are presented as means \pm SEMs. A P value < 0.05 was considered to indicate statistical significance.

RESULTS

Experiment 1: ad libitum meal

Food intake

Treatment affected the amount of energy consumed at the test meal 75 min after the preloads were provided to the subjects ($P < 0.001$). Food intake was lower after the HF cereal and WB treatments than after the LF cereal and water treatments (**Figure 1**). Energy intake was not different between the HF cereal and WB treatments and between the LF cereal and water treatments.

A significant treatment effect was observed on the percentage compensation for the energy in the preloads ($P < 0.05$). Compensation at the test meal for calories consumed in the HF cereal treatment ($99 \pm 19\%$) was significantly greater than after the LF cereal treatment ($42 \pm 23\%$) but not different from the WB treatment ($85 \pm 22\%$). The amount of water consumed with the test meal was not affected by treatment ($P = 0.3$) (data not shown).

Average appetite

All treatments except water decreased average appetite at 15 min ($P < 0.0001$). Average appetite was lowest after the HF cereal treatment followed by the LF cereal treatment, then the WB, and finally water (**Figure 2**). Average appetite increased with time ($P < 0.0001$), but no time-by-treatment interaction was observed ($P = 0.9$).

The average appetite AUC, calculated as the change from baseline, was affected by treatment ($P < 0.0001$). The HF cereal treatment resulted in the lowest AUC (-1792 ± 438.7 mm \cdot min), followed by the LF cereal ($-1224. \pm 334.6$ mm \cdot min), WB (-766 ± 342.8 mm \cdot min), and water (310 ± 141.3 mm \cdot min) treatments.

Blood glucose

Blood glucose concentrations were affected by both treatment ($P < 0.0001$) and time ($P < 0.01$) with a time-by-treatment interaction ($P < 0.01$). At 15, 30, 45, and 60 min, blood glucose concentrations after the LF cereal, HF cereal, and WB treatments

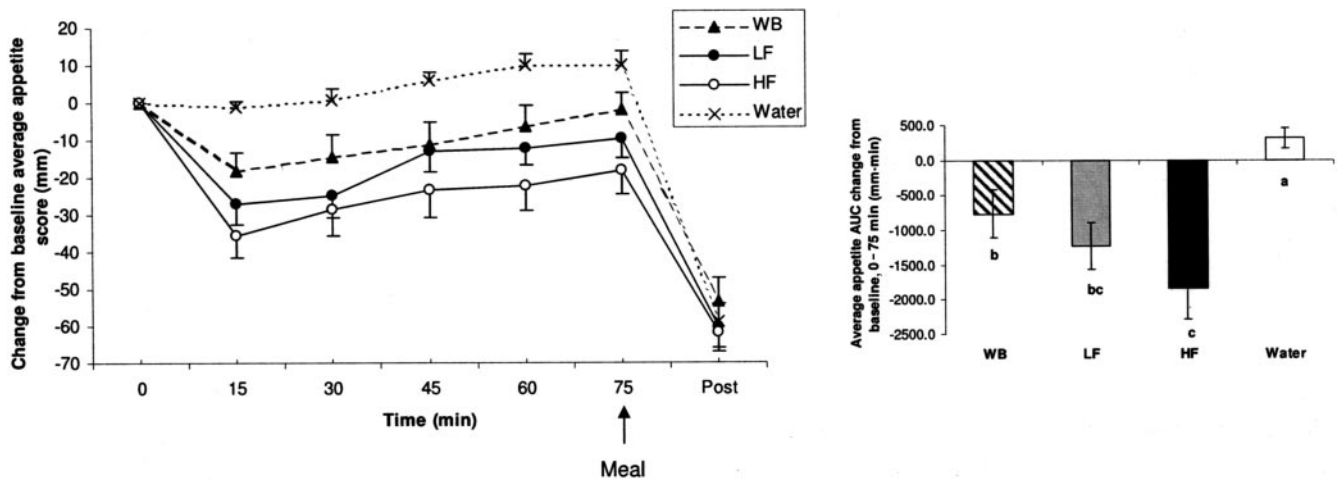


FIGURE 2. Average appetite score, change from baseline, measured by visual analog scales after consumption of white bread (WB), high-fiber cereal (HF), low-fiber cereal (LF), and water treatments before and after consumption of the ad libitum meal and net incremental area under the curve (AUC) in 16 healthy men. Data are presented as mean \pm SEM. A 2-factor ANOVA identified a significant effect ($P < 0.0001$) of both treatment and time with no interaction on average appetite score. Treatment affected average appetite AUC ($P < 0.0001$). Bars with different superscript letters are significantly different, $P < 0.05$ (Tukey's test).

did not differ. At 75 min, blood glucose after the LF cereal and water control was lower than after the HF cereal and WB treatments (Figure 3). Blood glucose AUC to 75 min did not differ among the HF cereal, WB, and LF cereal treatments but was higher than after the water ($P < 0.0001$).

