Postprandial lipid, glucose, insulin, and cholecystokinin responses in men fed barley pasta enriched with β-glucan[1,2]

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ABSTRACT

Background: Fiber regulates the rate and site of lipid and carbohydrate digestion and absorption and thus can modify the alimentary responses to a meal. When fiber sources containing viscous polysaccharides are included in a meal, a slower rate of carbohydrate and lipid absorption will modify the alimentary hormone and lipid responses.

Objective: We investigated in 11 healthy men the response of insulin, glucose, cholecystokinin, and lipid to 2 test meals containing β-glucan.

Design: One of the meals was high in fiber (15.7 g) and the other meal was low in fiber (5.0 g). The low-fiber meal contained pasta made with wheat flour. The high-fiber meals contained pasta prepared by replacing 40% of the wheat with 2 types of barley flour: barley naturally high in β-glucan and the other a flour enriched in β-glucan during processing.

Results: Plasma glucose and insulin concentrations increased significantly after all meals but the insulin response was more blunted after the barley-containing meals. The test meals were low in fat (25% of energy) but elicited an increase in plasma triacylglycerol and cholecystokinin. Cholecystokinin remained elevated for a longer time after the barley-containing meals. After the low-fiber meal, plasma cholesterol concentrations did not change significantly; however, 4 h after the barley-containing meals, the cholesterol concentration dropped below the fasting concentration and was significantly lower than that after the low-fiber meal.

Conclusions: Carbohydrate was more slowly absorbed from the 2 high-fiber meals. Consumption of the barley-containing meals appeared to stimulate reverse cholesterol transport, which may contribute to the cholesterol-lowering ability of barley. *Am J Clin Nutr* 1999;69:55–63.

KEY WORDS Fiber, barley, cholesterol, cholecystokinin, β-glucan, glucose, insulin, triacylglycerol, pasta, viscous polysaccharides, men

INTRODUCTION

β-Glucans are found in cereal grains, located primarily in the endosperm cell walls of both oats and barley, and are actively involved in the metabolic response to oat products (1–3). Long-term feeding studies incorporating β-glucan have shown reductions in plasma cholesterol in hypercholesterolemic men (4, 5).

A diet low in saturated fat and high in viscous polysaccharides, including β-glucan, resulted in a 7.5% reduction of serum cholesterol in hyperlipidemic men (6). Results recently reported from the Multiple Risk Factor Intervention Trial indicate that increasing fiber intake in a fat-modified diet provided reductions in blood total and LDL cholesterol (7). Postprandial studies that measured plasma triacylglycerol after a meal reported that the addition of dietary fiber to a meal increased triacylglycerol (8), decreased triacylglycerol (9), or had no effect (10). Postprandial cholesterol appears to remain unchanged or decreases slightly after a meal high in dietary fiber (8, 11). Sources of viscous polysaccharide slow the digestion and absorption of fat, which are likely to modify the appearance of triacylglycerol-rich lipoproteins (TRLs), either by altering their rate and magnitude of appearance in plasma or by altering their composition after a meal. Both effects could have implications for the process of reverse cholesterol transport, which is stimulated during the postprandial period and may contribute to the plasma cholesterol-lowering effect of viscous polysaccharides. Previous reports on the effect of fiber on alimentary lipemia have used meals containing 42–58% of energy from fat, which is substantially higher than the recommended fat intake for lowering the risk of heart disease. Reverse cholesterol transport can be stimulated during the alimentary period if diets low in fat are consumed. Thus, to understand the potential role of viscous polysaccharides in reverse cholesterol transport, their effect in a low-fat diet must be understood.

The gut hormone cholecystokinin may mediate some of the postprandial glycemic, insulinemic, and lipemic responses to viscous polysaccharides. The physiologic responses to cholecystokinin released from the small intestine include a delay in gastric emptying, blunted glycemic increases, and enhanced satiety—responses that have also been associated with consumption of viscous polysaccharides (12–14). The prolonged contact of lipid

with intestinal cells due to slower digestion after a high-fiber meal may promote a greater release of cholecystokinin (15). The present study design enabled us to test whether the release of cholecystokinin would be altered after a complete meal high in viscous polysaccharide.

Dietary fiber alters postprandial glycemia and insulinemia in both healthy (9, 16) and diabetic subjects (9, 17, 18). Many of the studies reporting such effects of fiber have tested isolated fiber sources independent of consumption of a complete mixed meal. Although these studies are useful for determining glycemic and insulinemic indexes, they are not physiologic because most individuals generally consume mixed meals, not isolated fiber sources. Discrepancies between the glucose and insulin patterns in response to mixed meals supplemented with fiber or to a sugar-containing test solution with added fiber have been reported and emphasize the importance of understanding the more typical pattern associated with eating a meal.

Recently, a method was developed to concentrate β-glucans in barley flour (19). When this enriched β-glucan flour was substituted for a portion of wheat flour in pasta and fed to healthy subjects, it lowered postprandial glycemia and insulinemia compared with a wheat pasta (20). Products made with enriched barley flour have been shown to have acceptable sensory properties (21), making the enriched flour a possible source of palatable viscous polysaccharides. A barley genotype, Prowashonupana, naturally high in β-glucan has been developed. Flour milled from this genotype results in β-glucan concentrations comparable with those found in β-glucan–enriched barley flours.

The purpose of the present study was to evaluate the postprandial glucose, insulin, lipid, and cholecystokinin responses in healthy men to complete test meals containing β-glucans from barley. Pasta prepared from β-glucan–enriched barley flour or barley flour milled from the naturally high β-glucan genotype was incorporated into meals to determine whether a difference exists between the source of the β-glucan, ie, concentrated flour or flour naturally high in β-glucan. A control wheat pasta was included for comparison.

