Effect of the glycemic index and content of indigestible carbohydrates of cereal-based breakfast meals on glucose tolerance at lunch in healthy subjects[1–3]

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ABSTRACT

Background: Diets with a low glycemic index (GI) have been shown to improve glucose tolerance in both healthy and diabetic subjects. Two potential mechanisms are discussed in relation to long-term metabolic effects: a decreased demand for insulin in the postprandial phase and formation of short-chain fatty acids from fermentation of indigestible carbohydrates in the colon.

Objective: The objective was to study the effect of the GI and the indigestible carbohydrate—resistant starch (RS) and dietary fiber (DF)—content of cereal-based breakfasts on glucose tolerance at a second meal (lunch) in healthy subjects.

Design: The effects of 7 test breakfasts with known GIs (GI: 52–99) and RS + DF contents (2–36 g) were evaluated. White-wheat bread was used as a reference breakfast (high GI, low RS + DF content). Glucose and insulin responses after the second meal were measured in healthy subjects. In addition, the satiating capacity of 4 of the 7 test breakfasts was estimated before and during the second meal.

Results: Two of the 4 low-GI breakfasts improved glucose tolerance at the second meal. Only these 2 breakfasts were capable of postponing the in-between-meal fasting state. There was no measurable effect of fermentable carbohydrates on glucose tolerance at the second meal. The highest satiety score was associated with the barley breakfast that had a low GI and a high RS + DF content.

Conclusions: Glucose tolerance can improve in a single day. Slow absorption and digestion of starch from the breakfast meal, but not the content of indigestible carbohydrates in the breakfast meal, improved glucose tolerance at the second meal (lunch). *Am J Clin Nutr* 1999;69:647–55.

KEY WORDS Barley genotypes, spaghetti, acetic acid, starch, glycemic index, insulinemic index, second-meal tolerance, dietary fiber, resistant starch, satiety, glucose tolerance, humans

INTRODUCTION

Any dietary intervention capable of lowering the insulin demand, improving insulin sensitivity, or both will likely reduce the incidence of disorders related to insulin resistance (eg, diabetes and dyslipidemia). Accumulating data suggest that a diet characterized by a low glycemic index (GI) may be capable of such. In 2 studies published recently, it was shown that a high-GI diet is associated with an increased risk of type 2 diabetes in both sexes (1, 2).

Several physiologic mechanisms may be responsible for the extended metabolic effects of a diet characterized by low-GI foods. A key event is probably the improved insulin economy in the postprandial phase. Thus, the elevated insulin secretion associated with a high-GI meal may increase peripheral glucose uptake to such an extent that blood glucose concentrations are lower than fasting concentrations (3). To compensate for the low blood glucose concentrations, fatty acids are released, which results in relative insulin resistance. On the contrary, a prolonged digestive phase, as occurs after a low-GI meal, will suppress the release of hepatic fatty acids for a longer time. This phenomenon might explain the improved glucose tolerance seen with lunch meals when preceded by a low-GI breakfast (ie, the so-called second-meal effect) (4–7).

Besides the favorable effects on glucose metabolism related to the slow release of starch in food, a high resistant starch (RS) concentration in the diet—which is frequently associated with low-GI foods—may also improve glucose and lipid metabolism because the addition of RS to the diet increases the total amount of indigestible carbohydrates in the diet and thus enhances the formation of short-chain fatty acids (SCFAs) (eg, acetic, propionic, and butyric acids) during fermentation in the colon (8).

The aim of this study was to determine the effect of the GI and the indigestible carbohydrate—RS and dietary fiber (DF)—content of a breakfast meal on glucose tolerance at a second meal (lunch) served 4 h after breakfast.

SUBJECTS AND METHODS

Subjects

Ten healthy volunteers, 6 women and 4 men aged 22–57 y, with normal body mass indexes ($\bar{x}$: 21.6 ± 1.5, in kg/m^2) partic-

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TABLE 1
Composition of the breakfast meals on a wet weight basis[1]

Breakfast	Bread	Barley flakes	Pasta[2]	Vinegar[3]	Potato starch	Cheese	Butter	Olive oil	Milk	Water	Coffee or tea
	g	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*mL*	*mL*	*mL*
Series 1											
WWB	123	—	—	—	—	27	7	—	100	150	150
HAB	159	—	—	—	—	20	7	—	100	150	150
HAB-longp	212	—	—	—	—	15	7	—	100	150	150
HAB-long	164	—	—	—	—	19	7	—	100	150	150
HAB-long + BF	115	62	—	—	—	—	5	—	100	150	150
Series 2											
WWB	122	—	—	—	—	23	—	8	—	250	150
WWB + raw potato starch	122	—	—	—	17	23	—	8	—	250	150
WWB + vinegar	122	—	—	20	—	23	—	8	—	250	150
Spaghetti	—	—	190	—	—	20	—	8	—	250	150

[1] WWB, white-wheat bread (reference meal); HAB, high-amylose barley bread baked under ordinary conditions; HAB-long, HAB bread baked for a long time at a low temperature; HAB-long + BF, HAB-long bread and barley flakes; HAB-longp, HAB-long bread made with preboiled flour.
[2] 74 g dried spaghetti.
[3] A vinaigrette sauce made from vinegar, water (20 g), and olive oil.

ipated in the study. None of the subjects were taking medication. The Ethics Committee of the Faculty of Medicine, Lund University, Sweden, approved the study protocol.