Blood glucose concentration after, compared with before, the ad libitum pizza meal was increased after the LF cereal (0.4 ± 0.2 mmol/L), WB (0.5 ± 0.3 mmol/L), and water (1 ± 0.3 mmol/L) treatments ($P < 0.05$) but was unchanged after the HF cereal treatment (-0.2 ± 0.2 mmol/L) when analyzed by Student's paired t test analysis. On the basis of a 1-factor ANOVA the increase in blood glucose after the LF cereal, WB, and water treatments was greater than after the HF cereal treatment ($P < 0.001$).

Physical comfort

No effect of treatment ($P = 0.8$) or time ($P = 0.1$) or time-by-treatment ($P = 0.5$) interaction was observed on ratings of

physical comfort taken during 1 h after the consumption of each treatment and after the ad libitum meal (data not shown).

Palatability

Subjective ratings of palatability for the pizza test meal were not different ($P = 0.6$). However, subjective ratings of palatability differed among treatments ($P < 0.0001$). The LF cereal treatment (78.9 ± 2.6 mm) was rated as more palatable than the HF cereal (65.4 ± 5.1 mm) and WB (53.9 ± 5.5 mm) treatments.

Experiment 2: preset meal

Blood glucose

Between 0 and 75 min (before consumption of the preset meal), blood glucose concentrations were not affected by treatment ($P = 0.4$). However, blood glucose increased with time ($P < 0.0001$), and a time-by-treatment interaction occurred ($P <$

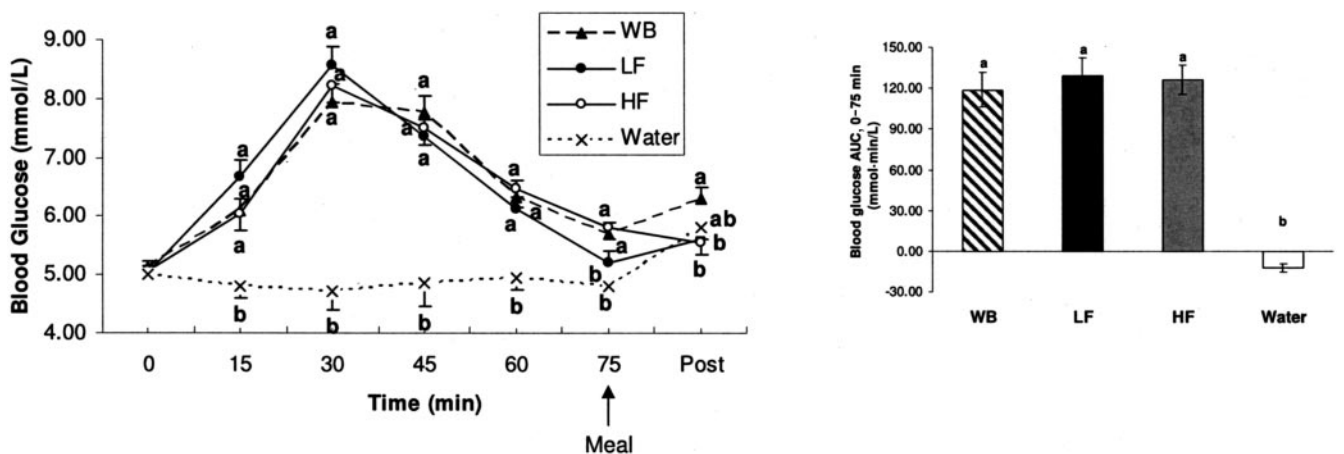


FIGURE 3. Blood glucose concentrations after consumption of white bread (WB), high-fiber cereal (HF), low-fiber cereal (LF), and water treatments and after consumption of the ad libitum meal and the net incremental area under the curves (AUCs) in 16 healthy men. Data are presented as mean \pm SEM. A 2-factor ANOVA showed a treatment effect on blood glucose concentrations ($P < 0.0001$). A significant effect of time ($P < 0.01$) and a time-by-treatment interaction ($P < 0.01$) were observed. Treatment affected blood glucose AUC ($P < 0.0001$). Bars with different superscript letters are significantly different, $P < 0.05$ (Tukey's test).