SUBJECTS AND METHODS

Subjects

Twelve healthy men were recruited for this study from the student and staff population at the University of California, Davis. A questionnaire and interview was used to screen out subjects with heart disease or diabetes and those who used medications. Potential subjects who exercised >1 h/d were excluded. Volunteers were screened for fasting cholesterol and triacylglycerol concentrations with a finger-stick test (Cholestech LDX Lipid Analyzer; Cholestech, Hayward, CA). Body mass index (BMI), calculated as body weight divided by height squared (kg/m²), was determined for each individual. Subjects with a fasting total cholesterol concentration between 4.1 and 6.2 mmol/L (160 and 240 mg/dL) and a triacylglycerol concentration <2.26 mmol/L (<200 mg/dL) were accepted into the study. In the original study design, we tested the potential correlation between BMI and the alimentary lipid response; subjects were selected with a BMI in the range of 22–25 or 27–29. Subject characteristics are shown in **Table 1**.

TABLE 1
Subject characteristics[1]

	$\bar{x} \pm SE$	Range
Age (y)	28.6 ± 2.0	21–42
Height (cm)	179.1 ± 1.9	168.0–188.0
Weight (kg)	81.7 ± 3.4	67.7–100.4
BMI (kg/m²)	25.3 ± 0.7	22.6–28.4

[1] $n = 11$.

Volunteers were instructed to maintain current dietary and exercise habits for the duration of the study. Subjects kept food records throughout the study to allow compliance with the experimental protocol to be assessed. A registered dietitian reviewed food records with subjects on each of the test days and checked them for completeness. Food records were analyzed by using NUTRITIONIST III (N-Squared Computing, San Bruno, CA). Subjects were informed about the experimental protocol before giving informed consent. The protocol was reviewed and approved by the Human Subjects Review Committees at the University of California at Davis and the US Department of Agriculture.

Test meals

The commercial low-fiber pasta (CLFP) was made from 100% commercial wheat semolina. The high-fiber pastas were prepared with semolina flour in which 40% of the semolina was replaced with either a β-glucan–enriched fraction of Waxbar barley flour (WBFP) or barley flour from Prowashonupana barley (PBFP), a cultivar naturally high in β-glucans. Waxbar barley flour was enriched with β-glucans by using the method described by Knuckles et al (19). Briefly, Waxbar flour was repeatedly milled and sifted through a 325-mesh sieve to remove barley starch and enrich the remaining flour with β-glucans. The 3 test pastas were prepared by feeding the flours into a Werner & Pfleiderer Continua extruder (Stuttgart, Germany) equipped with a steam preconditioner, 9 temperature-controlled barrel sections, and 1470-mm counter-rotating screws. The samples were extruded at a moisture content of 30% through a spaghetti die with 2-mm holes. The freshly extruded samples were tunnel-dried for 1 h, dried at ambient temperature for 3 h, equilibrated to ≈11% moisture in paper sacks at room temperature for 1 d, then stored in plastic bags in the freezer until used. An additional noncommercial, low-fiber pasta (NLFP) was made with the same ingredients used to make the CLFP but was processed into spaghetti with a homestyle pasta maker (21). We included this pasta to determine whether the increase in glucose observed after 3 h was related to the type of processing of the pasta. All pastas were boiled in unsalted water for a specified time, drained but not rinsed, and then served.

The food content and the composition of the test meals are listed in **Table 2**. All foods used were commercially available, except for the pastas. Each meal provided approximately one-third of each individual's estimated daily energy requirement. The composition of the cooked pastas is shown in **Table 3**. Both of the high-β-glucan pastas contributed ≈5 g β-glucan and ≈10 g other fibers for a total dietary fiber content of 15.7 g. The control pastas contained negligible amounts of β-glucan and 4.6 g total dietary fiber. The β-glucan content of the pastas was determined by the method described by McCleary et al (22, 23). The NLFP meal was similar in nutrient and food content to the 3 test meals that included the commercial, extruded pastas.

TABLE 2
Food content and composition of test meals[1]

	CLFP	PBFP	WBFP
Egg (g)	50.0	50.0	50.0
Canned chicken gravy (g)	119.0	119.0	119.0
Orange juice (g)	187.0	199.0	187.0
Turkey ham (g)	49.7	21.3	39.8
Margarine (g)	2.4	2.4	1.9
Butter (g)	2.3	2.3	1.9
Wheat pasta (g)	147.0	—	63.0
Natural β-glucan pasta (g)	—	170.0	—
β-Glucan–enriched pasta (g)	—	—	100.0
Protein (% of energy)	19	18	18
Carbohydrate (% of energy)	56	57	57
Fat (% of energy)	25	25	25

[1] CLFP, low-fiber wheat pasta; PBFP, naturally high-β-glucan–containing pasta; WBFP, β-glucan–enriched pasta.

TABLE 3
Composition of cooked pasta as served[1]

	CLFP	PBFP	WBFP
		g	
β-Glucan	0.3	5.2	5.0
Total dietary fiber[2]	4.6	15.7	15.7
Carbohydrate	72.0	75.0	74.0
Protein	13.7	19.1	15.5
Fat	1.5	2.8	2.2

[1] CLFP, low-fiber wheat pasta; PBFP, naturally high-β-glucan–containing pasta; WBFP, β-glucan–enriched pasta.
[2] Including β-glucans.