Methods

The effects of 7 cereal-based test breakfasts and a white-wheat bread (WWB) reference breakfast were evaluated and glucose and insulin responses after the second meal were measured in healthy subjects. In the first series of experiments, 4 barley-based test breakfasts were used. The differences in GIs (GI: 60–99) and RS + DF contents (2–36 g) of the breakfast meals were achieved by selecting barley genotypes containing different amounts of amylose and β-glucan, respectively. In the second series of experiments, the differences in GIs (GI: 52–92) and RS + DF contents (2–12 g) of the breakfast meals were achieved by using WWB and spaghetti meals.

Series 1

Five breakfast meals were fed to the subjects. Four of the meals were composed primarily of 3 high-amylose barley (HAB) bread varieties and the fifth meal was the reference WWB meal (**Table 1**). The barley breads contained 70% high-amylose whole-meal barley flour and 30% white-wheat flour (flour basis). The white-wheat flour was bought locally (Kungsörnen, Jämа, Sweden) and the high-amylose barley flour (Glacier; 42% amylose) was provided by Swalöf-Weibull AB (Svalöv, Sweden). The barley breads were baked, cooled, and cut into slices. The crusts were removed and the slices were wrapped in aluminum foil, put into plastic bags, and frozen until used. The day before being used, the bread slices were removed from the freezer and thawed at ambient temperature overnight. The barley-based and WWB reference breakfasts were served with butter and cheese (10% fat, wet wt) to balance the fat and protein contents of the meals. In addition, 100 mL low-fat milk (0.5% fat) and 150 mL water were served with each meal. All test meals contained 50.0 g available starch [determined according to Holm et al (9)], 15.3 g protein, and 9.6 g fat and provided 1465 kJ. Each breakfast meal was also served with 150 mL coffee or tea.

HAB

Seventy grams yeast was mixed with 600 g water (20°C), to which 200 g white-wheat flour, 450 g whole-meal barley flour, and 5 g salt were added. The dough was formed into 2 loaves, put into aluminum pouches, and proofed for 2 h. The bread was baked under ordinary baking conditions (45 min at 200°C).

HAB-long

The same ingredients as for the HAB bread were used, but the bread was proofed and then baked in pouches covered with aluminum foil at "pumpernickel" conditions, ie, for a long time (20 h) at a low temperature (120°C).

HAB-longp

Water (780 g) and 260 g whole-meal barley flour were preboiled for 2.5 min and put into a refrigerator to cool. Seventy grams yeast was mixed with 100 g water (20°C), to which 200 g white-wheat flour, 190 g whole-meal barley flour, 5 g salt, and the cooled, preboiled barley and water mixture were added. The bread was then proofed and baked in pouches in the same way as for the HAB-long bread.

HAB-long + BF

Seventy percent of the starch (35 g) in this bread was the same as for the HAB-long bread and 30% (15 g) was barley flakes made from a β-glucan–rich barley genotype (Prowashonupana, 17.5% β-glucans by dry wt; Con Agra, Omaha). The barley was processed as follows: the grains were soaked in cold water until soft and then flaked between rolls to a thickness of 0.5 mm in a full-scale plant. The barley flakes were not heat treated.

WWB

A standardized white-wheat reference bread was mixed, kneaded, fermented, and baked in 4 steps in a home baking machine (Elektro Helios BA 10, Sanyo, Tokyo) as described previously (10). The bread was made from 300 g white-wheat flour (Kungsörnen), 200 g water, 3 g dry yeast, 3 g salt, and 3 g monoacylglycerols.

Series 2

Three test breakfast meals and a WWB reference breakfast were served with cheese and olive oil and 150 mL coffee or tea (Table 1). In addition, 250 mL water was provided with each meal. All test meals contained 50.0 g starch, 15.3 g protein, and 12.0 g fat and provided 1554 kJ.

WWB + vinegar

A vinaigrette sauce made from vinegar (Spice Island, Specialty Brands Inc, San Francisco), water, and olive oil (Filippo Berio, Lucca, Italy) was served with the WWB.

WWB + raw potato starch

Native potato starch (Lyckeby Stärkelsen, Karlshamn, Sweden) was mixed with olive oil and used as a spread on the WWB.

Spaghetti

The spaghetti (Kungsörnen) was made from 100% durum wheat flour with added monoacylglycerols and dried at a high temperature after being mixed and formed with a pasta extruder. The spaghetti was boiled for 12 min in 1 L water (containing 1 g NaCl) before being served.

WWB

WWB was served as the reference meal.

Chemical analysis of breakfast products

A portion of each bread and the boiled spaghetti was dried and milled (Cyclotec, Tecator, Sweden) before analysis. The products, including the barley flakes, were analyzed for starch as described previously (11). Total starch was determined in the same way, after prior solubilization in 2 mol KOH/L (12). Protein (Kjeldahl analysis) and fat (13) were also determined. Total DF was analyzed gravimetrically according to the method of Asp et al (14), and values were corrected for the remaining starch. The in vitro amount of RS was determined with a recently developed method based on chewing and enzyme incubation at physiologic conditions (15).

