Consumption of Both Resistant Starch and β-Glucan Improves Postprandial Plasma Glucose and Insulin in Women

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OBJECTIVE — Consumption of a meal high in resistant starch or soluble fiber (β-glucan) decreases peak insulin and glucose concentrations and areas under the curve (AUCs). The objective was to determine whether the effects of soluble fiber and resistant starch on glycemic variables are additive.

RESEARCH DESIGN AND METHODS — Ten normal-weight (43.5 years of age, BMI 22.0 kg/m^2) and 10 overweight women (43.3 years of age, BMI 30.4 kg/m^2) consumed 10 tolerance meals in a Latin square design. Meals (1 g carbohydrate/kg body wt) were glucose alone or muffins made with different levels of soluble fiber (0.26, 0.68, or 2.3 g β-glucan/100 g muffin) and three levels of resistant starch (0.71, 2.57, or 5.06 g/100 g muffin).

RESULTS — Overweight subjects had plasma insulin concentrations higher than those of normal-weight subjects but maintained similar plasma glucose levels. Compared with low β-glucan–low resistant starch muffins, glucose and insulin AUC decreased when β-glucan (17 and 33%, respectively) or resistant starch (24 and 38%, respectively) content was increased. The greatest AUC reduction occurred after meals containing both high β-glucan–high resistant starch (33 and 59% lower AUC for glucose and insulin, respectively). Overweight women were somewhat more insulin resistant than control women.

CONCLUSIONS — Soluble fiber appears to have a greater effect on postprandial insulin response while glucose reduction is greater after resistant starch from high-amylose cornstarch. The reduction in glycemic response was enhanced by combining resistant starch and soluble fiber. Consumption of foods containing moderate amounts of these fibers may improve glucose metabolism in both normal and overweight women.

Diabetes Care 29:976–981, 2006

A variety of fiber components, especially soluble fiber and resistant starch, have beneficial effects on glucose tolerance in people with normal as well as impaired glucose tolerance (1,2). These effects include reductions in blood glucose and insulin (1,3) and improvement of glycemic control in diabetes (2). Glucose and insulin responses improved (decreased) after test meals containing soluble fibers, including pectin, Oatrim (oat fiber extract), guar gum, gum tragacanth, and methyl cellulose fibers, when compared with meals without soluble fiber (1,4).

Increased amylose or resistant starch (high amylose versus amylopectin) decreased postprandial glucose and insulin responses in people with either normal glucose tolerance or impaired glucose tolerance (3,5–8). Different amounts of resistant starch or high-amylose starch consumed in the meals as well as different recipes and storage conditions make direct comparison of studies difficult (3,8).

Hyperinsulinemia, an indication of insulin resistance, is one indicator of the potential to develop type 2 diabetes (9,10). Abnormal carbohydrate metabolism, especially with respect to elevated glucose or insulin concentrations in the blood, occurs with increasing age and weight (10,11). Insulin resistance (abnormal glucose metabolism and/or hyperinsulinemia) increases as weight increases and is more prevalent in obese subjects (up to 46% in obese subjects compared with 4% in a control population) (12).

Objectives of this study include assessment of the effect of various levels of resistant starch (from high-amylose cornstarch) and soluble fiber (β-glucan from Oatrim) on the improvement of glycemic response and insulin sensitivity in normal-weight and overweight or obese adults and determination of whether an interaction between the two carbohydrate sources might retard or improve glycemic response. The hypothesis of the study is that the effects of β-glucan and resistant starch are additive.