Study design

Each of the 12 subjects consumed each of the 3 test meals (CLFP, PBFP, and WBFP) on 3 different days, 1–3 wk apart in a randomized, crossover design. Five of these 12 subjects also consumed the NLFP meal. Subjects fasted for 12 h before the test period began, which started between 0800 and 1000 for all meals. A catheter was placed in an antecubital vein and a baseline (0 min) blood sample was drawn. Subjects then had 20 min to eat the test meal. Blood samples were drawn 30, 45, 60, 120, 180, 240, 300, and 360 min after the meal began. A continuous slow infusion of 0.9% NaCl maintained the catheter between blood drawings. Blood was collected into syringes and then transferred to Vacutainer tubes containing EDTA (Becton Dickinson, Rutherford, NJ) and centrifuged at $1200 \times g$ at 4°C for 20 min to separate plasma. Samples of plasma glucose, insulin, triacylglycerol, and cholesterol were stored at −20°C until assayed. For cholecystokinin analysis, 2 mL fresh plasma was passed through a C_{18} Sep-Pak cartridge (Waters, Milford, MA) and rinsed with 20 mL distilled, deionized water. The cartridges were preconditioned with 5 mL methanol and rinsed with 20 mL distilled, deionized water. The plasma-loaded cartridges were stored frozen at −70°C until assayed. The triacylglycerol-rich fraction was fractionated (24) from 2 mL fresh plasma (density < 1.0063 kg/L) by ultracentrifugation with a Sorvall fixed-angle rotor (TFT 45.6) in a Sorvall OTD-65B ultracentrifuge (Dupont Biomedical Products, Sorvall Instruments, Wilmington, DE). TRLs were collected by tube slicing.

Analytic procedures

Plasma glucose was determined by the glucose oxidase method (kit 315; Sigma Chemical Co, St Louis). Plasma and TRL lipid analyses (cholesterol and triacylglycerol) were performed in the University of California, Davis, Lipid Assay Laboratory, which is standardized by participation in the Centers for Disease Control's National Heart, Lung, and Blood Institute's Lipid Standardization Program (LSP-206). Plasma insulin was determined by radioimmunoassay according to the method of Yalow and Berson (25) with a modified precipitation method (26). Apolipoprotein (apo) B-48 and apo B-100 were quantified by using the method described by Schneeman et al (27).

Plasma cholecystokinin concentrations were measured with a previously described radioimmunoassay (28). Before radioim-

munoassay, plasma cholecystokinin adsorbed on thawed Sep-Pak cartridges was eluted into assay tubes with 3 mL of a solution of 50% acetonitrile and 0.025% trifluoroacetic acid and then dried by vacuum centrifugation at $1500 \times g$ for 12–14 h at ambient temperature (Speed Vac Concentrator SVC200H; Savant Instruments, Farmingdale, NY). Assay tubes were incubated for 3 d at 4°C in 1 mL gelatin-phosphate buffer containing antiserum at a titer of 1:1000000 and 2000 cpm 125I Bolton Hunter–labeled sulfated cholecystokinin-8 (Amersham, Arlington Heights, IL). Separation of bound from free radiolabel was achieved with 0.2 mL 3% dextran (average molecular weight: 87000; Sigma Chemical Co).

Statistical analysis

Two-factor, repeated-measures analysis of variance (ANOVA) was used to analyze the diet $\times$ time interaction. One-factor ANOVA was used to compare responses to the diets at different time points. One-sample t tests were used to determine differences between postprandial time points and baseline for each diet (STATVIEW 512t; Brain Power, Calabasas, CA). All values were converted to increments by subtracting baseline values from each time point. Values are expressed as means ± SEMs. Statistical significance was set at $P < 0.05$.

RESULTS

Subjects maintained their body weight and exercise habits throughout the experimental period. Subjects consumed 9710 ± 2390 kJ, 100 ± 39 g protein, 326 ± 96 g carbohydrate, 69 ± 26 g fat, 19 ± 9 g fiber, and 5 ± 11 g ethanol during the study period. Nutrient intakes during the time periods between test meals were not significantly different between subjects. Data analysis showed that BMI was not a significant factor in any of the measured responses; therefore, subjects with a high and low BMI were grouped together. One subject did not comply with the protocol and was dropped from data analysis. The initial concentration obtained at time 0 h for each variable is shown in **Table 4**. There were no significant differences in concentrations among the 3 test-meal groups.

Glucose

The postprandial glucose response pattern varied with meal type (**Figure 1**A). At 4 h postmeal, the 2 barley meals produced a larger increase from baseline than did the CLFP meal. Maximal mean glucose responses were 7.5 ± 0.4, 7.8 ± 0.6, and 7.3 ± 0.4 mmol/L for the CLFP, PBFP, and WBFP meals, respectively ($n = 11$; NS). Postprandial glucose increased significantly

TABLE 4
Initial concentration of each variable before the test meal was consumed[1]

	CLFP	PBFP	WBFP
Glucose (mmol/L)	5.6 ± 0.3	5.9 ± 0.5	5.1 ± 0.3
Insulin (pmol/L)	52.6 ± 12.0	45.7 ± 9.6	36.0 ± 4.3
Cholecystokinin (pmol/L)	4.0 ± 0.4	3.7 ± 0.3	3.9 ± 0.2
Plasma cholesterol (mmol/L)	4.7 ± 0.3	4.6 ± 0.3	4.6 ± 0.3
Plasma triacylglycerol (mmol/L)	1.2 ± 0.1	1.1 ± 0.1	1.1 ± 0.2
TRL-triacylglycerol (mmol/L)	0.7 ± 0.1	0.6 ± 0.1	0.6 ± 0.2
TRL-cholesterol (mmol/L)	0.3 ± 0.05	0.3 ± 0.04	0.3 ± 0.09
Apolipoprotein B-100 (nmol/L)	103.9 ± 10.8	95.7 ± 12.5	82.5 ± 18.5
Apolipoprotein B-48 (nmol/L)	5.1 ± 1.3	3.9 ± 1.5	3.5 ± 1.2

[1] $\bar{x}$ ± SEM. CLFP, low-fiber wheat pasta; PBFP, naturally high-β-glu-can–containing pasta; WBFP, β-glucan–enriched pasta; TRL, triacylglyc-erol-rich lipoprotein.

from baseline after all test meals. Glucose concentrations returned to baseline values 1 h after the barley meals, increased significantly above baseline 3 h postmeal, and remained above baseline until 6 h postmeal. Glucose concentrations returned to baseline values 45 min after the CLFP meal and remained so until 5 h postmeal, at which time they increased significantly above baseline. The area under the incremental glucose response curves (AUCs) were calculated from 0 to 6 h postmeal (CLFP: 4.2 ± 2.2 mmol·h/L; PBFP: 6.8 ± 1.5 mmol·h/L; WBFP: 7.1 ± 2.1 mmol·h/L). Because of the highly individual responses, the AUCs did not differ significantly.