Acute and second-meal studies in healthy subjects

GIs and insulinemic indexes of products included in the test breakfasts

The GIs and insulinemic indexes (IIs) of the HAB-longp, WWB + raw potato starch, and spaghetti meals were determined after the test meals had been fed to the subjects. The WWB meal and the test meals were fed to the subjects in random order after an overnight fast, ≈1 wk apart. The meals were given at the same time in the morning and were eaten within 12–15 min. The GI and II of the HAB-long + BF meal were determined from the individual indexes of the HAB-long bread [GI: 71; II: 89 (16)] and the barley flakes (GI: 40; II: 37; unpublished observations). The GIs and IIs of the remaining bread meals in series 1 (16) and series 2 (17) were determined previously.

Blood analyses in the acute study

Capillary blood samples were taken immediately before (0 min) and 30, 45, 70, 95, 120, and 180 min after the test breakfast. The blood samples (50 μL) were analyzed for glucose concentration with a glucose oxidase-peroxidase reagent. Capillary serum insulin was determined in blood samples (500 μL) taken before (0 min) the test meal and 30, 45, 95, and 120 min after the second meal. Serum insulin was determined with an enzyme-linked immunoassay kit (Boehringer Mannheim, Mannheim, Germany). GIs and IIs were calculated from the 95-min incremental postprandial blood glucose and insulin areas under curves, with WWB as the reference (GI and II: 100).

Second-meal study

Four hours after the test and reference breakfast meals in series 1 and 2, the subjects were served a second meal—a standardized high-GI lunch. This meal consisted of 100 g commercially fried and deep-frozen meatballs (ICA, Handlarna, Sweden), mashed potatoes (instant powder; Felix, Eslöv, Sweden), and 60 g canned sweet corn (Erasco, Lübeck, Germany). The meatballs were heated in a microwave oven for 2.5 min at 460 W. The instant potato powder was reconstituted with 250 mL boiling water before being served. In addition, 250 mL water and 150 mL coffee or tea were served with each meal.

Blood analyses in the second-meal study

Capillary blood samples were taken before the breakfast meal to determine fasting blood glucose and insulin concentrations. In addition, blood samples were taken immediately before the second meal (0 min, ie, 4 h after breakfast) and 30, 45, 70, 95, 120, and 180 min after the second meal for glucose determination. Capillary serum insulin was determined before lunch (0 min) and 30, 45, 95, and 120 min after the lunch.

Satiety scores

For the series 1 experiments (barley-based meals), satiety was estimated immediately before (0 min, ie, 4 h after breakfast) and 15, 45, 95, 120, and 180 min after the second meal according to the method of Haber et al (18) on the basis of a scoring system with grades from −10 (extreme hunger) to 10 (extreme satiety).

Statistical methods

The results are expressed as means ± SEMs and the statistical significance of differences was assessed by the Wilcoxon matched-pairs signed-rank test followed by a Bonferroni adjustment. The SPSS/PC+ advanced statistics program (version 2.0; SPSS Inc, Chicago) was used. A value of $P < 0.05$ was considered significant.

RESULTS

RS and DF contents of the test breakfasts

The HAB-long + BF meal had a high RS + DF content (36 g wet wt) (**Table 2**). The RS + DF content of the HAB, HAB-long, and HAB-longp meals was intermediate (11–19 g), whereas the RS + DF content of the reference WWB meal was low (2 g). Raw potato starch contributed a high amount of RS to the WWB + raw potato starch meal, yielding an intermediate total RS + DF content (12 g wet wt). In contrast, the WWB + vinegar, spaghetti, and WWB meals had low RS + DF contents (2 g).

Glycemic and insulinemic indexes of the test breakfasts

The GIs and IIs of all the test breakfasts are given in Table 2. The GI and II were 82 and 81, respectively, for the HAB-longp meal, which were not significantly different from those of the WWB reference meal (Table 2). The HAB meal had high indexes, whereas the GI of the HAB-long meal was significantly lower than that of the WWB (16). The II for the HAB-long meal, however, was not significantly different from that of the WWB meal (16). The GI and II of the HAB-long + BF meal were low. The GI and II of the WWB + raw potato starch meal and the WWB reference meal were the same, 92. In contrast, the indexes for the spaghetti meal (GI: 52; II: 42) and the WWB + vinegar meal were low (17).

TABLE 2
Nutrient content (wet weight basis), glycemic (GI) and insulinemic (II) indexes, and resistant starch and dietary fiber (RS + DF) contents of the breakfast meals[1]