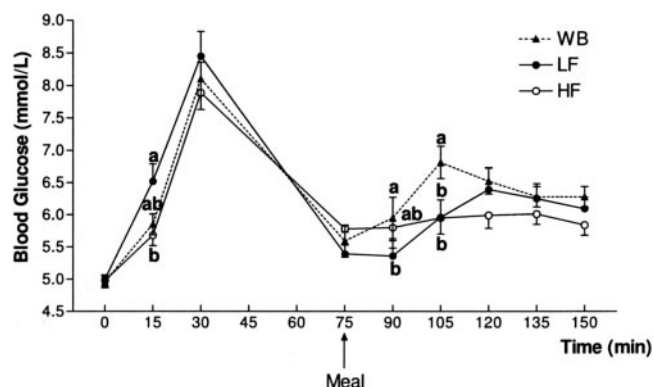


FIGURE 4. Blood glucose concentration after consumption of white bread (WB), high-fiber cereal (HF), and low-fiber cereal (LF) treatments at 0–75 min and after the preset meal at 75 min in 15 healthy men. Data are presented as mean \pm SEM. Between 0 and 75 min, blood glucose concentrations were not affected by treatment ($P = 0.4$) but increased with time ($P < 0.0001$) with a time-by-treatment interaction ($P < 0.05$). After the preset meal (75–150 min), blood glucose concentrations were affected by treatment ($P < 0.05$) and time ($P < 0.0001$) with a time-by-treatment interaction ($P < 0.0001$). Means with different superscript letters are significantly different, $P < 0.05$ (Tukey's t test).

0.05). At 15 min, the LF cereal treatment resulted in a larger increase in blood glucose than did the HF cereal treatment; WB was intermediate (**Figure 4**). Blood glucose AUC between 0 and 75 min did not differ among treatments ($P = 0.7$).

After the preset meal (75–150 min), blood glucose concentrations were affected by treatment ($P < 0.05$) and time ($P < 0.0001$) with a time-by-treatment interaction ($P < 0.0001$). At 90 min, blood glucose after the LF cereal treatment was significantly lower than after the WB treatment, but both were not different from the HF cereal treatment. At 105 min, blood glucose after the WB treatment was higher than after both the HF and LF cereal treatments (**Figure 4**).

Paired t test analysis showed that blood glucose after compared with immediately before the preset meal was higher at 105, 120, 135, and 150 min after the LF cereal and WB treatments. However, it was unchanged after the HF cereal treatment ($P < 0.05$).

A treatment effect was observed on postmeal glucose AUC from 90 to 150 min ($P < 0.05$). AUC after the HF cereal treatment (3.6 ± 14.2 mmol·min) was lower than after the LF cereal treatment (42 ± 12.5 mmol·min), but both were not different from the WB treatment (26.9 ± 12.4 mmol·min), which was intermediate.

Average appetite

Between 0 and 15 min, average appetite decreased and then increased from 15 to 75 min after all treatments ($P < 0.0001$), but average appetite did not differ among treatments ($P = 0.4$), and no time-by-treatment interaction was observed ($P = 0.3$) (**Figure 5**). Appetite AUC between 0 and 75 min was not affected by treatment ($P = 0.1$). Individual appetite scales, including ratings for hunger, fullness, desire to eat, and prospective consumption, did not differ among treatments, and no time-by-treatment interaction was observed (data not shown). Between 0 and 15 min, hunger, desire to eat, and prospective consumption decreased and then increased from 15 to 75 min after all treatments, whereas ratings for fullness increased between 0 and 15 min and then decreased from 15 to 74 min after all treatments ($P < 0.0001$). AUC for fullness was significantly higher after the

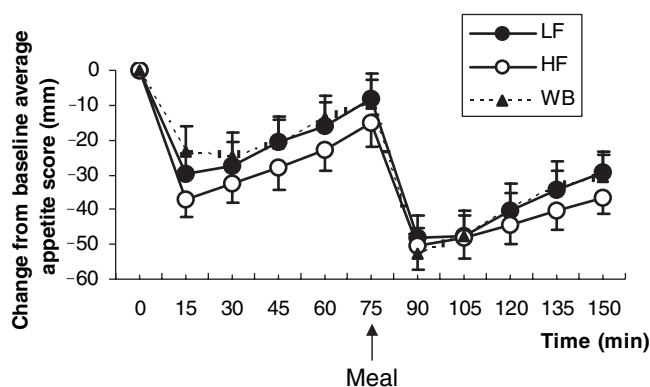


FIGURE 5. Average appetite score, change from baseline, measured by visual analog scales from 0–75 min after consumption of white bread (WB), high-fiber cereal (HF), and low-fiber cereal (LF) and after the preset meal (90–150 min) in 15 healthy men. Data are presented as mean \pm SEM. No significant effect of treatment was observed, but average appetite increased with time ($P < 0.0001$) with no significant interaction.