Glucose data for the subset of 5 subjects who consumed the NLFP meal in addition to the 3 commercial, extruded pasta meals (CLFP, PBFP, and WBFP) showed a different response pattern (Figure 1B). The NLFP meal resulted in a plasma glucose concentration that was significantly above baseline 30 min and 5 h postmeal. Glucose concentrations after the NLFP meal were significantly different from concentrations after the WBFP meal 6 h postmeal, but were not significantly different from concentrations after the CLFP and PBFP meals. The increase in glucose concentrations 6 h after the 3 extruded pasta meals was ≥7-fold higher than the increase after the NLFP meal. Maximal glucose responses occurred 6 h after both the CLFP and WBFP meals, 4 h after the PBFP meal, and 30 min after the NLFP meal. AUCs were not significantly different (CLFP: 4.4 ± 4.8 mmol·h/L; PBFP: 7.4 ± 2.9 mmol·h/L; WBFP: 9.0 ± 2.9 mmol·h/L; NLFP: 2.8 ± 1.0 mmol·h/L).

Insulin

Plasma insulin (Figure 1C) peaked 30 min (488.5 ± 45.3, 370.7 ± 49.3, and 349.9 ± 39.8 pmol/L for CLFP, PBFP, and WBFP, respectively) after all meals and remained significantly above baseline for 6 h. At 30 min postmeal, insulin was higher after the CLFP meal than after the WBFP ($P < 0.05$) and PBFP (NS) meals. At 1 h postmeal, insulin was significantly higher after the PBFB meal than after either the CLFP or WBFP meal; at 5 h postmeal, insulin was higher after the PBFB meal than after the CLFP meal only. The AUCs for insulin were not significantly different (CLFP: 528.4 ± 54.5 pmol·h/L; PBFP: 655.3 ± 67.6 pmol·h/L; WBFP: 498.2 ± 57.8 pmol·h/L). Because of the apparent biphasic glucose response, AUCs for insulin were calculated for the time periods 0–1 and 2–6 h post-meal. Although there were no significant differences in AUCs for glucose, the AUCs for insulin 0–1 h postmeal were significantly higher after the CLFP than after the WBFP meal and were signi-
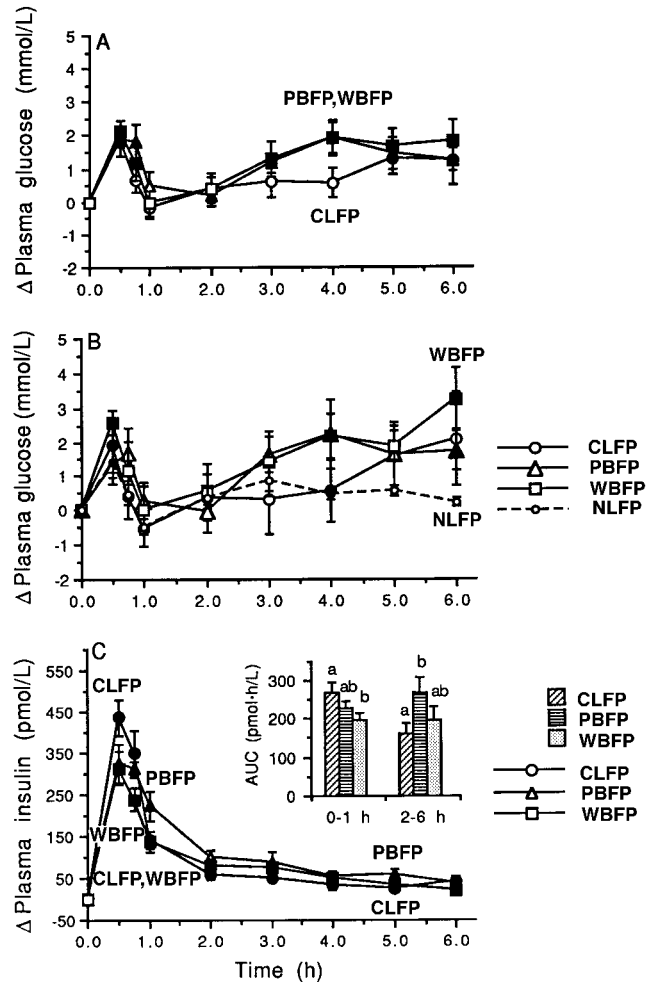

FIGURE 1. Mean (±SEM) changes from baseline in plasma glucose (A) and insulin (C) concentrations in 11 healthy men after consumption of test meals containing high- or low-fiber pasta and in a subset ($n = 5$) of these men (B) after consumption of a test meal containing a noncommercial, low-fiber pasta made with a homestyle pasta maker. Values that are significantly ($P \leq 0.05$) different from baseline are indicated by filled symbols. Meal designations above and below a time point indicate which groups differed significantly. Incremental areas under the curve for insulin are inset as a bar graph. For each time period, different letters indicate significant differences between meals. CLFP, low-fiber wheat pasta; PBFP, naturally high β-glucan–containing pasta; WBFP, β-glu-can–enriched pasta; NLFP, low-fiber wheat pasta made with a noncommercial homestyle pasta maker.

ficantly lower after the CLFP than after the PBFP meal 2–6 h postmeal.