Breakfast	Starch	Protein	Fat	RS	DF[2]	GI	II	RS + DF
	g	*g*	*g*	*g*	*g*	*%*	*%*	*g*
Series 1								
WWB	50.0	15.3	9.6	0.1	2	100 (high)	100	2.1 (low)
HAB	50.0	15.3	9.6	1.4	10	99 (high)[3]	113[3]	11.4 (intermediate)
HAB-longp	50.0	15.3	9.6	6.8	12	82.5 ± 9.8 (high)[4]	80.8 ± 7.7	18.8 (intermediate)
HAB-long	50.0	15.3	9.6	5.1	11	71 (low)[5,6]	89[3]	16.1 (intermediate)
HAB-long + BF	50.0	15.3	9.6	11.2	25	60 (low)[7]	70[7]	36.2 (high)
Series 2								
WWB	50.0	15.3	12.0	0.1	2	100 (high)	100	2.1 (low)
WWB + raw potato starch	50.0	15.3	12.0	9.7	2	91.8 ± 15.7 (high)	91.6 ± 13.0	11.7 (intermediate)
WWB + vinegar	50.0	15.3	12.0	0.1	2	64 (low)[6,8]	65[6,8]	2.1 (low)
Spaghetti	50.0	15.3	12.0	0.2	2	52.1 ± 10.6 (low)[6]	42.3 ± 8.0[6]	2.2 (low)

[1] WWB, white-wheat bread (reference meal); HAB, high-amylose barley bread baked under ordinary conditions; HAB-long, HAB bread baked for a long time at a low temperature; HAB-long + BF, HAB-long bread and barley flakes; HAB-longp, HAB-long bread made with preboiled flour.
[2] Analyzed according to the method of Asp et al (14) and corrected for starch remnants in the DF fraction.
[3] Reference 16.
[4] $\bar{x}$ ± SEM.
[5] Reference 16.
[6] Significantly different from WWB, $P < 0.05$ (Wilcoxon matched-pairs signed-rank test).
[7] Calculated from the individual indexes of HAB-long and BF (GI: 40; II: 37; unpublished observations).
[8] Reference 17.

Glucose and insulin responses after the second-meal study

Blood glucose concentrations determined immediately before and after the second meal (lunch) in series 1 and 2 are shown in **Figures 1** and **2**, respectively. In series 1, the blood glucose concentration just before the second meal was significantly higher after the HAB-long + BF breakfast than after the WWB breakfast (Figure 1 and **Table 3)**. In contrast, blood glucose concentrations after the HAB-long + BF breakfast 30 and 70 min after the second meal were significantly lower than after the WWB breakfast. Also, blood glucose (Table 3) and insulin (**Table 4**) concentrations after the HAB-longp breakfast, 45 min after the second meal, were significantly lower than those after the WWB breakfast. No significant differences in insulin concentrations were observed after the other test breakfasts when determined at any time point after the second meal.

In series 2, there were no significant differences in blood glucose and insulin responses to the second meal after the WWB, WWB + raw potato starch, or WWB + vinegar breakfasts (Figure 2, Tables 3 and 4). In contrast, significantly lower glucose (45–70 min after the second meal) and insulin (0–45 min after the second meal) concentrations were observed after the spaghetti than after the WWB breakfast. Similar to the response seen after the HAB-long + BF breakfast in series 1, the blood glucose concentration

TABLE 3
Blood glucose concentrations in healthy subjects immediately before (ie, 4 h after breakfast) and after the standardized lunch meal, preceded by different cereal-based breakfasts[1]

		Glucose concentration						
Breakfast	Fasting concentration	0 min (4 h)	30 min	45 min	70 min	95 min	120 min	180 min (7 h)
	mmol/L	*mmol/L*						
Series 1								
WWB	4.6 ± 0.1^{a}	4.4 ± 0.0^{a}	7.1 ± 0.2^{a,b}	7.0 ± 0.4^{a}	5.9 ± 0.3^{a}	4.9 ± 0.2^{a}	4.6 ± 0.1^{a,b}	4.3 ± 0.1^{a,b}
HAB	4.7 ± 0.1^{a}	4.5 ± 0.1^{a,b}	7.2 ± 0.3^{a}	6.6 ± 0.5^{a,b}	5.6 ± 0.3^{a,b}	4.8 ± 0.1^{a}	4.5 ± 0.1^{a,b}	4.3 ± 0.1^{b}
HAB-longp	4.7 ± 0.1^{a}	4.5 ± 0.1^{a}	7.0 ± 0.3^{b}	6.5 ± 0.4^{b}	5.6 ± 0.3^{a,b}	4.8 ± 0.2^{a}	4.4 ± 0.1^{a}	4.3 ± 0.1^{a,b}
HAB-long	4.6 ± 0.2^{a}	4.5 ± 0.1^{a,b}	7.0 ± 0.4^{a,b,c}	6.7 ± 0.5^{a,b}	5.4 ± 0.3^{a,b}	4.6 ± 0.1^{a}	4.6 ± 0.1^{a,b}	4.4 ± 0.1^{a,b}
HAB-long + BF	4.6 ± 0.1^{a}	4.7 ± 0.1^{b}	6.6 ± 0.2^{c}	6.4 ± 0.4^{a,b}	5.3 ± 0.2^{b}	4.8 ± 0.1^{a}	4.8 ± 0.2^{b}	4.6 ± 0.1^{c}
Series 2								
WWB	4.4 ± 0.1^{a}	4.4 ± 0.1^{a}	7.4 ± 0.3^{a}	7.2 ± 0.4^{a}	5.9 ± 0.3^{a}	4.9 ± 0.2^{a}	4.4 ± 0.1^{a}	4.3 ± 0.1^{a}
WWB + raw potato starch	4.5 ± 0.1^{a}	4.3 ± 0.1^{a}	7.3 ± 0.3^{a}	7.3 ± 0.4^{a}	5.7 ± 0.3^{a}	4.7 ± 0.2^{a}	4.3 ± 0.1^{a}	4.2 ± 0.1^{a}
WWB + vinegar	4.5 ± 0.1^{a}	4.4 ± 0.1^{a}	7.2 ± 0.2^{a}	6.9 ± 0.4^{a}	5.3 ± 0.2^{a,b}	4.8 ± 0.2^{a}	4.5 ± 0.1^{a}	4.3 ± 0.1^{a}
Spaghetti	4.5 ± 0.1^{a}	4.8 ± 0.1^{b}	7.2 ± 0.2^{a}	6.1 ± 0.3^{b}	5.0 ± 0.2^{b}	4.6 ± 0.2^{a}	4.5 ± 0.2^{a}	4.5 ± 0.1^{a}