HF cereal treatment (2536.0 ± 412.3 mm·min) than after the WB (1736.0 ± 486.5 mm·min) and LF cereal (1582.0 ± 364.7 mm·min) treatments ($P < 0.05$). AUCs for hunger, desire to eat, and prospective consumption were not affected by treatment.

Between 90 and 150 min, after consumption of the preset meal, treatment did not affect the overall appetite scores ($P = 0.8$). Average appetite increased with time ($P < 0.0001$) without a time-by-treatment interaction ($P = 0.4$) (**Figure 5**). Average appetite response to the preset meal was unchanged after all treatments from 90 to 150 min. Appetite AUC between 90 and 150 min was not affected by treatment ($P = 0.3$). Individual appetite scales, including hunger, fullness, desire to eat, and prospective consumption, changed with time ($P < 0.0001$) but were not different among treatments, and no time-by-treatment interaction was observed (data not shown). AUCs for fullness, hunger, desire to eat, and prospective consumption were not affected by treatment.

Physical comfort

No effect of treatment ($P = 0.2$) or time ($P = 0.5$) or time-by-treatment ($P = 0.7$) interaction was observed on ratings of physical comfort taken during the 2 h after the consumption of each treatment and after the preset meal.

Palatability

No differences in subjective ratings of palatability for the pizza meal were found ($P = 0.8$) (data not shown). However, the subjective ratings of palatability differed among treatments. The LF cereal treatment (82 ± 3 mm) was rated as more palatable than the HF cereal treatment (66 ± 5 mm), which was more palatable than the WB treatment (47 ± 8 mm) ($P < 0.0001$).

DISCUSSION

This study shows that the insoluble fiber content of a HF cereal reduces subjective appetite and food intake and improves postprandial glucose response after a meal consumed a short time later by healthy men. These effects are independent of its effect on blood glucose concentration before the meal.

Insoluble fiber in the HF breakfast cereal, when given in high amounts (33 g), reduced ad libitum food intake more than a LF

cereal and water (Figure 1), resulting in the highest caloric compensation among treatments. Other studies have reported lower short-term food intake after consumption of the same cereal (Fiber One) (14) or another high insoluble fiber cereal (All Bran) (30) when compared with LF cereals. Although the effect of the insoluble fiber has been attributed to its effect on blood glucose response to the cereals (30), those prior studies did not equalize the amount of available carbohydrate among treatments. As a result, their HF cereals were also lowest in available carbohydrate, and a lower glycemic response would be expected. In contrast, except for fiber, we equalized macronutrient content, volume, weight, and calories among the treatments (Table 1). Consequently, the observed effect of the HF cereal might be more directly attributed to its insoluble fiber content.

The insoluble fiber in this breakfast cereal appears to have direct action on mechanisms of satiety and food intake. Although it was assumed that lower food intake results from the low-glycemic response to HF cereals (15), differences in the glycemic effect of the treatments before the test meal provide an unlikely explanation for the present results. All our treatments, in both experiments, led to similar increases in blood glucose before the meal. Furthermore, in many short-term studies of sugar and carbohydrates, an inverse relation between blood glucose and food intake is found (22, 23).

The HF cereal led to a greater suppression in appetite scores and increased fullness scores than did the WB or LF cereal treatments, and the scores were associated with decreased food intake. This immediate effect of the high insoluble fiber cereal on satiety and food intake suggests that its effects were primarily in the small intestine. Insoluble fiber increases the rate of small intestine transit (12), which has the effect of reducing starch absorption (31). In humans, carbohydrate carried into the distal small intestine can elevate and prolong for 2–4 h the secretion of glucagon-like peptide 1 (32, 33), a hormone known to contribute to satiety and food intake suppression (34) and glucoregulation (35) in humans. Furthermore, high insoluble fiber cereal was shown to increase plasma concentrations of the satiety hormone cholecystokinin more than LF cereals (15). Although increased short-chain fatty acids occur from colonic fermentation of fiber and undigested starch entering the colon, it is unlikely to be the mechanism explaining the effects seen on satiety and food intake. Increased production of breath histamine 2, a product of bacterial fermentation reactions, was not found until 1 h after ingestion of a high insoluble fiber cereal (Fiber One, 57g) (14). Measurement of gut hormones after consumption of insoluble fiber may contribute to an explanation of its short-term effects on food intake (36).