Cholecystokinin

Cholecystokinin increased significantly above baseline after each meal. Maximal mean cholecystokinin responses were as follows: CLFP: 7.7 ± 1.5 pmol/L at 1 h; PBFP: 6.4 ± 0.7 pmol/L at 45 min; WBFP: 6.8 ± 0.8 pmol/L at 30 min (**Figure 2**). Chole-cystokinin concentrations had returned to baseline concentra-tions 3 h after the CLFP meal, whereas concentrations remained significantly above baseline 2 h after the 2 barley-containing meals (PBFP and WBFP). Cholecystokinin returned to baseline 6 h after the WBFP meal. The calculated incremental AUCs were
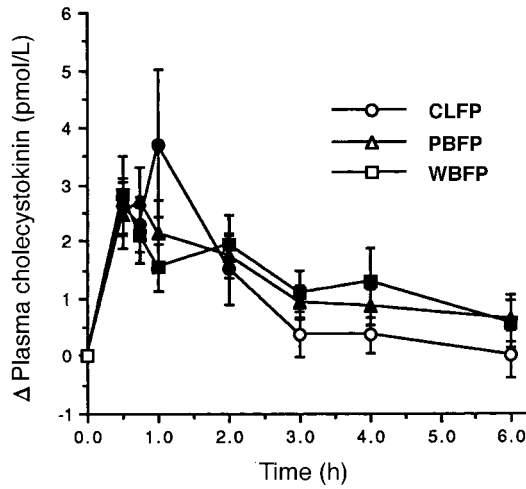
FIGURE 2. Mean (±SEM) changes from baseline in plasma chole-cystokinin concentrations in 11 healthy men after consumption of test meals containing high- or low-fiber pasta. Values that are significantly ($P \leq 0.05$) different from baseline are indicated by filled symbols. CLFP, low-fiber wheat pasta; PBFP, naturally high β-glucan–containing pasta; WBFP, β-glucan–enriched pasta.

not significantly different (CLFP: 6.4 ± 1.5 pmol·h/L; PBFP: 7.5 ± 1.1 pmol·h/L; WBFP: 8.1 ± 1.9 pmol·h/L).

Triacylglycerol

Plasma triacylglycerol concentrations increased significantly from baseline after all meals, but the response was not significantly different among the test-meal groups. Concentrations were significantly greater than baseline values 1, 2, 3, and 4 h after the CLFP meal and 2, 3, and 4 h after the PBFP meal (**Figure 3**). After the CLFP meal, triacylglycerol concentrations were higher 1, 2, 3, and 4 h postmeal. After the PBFP meal, triacylglycerol concentrations were higher 2, 3, and 4 h postmeal. Triacylglycerol concentrations after the WBFP meal were significantly higher than baseline only at 3 h. Maximal incremental responses occurred 3 h after all meals and were 0.3 ± 0.1, 0.4 ± 0.1, and 0.3 ± 0.1 mmol/L for the CLFP, PBFP, and WBFP meals, respectively. The AUCs for the different meals were not significantly different (CLFP: 1.0 ± 0.4 mmol·h/L; PBFP: 1.0 ± 0.2 mmol·h/L; WBFP: 0.7 ± 0.4 mmol·h/L).

Cholesterol

Both barley meals resulted in a significantly lower cholesterol increment at 30 min than did the CLFP meal. The WBFP meal also resulted in a lower incremental response at 4 h than did the CLFP meal. Maximal increments were 0.086 ± 0.062 mmol/L after the CLFP meal, −0.162 ± 0.065 mmol/L after the PBFP meal, and −0.218 ± 0.088 mmol/L after the WBFP meal. The incremental AUCs, although not significantly different among test-meal groups, were positive for the CLFP meal and negative for both of the barley meals (CLFP: 0.15 ± 0.03 mmol·h/L; PBFP: −0.48.0 ± 0.31 mmol·h/L; WBFP: −0.60 ± 0.31 mmol·h/L).

TRL-triacylglycerol and cholesterol

TRL-triacylglycerol concentrations increased significantly from baseline after all meals (**Figure 4**). Triacylglycerol concentrations were still greater than baseline concentrations 4 h after
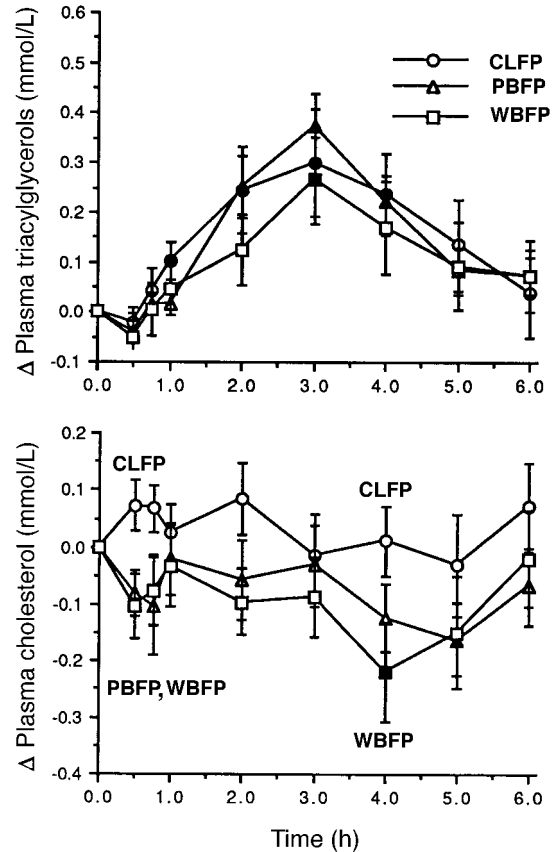

FIGURE 3. Mean (±SEM) changes from baseline in plasma triacyl-glycerol and cholesterol concentrations in 11 healthy men after consumption of test meals containing high- or low-fiber pasta. Values that are significantly ($P \leq 0.05$) different from baseline are indicated by filled symbols. Values that are significantly different from each other at a given time point are indicated by meal designation above and below the line at that time point. CLFP, low-fiber wheat pasta; PBFP, naturally high β-glucan–containing pasta; WBFP, β-glucan–enriched pasta.

both the CLFP and PBFP meals, returning to baseline 6 h post-meal. Concentrations remained above baseline 2 and 3 h after the WBFP meal. There were no significant differences in responses to the meals. Incremental AUCs were not significantly different among test-meal groups (CLFP: 0.90 ± 0.34 mmol·h/L; PBFP: 1.05 ± 0.14 mmol·h/L; WBFP: 0.82 ± 0.36 mmol·h/L). The TRL-cholesterol response was not significantly different among test-meal groups. Cholesterol increased significantly above base-line after the PBFP meal but not after the other 2 meals (Figure 4). The AUCs were not significantly different among test-meal groups (CLFP: 0.13 ± 0.13 mmol·h/L; PBFP: 0.24 ± 0.09 mmol·h/L; WBFP: 0.11 ± 0.18 mmol·h/L).