[1] $\bar{x}$ ± SEM; n = 10. WWB, white-wheat bread (reference meal); HAB, high-amylose barley bread baked under ordinary conditions; HAB-long, HAB bread baked for a long time at a low temperature; HAB-long + BF, HAB-long bread and barley flakes; HAB-longp, HAB-long bread made with preboiled flour. Values within the same series and column with different superscript letters are significantly different, $P < 0.05$ (Wilcoxon matched-pairs signed-rank test followed by Bonferroni adjustment).

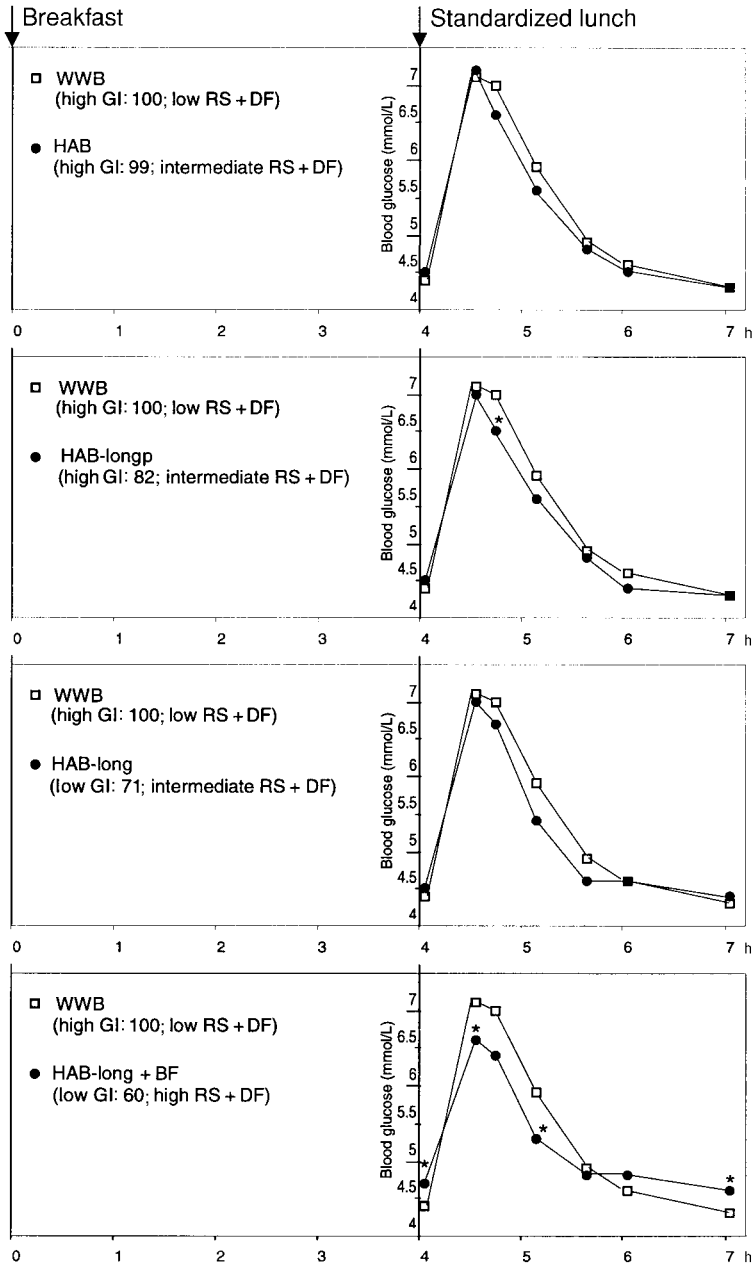

FIGURE 1. Mean blood glucose concentrations in healthy subjects after the second meal (standardized lunch), which was preceded by breakfast meals with different glycemic indexes (GIs) and resistant starch and dietary fiber (RS + DF) contents: white-wheat bread (WWB; reference meal), high-amylose barley (HAB) bread baked under normal conditions, HAB bread baked for a long time at a low temperature (HAB-long), HAB-long bread made with preboiled flour (HAB-longp), and HAB-long bread and barley flakes (HAB-long + BF). *Significantly different from WWB, $P < 0.05$ (Wilcoxon matched-pairs signed-rank test followed by Bonferroni adjustment).

just before lunch was significantly higher after the spaghetti than after the WWB breakfast.