RESEARCH DESIGN AND METHODS

— Twenty women were selected for the study after clinical analysis of fasting blood and urine samples and a medical evaluation of their health history. Subjects were selected based on the following criteria: *1*) weight stable for 6 months before the study, *2*) normotensive, *3*) nondiabetic fasting glucose, *4*) no history of disease affecting carbohydrate metabolism, *5*) taking no medication known to affect glucose or lipid metabolism, and *6*) no current disease found by a routine urinalysis and blood screen. Control subjects averaged 43.4 years old, 61.6 kg, with BMI 22.0 kg/m^2, 29.7% body fat, fasting glucose 4.92 mmol/l, and triglycerides 0.98 mmol/l. Overweight women were paired for age with control subjects and averaged 43.3 years old, 81.7 kg, with BMI 30.4 kg/m^2, 37.6% body fat, fasting glucose 5.01 mmol/l, and triglycerides 1.20 mmol/l. The design and purpose of the study were explained to the subjects both orally and in writing. The

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Received for publication 19 October 2005 and accepted in revised form 18 January 2006.

Abbreviations: AUC, area under the curve; HOMA, homeostasis model assessment.

A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

DOI: 10.2337/dc05-2012

study was approved to include both men and women by the institutional review board of The Johns Hopkins University Bloomberg School of Public Health. Due to facility and staff limitations, women were studied first.

Subjects were given a standard equilibration diet containing 30% fat, 55% carbohydrate, and 15% protein for 2 days before and the day of sample collection. Body weight was used to determine energy intake for the controlled diet, and subjects consumed that same amount of energy during all 10 periods. The menu was identical before each tolerance. Subjects consumed their self-selected diets between tolerance meals.

Blood was collected after a 10 h fast. Subjects then consumed 1 g carbohydrate/kg body wt either as a glucose solution plus 100 g water or a test muffin containing an equal amount of total carbohydrate plus water equal to that in the glucose tolerance. Nine muffin types were made that contained either *1*) standard cornstarch, *2*) a 50/50 blend of standard and high-amylose cornstarches, or *3*) high-amylose cornstarch providing 0.71, 2.57, or 5.06 g resistant starch/100 g muffin, respectively. Each of the three starches was combined with Oatrim (1, 2.5, or 10% β-glucan by weight) providing 0.26, 0.68, or 2.3 g β-glucan/100 g muffin, respectively. The 10 meal tests were performed in a Latin square design. The starches were provided by American Maize-Product Company (Hammond, IN). The Oatrims were provided by Quaker Oats (St. Louis, MO) and ConAgra (Omaha, NE). In addition to the starch and Oatrim, muffins contained baking powder, salt, gluten, egg, milk, oil, and sweetener.

Sample collection and analyses

Blood samples were collected before treatment and at 1, 2, 3, and 4 h after the meal was given. Glucose was determined on an automated spectrophotometric system (Baker Instruments, Allentown, PA). Insulin (Diagnostics Products, Los Angeles, CA) was determined by radioimmunoassay. Two-hour postprandial response areas under the curve (AUCs) were calculated using the trapezoid method.

The amount of resistant starch in the muffins was determined using AOAC (Association of Official Analytic Chemists) method 991.43 (13) with and without pretreatment with DMSO. Starch was calculated from the glucose content in enzyme hydrolysate as determined by high-performance anion exchange chromatography (13). The β-glucan content of the Oatrim was determined enzymatically by AACC (American Association of Cereal Chemists) method 32-23 (14).

Data calculations and statistical analyses

Power analysis for sample size has determined that a 10% difference in insulin response, a critical variable in testing the hypothesis, can be detected with $n = 8$ in each group with a significance level of $P < 0.05$. However, to ensure power to reach desired statistical outcomes and allow for voluntary withdrawal, we increased the number of subjects to 10 per group. When samples were analyzed after the study, one control and one overweight woman were found to have abnormal glucose concentrations. Analyses were rerun eliminating the data from these women. Insulin resistance was calculated using the homeostasis model assessment ($\text{HOMA} = \text{insulin}^{\mu U/ml} \times \text{glucose}^{mmol/l}/22.5$) (15) and a method using a published index of glucose disposal rates corrected for fat-free mass (FFM) based on fasting insulin and triglyceride concentrations {$\text{MFFM} = \text{EXP}[2.63 - 0.28 \times (\log \text{insulin}^{nmol/l}) - 0.31 \times (\log \text{triglyceride}^{nmol/l})]$} (16). All fasting data were utilized for these analyses. Data were analyzed statistically with a mixed-models procedure for repeated-measures ANOVA (PCSAS, version 8.0; SAS Institute, Cary, NC). Data were evaluated for the main effects of treatment (glucose or level of amylose and β-glucan), group (control versus overweight women), time, and interactions among the main effects. Insulin data were log transformed before statistical analysis because of no homogeneity of variance. Data reported are least-squares means ± SE. When effects were statistically significant, mean comparisons were done with Sidak-adjusted *P* values so that the experiment-wise error was $P < 0.05$.