Apo B-48 and apo B-100

Apo B-48 concentrations increased significantly above base-line at all time points for all meals (**Figure 5**). Peak responses occurred 2, 3, and 4 h after the CLFP, PBFP, and WBFP meals, respectively, and the mean incremental response was highest after the PBFP meal (5.3 ± 0.8 nmol/L). The AUCs for each meal were not significantly different (CLFP: 25.5 ± 5.9 nmol·h/L; PBFP: 20.9 ± 3.2 nmol·h/L; WBFP: 17.4 ± 3.2 nmol·h/L). The increase in apo B-100 concentrations was significantly greater
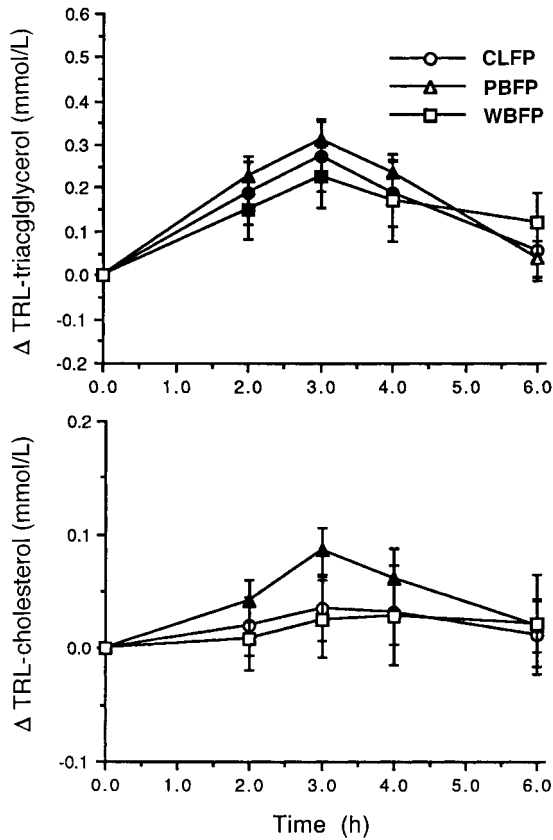
FIGURE 4. Mean (±SEM) changes from baseline in plasma triacylglycerol-rich lipoprotein (TRL) triacylglycerol and cholesterol concentrations in 11 healthy men after consumption of test meals containing high- or low-fiber pasta. Values that are significantly ($P \le 0.05$) different from baseline are indicated by filled symbols. CLFP, low-fiber wheat pasta; PBFP, naturally high β-glucan–containing pasta; WBFP, β-glucan–enriched pasta.
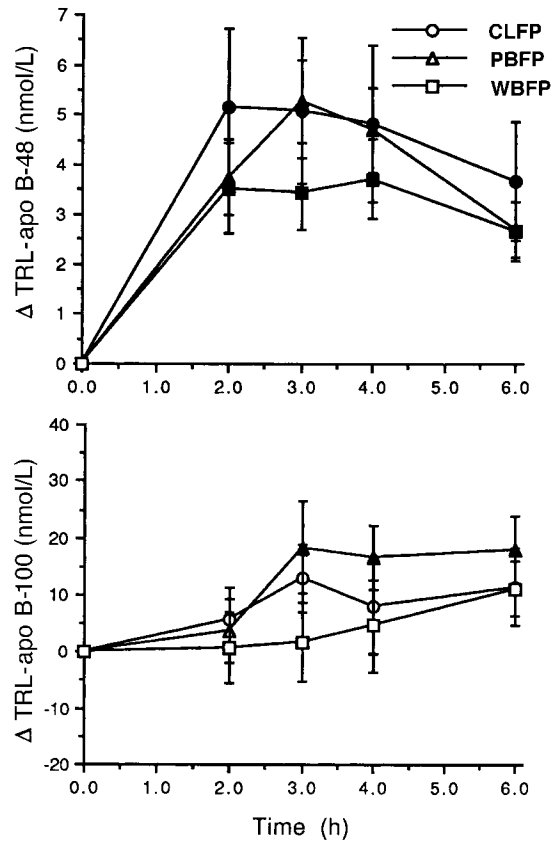
FIGURE 5. Mean (±SEM) changes from baseline in plasma triacylglycerol-rich lipoprotein (TRL) apolipoprotein (apo) B-48 and apo B-100 concentrations in 11 healthy men after consumption of test meals containing high- or low-fiber pasta. Values that are significantly ($P \le 0.05$) different from baseline are indicated by filled symbols. CLFP, low-fiber wheat pasta; PBFP, naturally high β-glucan–containing pasta; WBFP, β-glucan–enriched pasta.

than baseline 3, 4, and 6 h after the PBFP meal and 6 h after the WBFP meal (Figure 5). The AUCs were not significantly different among test-meal groups (CLFP: 68.7 ± 17.4 nmol·h/L; PBFP: 76.7 ± 25.3 nmol·h/L; WBFP: 54.8 ± 20.1 nmol·h/L).