Satiety

The satiety score was higher after the HAB-long + BF and HAB-longp breakfasts than after the WWB breakfast when estimated just before the second meal was served (**Table 5**). A higher satiety score was noted after the HAB-long + BF breakfast than after the WWB breakfast 45–95 min after the second meal. Satiety was also significantly higher after the HAB-long meal than after the WWB meal when estimated 45 min after the second meal. The same was true for the HAB-longp meal 95 min after the second meal.

DISCUSSION

The results of the present study add evidence that a low-GI breakfast may improve glucose tolerance at a subsequent lunch meal in healthy subjects. Consequently, the HAB-long + BF breakfast, which was characterized by a GI of 60 (low) and an II of 70 (low) improved insulin economy at lunch. Similarly, the

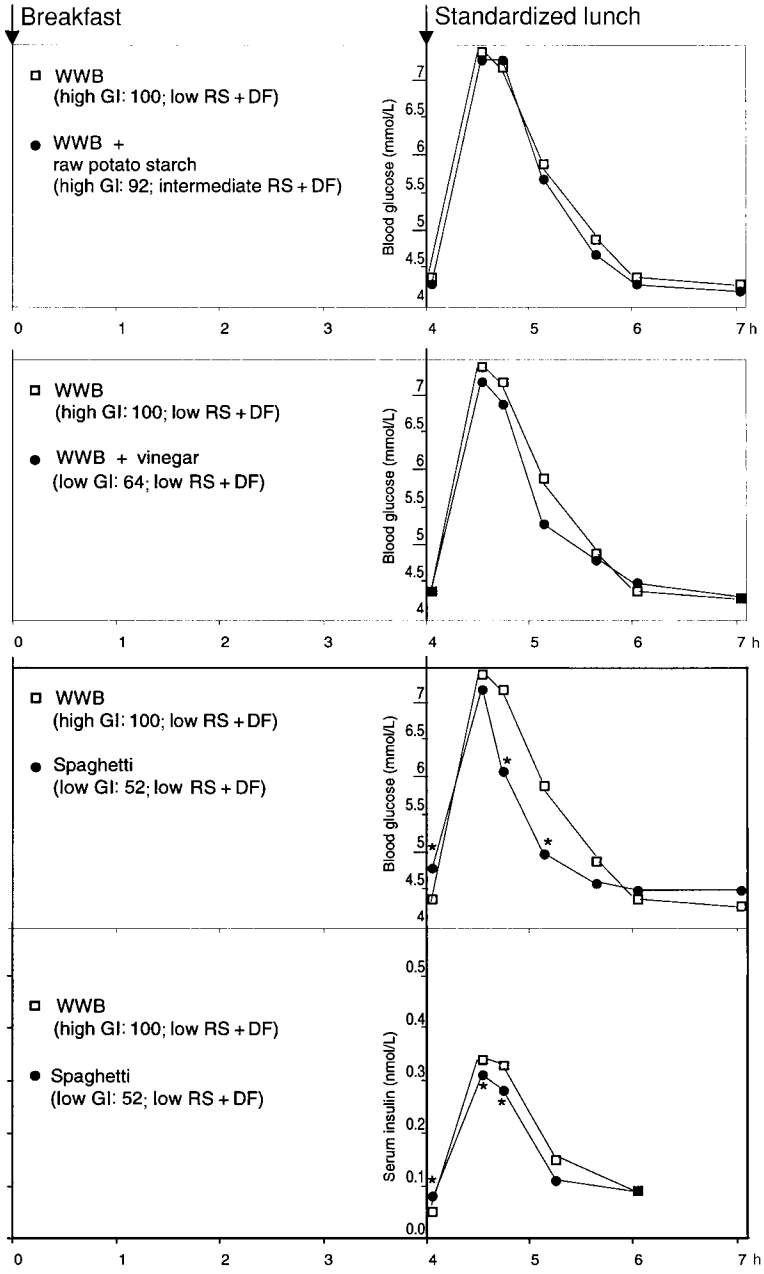

FIGURE 2. Mean blood glucose and insulin concentrations in healthy subjects after the second meal (standardized lunch), which was preceded by breakfast meals with different glycemic indexes (GIs) and resistant starch and dietary fiber (RS + DF) contents: white-wheat bread (WWB; reference meal), WWB + raw potato starch, WWB + vinegar, and spaghetti. *Significantly different from WWB, $P < 0.05$ (Wilcoxon matched-pairs signed-rank test followed by Bonferroni adjustment).

spaghetti breakfast, which had a GI of 52 (low) and an II of 42 (low), improved not only glycemia but also the insulin response after the standardized second meal. In addition, the in-between-meal fasting state was postponed after the HAB-long + BF and spaghetti breakfasts, as judged from a net increment in glucose that was greater 4 h after breakfast than was the glucose concentration after the WWB breakfast, ie, just before the second meal was consumed. Surprisingly, the HAB-long and WWB + vinegar breakfasts did not alter glucose tolerance significantly at lunch, despite their comparatively low GIs—71 and 64, respectively. However, unlike the HAB-long + BF and the spaghetti breakfasts, no net increment in blood glucose was observed 4 h after the breakfast meals. Consequently, the avoidance of the in-between-meal fasting state might be an important determinant of improvements in 4-h second-meal glucose tolerance.