An effect of HF cereal on the glycemic response to the test meal was evident in both experiments. In the first experiment, blood glucose response to the ad libitum meal 75 min later was suppressed after the HF cereal treatment but increased after the WB and LF cereal treatments. This occurred despite a similar blood glucose response after consumption of the treatments, suggesting that insoluble fiber did not have a regulatory effect on blood glucose concentrations before the meal but affected the postmeal response independently. However, the reduced postmeal glucose response after the HF cereal compared with the other treatments was somewhat uncertain because different amounts of calories were consumed at the in ad libitum meal, and glucose was measured only once after the meal. Therefore, in the second experiment, we investigated the effect of insoluble fiber

on blood glucose concentrations after a preset meal of fixed energy and macronutrient content.

The results of experiment 2 also showed that the HF cereal prevented a postmeal rise in blood glucose and support the suggestion that the glycemic response after the test meals was unrelated to its effects on blood glucose concentrations before the meal. Previous research has concluded that a reduced glycemic response after a “second meal” is due to fiber slowing absorption and lowering glycemic response before the meal as well as continuing to exert this effect for some duration even after carbohydrate is later consumed (37–39). However, a lower glycemic response at the second meal has been observed after soluble but not after insoluble fiber. Lower glucose responses after a meal were observed when lentils and barley, both low-glycemic index foods rich in soluble and fermentable fiber, were consumed as the first meal, but not after whole-meal bread, a high-glycemic index food rich in insoluble fiber (37, 40). Similarly, the addition of guar gum, a soluble fiber, to a glucose load resulted in a lower glucose response before and after a second meal (41, 42).

Bacterial fermentation may have been a factor in the postmeal glucose response. Short-chain fatty acids increase proglucagon mRNA in rats (43) and secretion of incretin hormones, including glucagon-like peptide 1 (44), reduce postprandial glycemic responses (45), as well as reduce gastric tone (46–48), resulting in better glucose tolerance. When lactic acid and lactulose, both boosting colonic fermentation, were added to a high-glycemic index treatment, glucose response was suppressed at the second meal 4 h later (46, 49). It remains to be seen whether the postmeal effect of insoluble fiber on blood glucose occurs in response to meals consumed >75 min later and whether smaller doses of insoluble fiber will give similar benefits.

In the first experiment, the WB treatment also reduced energy intake at the test meal compared with cornflakes. Although both had a LF content, the difference in consistencies among the treatments may have been a factor. The WB treatment was consumed as a whole slice with milk on the side, whereas the LF cereal treatment was consumed in the milk, a semisolid consistency consumed with a spoon. In the second experiment, we corrected for the consistency differences by slicing and dipping the WB in milk. Consequently, the appetite response after the WB treatment was decreased similarly to the LF and HF cereal treatments unlike the first experiment. This decrease might be due to the lower reported palatability of the WB treatment, but more likely the more solid consistency resulted in greater satiety (50, 51). Several mechanisms may account for this phenomenon. Furthermore, both early and pancreatic exocrine and endocrine responses to oral stimulation with solid stimuli are greater than those to fluids (52–54). A cephalic phase release of the satiety-promoting peptide, cholecystokinin, was also shown with a solid meal (55). In contrast, fluids are emptied at a more rapid rate from the stomach (56–58), resulting in a more rapid time course of activation and shorter duration of effect on satiety signals arising from the gut or proximal duodenum (59, 60).

The composition of the starch and protein in the treatments does not explain their effects on food intake. The digestible carbohydrate in the WB and HF cereal treatments is composed of primarily wheat flour, whereas cornflakes are composed of cornstarch. However, both wheat flour and cornstarch have a similar ratio of amylose to amylopectin (25:75). The composition of starches, more specifically the ratio of amylose to amylopectin, is a determinant of satiety because it influences the metabolic



responses after ingestion (61). Unlike the LF cereal treatment, both the HF cereal and WB treatments had a similar protein source, wheat gluten, but the amounts of protein consumed are likely too small to be of significance. Studies showing that protein source plays a role in the way proteins suppress food intake and appetite have used much larger doses of proteins (62).

The observed suppression in appetite and short-term food intake after insoluble fiber supports a role for insoluble fiber in weight loss or weight maintenance on the long term. Consumption of insoluble fiber for 1 mo was shown to result in weight loss in both healthy (63) and obese persons (64). Furthermore, studies have reported that overweight subjects given insoluble fiber supplements after weight reduction were able to sustain their weight loss compared with subjects given a placebo (19).

In conclusion, the insoluble fiber found in a high-fiber ready-to-eat breakfast cereal suppresses appetite, lowers food intake, and improves glucose response to a meal consumed 75 min later. The potential of insoluble fibers in the management of obesity and related metabolic disorders warrants further study.

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