DISCUSSION

In the present study, the postprandial response of healthy subjects to a complete meal that incorporated pasta made from wheat flour or wheat flour plus either barley flour enriched with β-glucan or barley flour from a high β-glucan genotype, was determined. All subjects consumed pastas that were processed by using a commercial method of extrusion. In addition, a subset of subjects was fed an additional meal that contained pasta made from wheat flour that was processed with a noncommercial home pasta maker so that the glucose response to a commercial and noncommercial pasta could be compared. The high-fiber meals, which contained barley flour, did not blunt the overall postprandial glucose response. Although the plasma glucose response did not differ significantly after the pasta-containing meals, the plasma insulin response did differ, indicating that carbohydrate from the meal with β-glucan–enriched pasta (WBFP) was digested and absorbed more slowly than that from the low-fiber meal (CLFP). The peak insulin response 1 h after the CLFP meal

and the AUC for insulin 0–1 h after the CLFP meal were significantly higher than those after the WBFP meal. Several studies have reported differences in the glycemic response to individual foods; however, incorporation of these foods into a meal can obscure differences in the plasma glucose response (29–31) and can stimulate the insulin response because of the release of cholecystokinin (14).

Although the overall glucose response did not differ as a result of pasta type, a second increase in plasma glucose began 2 h after ingestion of the high-β-glucan barley pastas and 4 h after ingestion of the control wheat pasta. Many postprandial studies, especially glycemic studies, measure glucose and other plasma variables for only 2–3 h after a meal and thus miss changes that occur later than this. Cara et al (32) reported a marked increase in serum glucose 3 h after ingestion of a pasta meal in healthy subjects. In the present study, the second peak may have been due to slower digestion of the pasta that was prepared by extrusion. Results from the subgroup of 5 subjects who consumed a homemade pasta meal indicated that a factor inherent to the 3 extruded pastas led to this delayed increase in plasma glucose. Such a delay is most likely explained by slower digestion and absorption of the carbohydrate in extruded pastas. Tests in rats have shown that extrusion processes can affect the structural characteristics of cereal grains and consequently the meta-

bolic response to the product (33). Rice noodles, processed by extrusion, blunted blood glucose response in healthy subjects; however, subjects were only followed for 60 min postmeal, so the extended metabolic response was not known (34). The investigator postulated that the starch in the rice noodles retrograded, making it more difficult to digest. The extruded pastas were more difficult to chew, as reported verbally by subjects, which may have led to larger particle sizes entering the small intestine and slower penetration by the digestive enzymes. In addition, the fiber in the barley-containing pastas may have provided an additional physical interference to starch degradation.

Although the secondary increase in plasma glucose was not associated with a second peak in insulin response, plasma insulin concentrations were elevated above baseline for the 2–6 h period. The lack of a sharp increase may have been due to a slower release of carbohydrate from the extruded pasta-containing meals. Cholecystokinin may have a role in enhancing insulin release (14). Results in rats suggest that the insulin response to cholecystokinin is dose dependent (35); therefore, the increase in cholecystokinin above baseline 3–6 h postmeal may not have been large enough to produce an insulin response. A late postprandial increase in glucose may be advantageous for providing energy in a long-term, sustained activity.

The lack of difference in glycemic responses, despite different insulin concentrations, suggests that this difference in response to the high- and low-fiber pastas may have been due to the relatively low glycemic response to pasta, as reported by several investigators. The glycemic response to various processing conditions of pasta was lower after consumption of spaghetti and linguine than it was after consumption of bread made with the same ingredients, but differed only slightly between the pasta types (36). Järvi et al (37) reported similar results when comparing the glycemic response to a pasta meal with that to a meal containing bread made with pasta ingredients. Peak increases in blood glucose concentrations in the present study (1–2 mmol/L) were similar to those in other studies in healthy subjects after consumption of pasta (36, 38, 39). Thus, the use of pasta as the fiber-supplemented food in the test meal resulted in overall lower increases in glucose after the meal but no differences in plasma glucose concentrations based on the fiber content of the pasta.

In addition to plasma glucose and insulin, we sought to characterize plasma postprandial cholecystokinin responses to pasta meals. The cholecystokinin response to the meals was in general lower than responses reported in the literature and did not differ among the test-meal groups. Few studies have been undertaken to determine plasma cholecystokinin concentrations after a mixed meal with solid foods low in fat. Mössner et al (40) reported that the plasma cholecystokinin response is lower after a solid than after a liquid meal of the same composition, which, in addition to the lower fat content of the diet, may contribute to the lower cholecystokinin concentrations observed in the present study. The few mixed-meal studies that used solid foods reported conflicting results of the effect of fiber. Fifteen grams of pectin did not alter the cholecystokinin response in obese subjects (41). However, their test meal contained only 1046 kJ (250 kcal) and the macronutrient composition was not given, making comparisons with the present study difficult. DiLorenzo et al (41) reported that gastric emptying was delayed and satiety increased by pectin but that the cholecystokinin response was not changed, which led them to suggest that some factor other than cholecystokinin may have been responsible for the effects of fiber (41).

Holt et al (42) studied the effect of cholecystokinin on satiety and reported that the cholecystokinin response was higher when the glycemic impact of food was low. Their studies indicated that a high-fiber cereal with low glycemic and insulinemic indexes had the largest cholecystokinin response, suggesting a direct effect of fiber on plasma cholecystokinin. Mössner et al (40) fed their subjects several different meals and found that a liquid meal high in fiber resulted in higher plasma cholecystokinin concentrations than did a low-fiber, control diet. They also fed their subjects 2 solid meals, 1 that was high in fiber and 1 that included spaghetti. Interestingly, the spaghetti meal produced a larger plasma cholecystokinin response than did the high-fiber meal, suggesting that the response to spaghetti is different from that of other starchy foods and could explain why there were no significant differences in the cholecystokinin response to the different pastas used in the present study.