A second-meal effect in the form of a reduced glucose response to a standardized lunch was also shown after a low-GI lentil breakfast (5). The mechanism may be the slow release of starch in the small intestine, as judged from experiments using an increased meal frequency to mimic the small intestinal events

TABLE 4
Insulin concentrations in healthy subjects immediately before (ie, 4 h after breakfast) and after the standardized lunch meal, preceded by different cereal-based breakfasts[1]

Breakfast	Fasting concentration	Insulin concentration				
		0 min (4 h)	30 min	45 min	95 min	120 min (6 h)
	nmol/L			*nmol/L*		
Series 1						
WWB	0.06 ± 0.01[a]	0.05 ± 0.01[a]	0.34 ± 0.03[a]	0.33 ± 0.07[a]	0.15 ± 0.04[a]	0.09 ± 0.02[a]
HAB	0.07 ± 0.01[a]	0.07 ± 0.01[b]	0.40 ± 0.07[a]	0.34 ± 0.08[a,b]	0.13 ± 0.02[a]	0.09 ± 0.02[a]
HAB-longp	0.07 ± 0.01[a]	0.06 ± 0.01[b]	0.38 ± 0.06[a]	0.29 ± 0.07[b]	0.13 ± 0.02[a]	0.10 ± 0.02[a]
HAB-long	0.07 ± 0.01[a]	0.07 ± 0.01[b]	0.34 ± 0.05[a]	0.30 ± 0.05[a,b]	0.11 ± 0.02[a]	0.09 ± 0.02[a]
HAB-long + BF	0.07 ± 0.01[a]	0.07 ± 0.01[b]	0.30 ± 0.04[a]	0.30 ± 0.05[a,b]	0.13 ± 0.01[a]	0.11 ± 0.01[a]
Series 2						
WWB	0.06 ± 0.00[a]	0.05 ± 0.00[a]	0.41 ± 0.06[a,b]	0.38 ± 0.07[a]	0.14 ± 0.02[a]	0.08 ± 0.02[a]
WWB + raw potato starch	0.06 ± 0.01[a]	0.06 ± 0.01[a,b]	0.40 ± 0.05[a,b]	0.35 ± 0.04[a,b]	0.13 ± 0.02[a]	0.08 ± 0.01[a]
WWB + vinegar	0.07 ± 0.00[a]	0.06 ± 0.01[b]	0.37 ± 0.04[a,b,c]	0.33 ± 0.05[a,b]	0.10 ± 0.02[a]	0.09 ± 0.02[a]
Spaghetti	0.06 ± 0.00[a]	0.08 ± 0.01[b]	0.31 ± 0.02[c]	0.28 ± 0.04[b]	0.11 ± 0.02[a]	0.09 ± 0.01[a]

[1] $\bar{x}$ ± SEM; n = 10. WWB, white-wheat bread (reference meal); HAB, high-amylose barley bread baked under ordinary conditions; HAB-long, HAB bread baked for a long time at a low temperature; HAB-long + BF, HAB-long bread and barley flakes; HAB-longp, HAB-long bread made with preboiled flour. Values within the same series and column with different superscript letters are significantly different, $P < 0.05$ (Wilcoxon matched-pairs signed-rank test followed by Bonferroni adjustment).

after ingestion of "lente" foods. Thus, when healthy subjects consumed a 50-g glucose drink over 180 min (sipping) as opposed to over 5 min (bolus), there was a dramatic reduction in the 4-h area under the curve for insulin (19). Interestingly, an intravenous glucose tolerance test performed 4 h after the drink was finished indicated a more rapid decline in blood glucose after sipping. Furthermore, in a study in healthy subjects consuming liquid diets, a decrease in serum cholesterol was seen in a single day when many small meals were eaten rather than one big meal (20). These findings support a mechanism related to a slow rate of glucose delivery to the blood. Secondary to a prolonged digestive phase is a prolonged suppression of plasma fatty acids, which has been shown to be associated with improved insulin action (7).

In the present study, attempts were made to evaluate separately the mechanisms discussed in relation to second-meal effects. Thus, the potential effect of SCFAs produced during colonic fermentation of indigestible carbohydrates must be considered. However, despite considerable concentrations of RS and DF, particularly in the high-GI HAB-longp meal (19 g), the content of fermentable carbohydrates, per se, did not influence glucose tolerance after the second meal. Similarly, the lack of effect after the high-GI WWB + raw potato starch test meal (10 g RS) supports this finding. These observations agree with those of Giacco et al (21), who showed no effect on second-meal glucose tolerance after a breakfast high in RS (16 g). Moreover, in the present study, the most prominent effect on second-meal glucose tolerance was noted after the spaghetti breakfast, which contained a low amount of indigestible carbohydrates (2 g).