Although differences in cholecystokinin concentrations were not observed among the meals, the pattern of cholecystokinin response was different; 3 h postmeal the plasma cholecystokinin concentration had returned to baseline after the low-fiber meal but remained significantly elevated after the high-fiber meals. This prolonged elevation in cholecystokinin concentration may reflect the prolonged presence of fat in the small intestine as a result of the slower digestion and absorption of fat after the high-fiber meals. Sustained stimulation of cholecystokinin release by slower lipid absorption has been associated with greater feelings of satiety (15).

Postprandial concentrations of cholesterol and triacylglycerol were determined in addition to hormone response. The type of pasta had no effect: plasma and TRL-triacylglycerol concentrations did not differ significantly among the 3 test-meal groups, but did increase significantly from fasting values after all 3 meals. The increase in TRL-triacylglycerol was associated with a significant increase in apo B-48, which is the apolipoprotein found in intestinally derived TRLs. These increases were observed even though the diet only provided 25% of energy from fat. Data from Dubois et al (43) suggest that meals with < 18% of energy from fat do not evoke an increase in plasma triacylglycerol concentrations. Most postprandial studies in the literature used higher dietary fat intakes, usually 40–50% of energy, to evoke alimentary lipemia (4, 8, 9, 27, 44); however, even low-fat diets will cause alimentary lipemia. The increase in plasma and TRL-triacylglycerols is due to an accumulation of both chylomicron remnants and hepatic VLDLs (27).

The lack of fiber-induced differences in plasma and TRL-triacylglycerols may be related to the low daily fiber intake in the background diet of subjects. Dubois et al (45) reported significantly higher lipemia when a test meal was supplemented with oat bran but only in subjects who consumed a high-fiber background diet for 14 d before the test meal. All previously reported studies that examined the effect of fiber on postprandial lipemia, in single test-meal studies with a design similar to ours, used higher dietary fat intakes than we did, and the results are variable. Redard et al (8) found that guar gum and oat bran added to a test meal resulted in higher lipemia than that from a low-fiber test meal. Gatti et al (9) reported lower triglyceridemia after a test meal containing guar-enriched pasta was eaten. Soybean fiber added to tomato sauce fed with pasta resulted in a slight rise in triacylglycerol compared with a low-fiber and a pea-fiber meal (45). It is likely that different methods of incorporating fiber into the meal as well as differences in the type of dietary fiber and the

amount and type of fat in the test meal contributed to this variability. Overall, these results are consistent with the idea that there are other factors in addition to the fiber content of the meals that contribute to the triglyceridemic response. Further research is needed to define the specific role of fiber and to determine the interaction between dietary fat and fiber so that recommended intakes of these 2 dietary components can be clarified.

Although no differences in triacylglycerol responses were observed, postprandial cholesterol did differ among the dietary treatment groups. Chronic fiber consumption has been shown to lower total plasma cholesterol (4–7, 9). Our laboratory has hypothesized that sources of viscous fiber may alter plasma cholesterol via a slowing of the digestion and absorption of lipid and subsequent modification in the pattern of alimentary lipemia or composition of postprandial lipoproteins. Differences in plasma cholesterol responses to CLFP and both the PBFP and WBFP meals provide support for this hypothesis. Our findings suggest that viscous polysaccharides are likely to be most effective in lowering plasma cholesterol concentrations when fed in conjunction with low-fat meals. These results are in contrast with those of previous studies that reported an increase or no change in plasma cholesterol after a fiber-supplemented meal (8, 46). However, these studies supplemented high-fat meals with fiber rather than incorporating fiber-enriched foods into a low-fat meal. The significant differences in plasma cholesterol concentrations seen in the present study in response to the different diets appeared to be related to subtle shifts in the plasma triacylglycerol response after a meal. The peak in plasma triacylglycerol occurred 3 h after the meals were consumed, whereas the lowest plasma cholesterol concentration after consumption of the WBFP and PBFP meals occurred later (4 and 5 h, respectively). This shift suggests that the postprandial elevation of triacylglycerol stimulated cholesterol transfer into TRLs and subsequent clearance from the plasma, ie, reverse cholesterol transfer. Cholesterol transferred to intestinal lipoproteins is cleared primarily by the liver, enabling reverse cholesterol transport. Fiber-rich barley fractions have also been shown to increase cholesterol excretion from the intestine (47). Thus, the ability of barley-enriched meals to favor reverse cholesterol transport as well as to reduce cholesterol absorption contributes to its efficacy as a cholesterol-lowering dietary factor.

Although the alimentary responses to the 2 barley-containing meals were generally similar, they did not always differ significantly in the same manner from the control. Both barley-containing meals provided similar amounts of total dietary fiber and β-glucans; thus, the differences in the pattern of response were likely due to factors other than the fiber content of the meal. The types of barley in the 2 meals differed in that one was naturally high in β-glucans and the other was enriched with β-glucans. In addition, the pastas may have had different amylose contents. Prowashonupana barley is a cultivar that is naturally higher in β-glucans and typically lower in amylose than other barley varieties; the content of β-glucans in Waxbar barley is made higher by milling and sifting repeatedly to enrich the flour (19). We were not able to measure the amylose content of the pasta used in the present study; however, previous studies indicated that a high amylose content is associated with reduced postprandial glycemia, which is consistent with the lower insulin response to WBFP 0–1 h postmeal (48–50). In the present study, it was impossible to determine whether the amylose content of the pasta or the form of β-glucan enrichment of the pasta was

responsible for the different responses to the 2 barley types. Although both types of barley used clearly contributed to an increase in fiber intakes, specifically β-glucan intakes, the Waxbar barley flour appeared to have a greater effect on both glycemic and lipemic responses.

The postprandial glucose, insulin, and cholecystokinin responses of subjects in the present study after consumption of barley-containing pasta, either naturally high in or enriched with β-glucans, support the hypothesis that viscous polysaccharides in the diet slow the rate of carbohydrate and lipid digestion and absorption. The changes in blood cholesterol after a low-fat meal support the hypothesis that viscous polysaccharides lower plasma cholesterol, in part, by facilitating reverse cholesterol transport.

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