The fast rate at which indigestible carbohydrates are metabolized by the colonic microflora is likely to affect the time needed to reach physiologically active SCFA concentrations in the blood. Thus, whereas breath-hydrogen excretion peaks as soon as 1 h after lactulose ingestion (5), certain RS fractions (eg, raw potato starch) appear to raise breath hydrogen more slowly (9–11 h) (22). However, few studies are available with realistic composite foods containing natural sources of RS and DF. In a study by Thorburn et al (8) in healthy subjects, it was reported that an evening meal high in soluble and fermentable DF lowered glucose

TABLE 5
Satiety scores obtained in healthy subjects immediately before (ie, 4 h after breakfast) and after the standardized lunch meal, preceded by different barley-based breakfasts and the reference breakfast[1]

Breakfast	Satiety score					
	0 min (4 h)	15 min	45 min	95 min	120 min	180 min (7 h)
WWB	−7.4 ± 0.5[a]	2.0 ± 1.4[a]	1.5 ± 1.2[a]	−0.8 ± 1.3[a]	−1.6 ± 1.5[a]	−3.1 ± 1.9[a]
HAB	−6.2 ± 0.6[a]	4.4 ± 0.9[a]	3.2 ± 0.9[a,b]	0.4 ± 1.3[a,b]	−0.7 ± 1.5[a]	−2.6 ± 1.2[a]
HAB-longp	−5.5 ± 0.7[b]	3.6 ± 0.9[a]	3.4 ± 0.9[a,b]	2.1 ± 0.9[b]	−0.1 ± 1.2[a]	−3.0 ± 1.3[a]
HAB-long	−5.4 ± 0.6[a,b]	2.8 ± 1.3[a]	3.9 ± 0.9[b]	0.9 ± 1.5[a,b]	0.0 ± 1.1[a]	−3.3 ± 1.0[a]
HAB-long + BF	−3.5 ± 1.0[b]	3.4 ± 1.1[a]	3.6 ± 0.9[b]	0.8 ± 0.9[b]	−0.3 ± 1.1[a]	−2.5 ± 1.2[a]

[1] $\bar{x}$ ± SEM; n = 10. WWB, white-wheat bread (reference meal); HAB, high-amylose barley bread baked under ordinary conditions; HAB-long, HAB bread baked for a long time at a low temperature; HAB-long + BF, HAB-long bread and barley flakes; HAB-longp, HAB-long bread made with preboiled flour. Satiety was estimated according to the method of Haber et al (18) on the basis of a scoring system from −10 (extreme hunger) to 10 (extreme satiety). Values within the same column with different superscript letters are significantly different, $P < 0.05$ (Wilcoxon matched-pairs signed-rank test followed by Bonferroni adjustment).

output the following morning, suggesting an influence of SCFAs on glucose metabolism. In contrast, Wolever et al (23) found no overnight effect related to fermentation of DF in a comparison of whole-meal wheat bread and white bread meals. However, the main DF in whole-meal wheat flour is cellulose, a component known to be poorly fermented in the large intestine (24). Consequently, fermentable fiber sources as well as RS fractions may be of metabolic importance if there is a sufficient concentration of SCFAs in the blood.

In the present study, satiety scores were also estimated after the breakfast meals in series 1. Subjects reported higher satiety 4 h after eating the HAB-long + BF than after the WWB meal. This may have been because of the prolonged absorptive phase noted after consumption of this breakfast. However, test meals rich in DF have been reported to increase satiety (25).Thus, the high indigestible carbohydrate content of the HAB-long + BF breakfast may also have contributed to the higher satiety score. Although the voluntary intake at lunch was not recorded, higher satiety 4 h after breakfast could be expected to lower energy intake at lunch. The satiety score was not only significantly higher 4 h after the HAB-long + BF breakfast than after the reference (WWB) meal, but was higher 45 and 95 min after the second meal, suggesting that this breakfast had a positive effect on satiety that extended beyond the breakfast meal. Satiety was also significantly higher after the HAB-long meal than after the WWB meal when estimated 45 min after the second meal; the same was true for the HAB-longp meal 4 h after the breakfast and 95 min after the second meal.

In a study by Raben et al (26), satiety after consumption of pregelatinized or raw potato starch was determined. The pregelatinized starch was more satiating than was the slowly and incompletely digested raw potato starch, probably because this starch was so slowly digested that it failed to increase postprandial blood glucose concentrations to any appreciable extent. In contrast, in the present study, the HAB-long + BF breakfast—which had the lowest GI and the highest RS content—produced the greatest satiety.

In the present study, the second-meal effect of the HAB-long + BF (low GI, high RS + DF content), and particularly the spaghetti breakfast (low GI, low RS + DF content), may be one mechanism whereby low-GI diets improve glucose metabolism. Thus, it can be concluded that the content of fermentable carbohydrates per se did not influence second-meal glucose tolerance. In several papers, long-term (2–12 wk) metabolic benefits of low-GI foods have been reported (27–30). Results from the present study support the theory that glucose tolerance can change over 1 d because improved insulin sensitivity was observed by lunchtime after consumption of some of the low-GI breakfasts.

Second-meal effects of low-GI foods have been reported previously. However, in only a few studies were the test meals composed of commonly eaten foods. Moreover, the observation that foods with similar GIs, of 52–64, may differ in their capacity to modify second-meal glucose tolerance is new and the mechanism remains to be elucidated. Consequently, despite a low GI of 64, the WWB + vinegar breakfast did not influence glucose tolerance at lunch. The avoidance of the in-between-meal fasting state might be an important determinant of second-meal glucose tolerance. In addition to the GIs of meals, late postprandial glycemia may be an important factor in the cumulative metabolic effects of starchy foods.

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