RESULTS — β-Glucan intake averaged 0.3, 0.9, and 3.7 g β-glucan for the low–, mid–, and high–β-glucan meals, respectively. Resistant starch intake averaged 0.9, 3.4, and 6.5 g for the low–, mid–, and high–resistant starch meals, respectively. Because overweight women consumed a higher amount of total carbohydrate, they consumed more β-glucan and resistant starch. Mean differences between the groups of control and overweight women were ~0.08, 0.2, and 1.0 g for the three levels of β-glucan, respectively and 0.2, 0.8, and 1.6 for the three levels of resistant starch, respectively. These differences in intake do not appear to have affected results, since there were minimal differences between the groups.

Significant differences were observed in plasma glucose concentrations (Table 1) after the 10 meals were consumed (time, $P < 0.001$; treatment-by-time interaction, $P < 0.009$). Since there was no statistically significant group ($P = 0.869$), group by treatment ($P = 0.089$), or group by time ($P = 0.746$), the two groups of women were combined. Plasma glucose concentrations of the combined weight groups after the glucose were higher at 2 h and lower at 3 h than after the test meals. Glucose concentration at 2 h after the high–β-glucan/high–resistant starch meal was significantly lower than after meals with low or medium β-glucan. Glucose concentrations at 1 h after the meals were lowest after the high–β-glucan/high– and mid–resistant starch meals.

Insulin responses (Table 2) were significantly affected by treatment ($P < 0.001$), time ($P < 0.0001$), and treatment-by-time interaction ($P < 0.04$). Mean fasting 3- and 4-h insulin concentrations were not significantly different among treatments. Insulin concentrations at 30 min and 2 h after the high–β-glucan /high–resistant starch meals were lowest. At 1 h after the meals, the high β-glucan with high or medium resistant starch significantly lowered insulin levels. There were significant differences by group ($P < 0.017$) and group-by-treatment interaction ($P < 0.006$) in plasma insulin responses. Overweight women had significantly higher mean insulin compared with control. Overweight women had the lowest insulin concentrations within a β-glucan level when the meal contained the highest amount of β-glucan. Mean insulin concentrations of control women were less affected by treatment.

Differences in the β-glucan and resistant starch content of the meals resulted in a significant difference in glucose area under the curve (AUC) by treatment ($P = 0.05$) (Fig. 1) but not by group ($P = 0.774$) or treatment by group ($P = 0.661$). Glucose AUCs were significantly reduced only after the meals with high or moderate resistant starch and high β-glucan. Compared with low–β-glucan/low–

Table 1—*Glucose responses (mmol/l) after glucose and nine meals containing three levels of resistant starch and three levels of β-glucan*

	Time					
Treatment	Fasting	30 min	1 h	2 h	3 h	4 h
Glucose	5.99	9.11*	7.54*†	6.05	5.06‡	5.30
Low β-glucan						
Low RS	6.11	8.92*†	7.75*†	6.39	5.88*†	5.60
Mid RS	5.90	8.08‡	7.37†	6.31	6.31*	5.44
High RS	6.03	8.04‡	7.32*†	5.79	5.93*†	5.53
Medium β-glucan						
Low RS	6.11	8.56*†‡	8.13*	6.30	5.58†‡	5.62
Mid RS	5.93	8.29†‡	7.15†	6.10	5.59†‡	5.66
High RS	6.13	8.10‡	7.46*†	6.18	5.99*†	5.87
High β-glucan						
Low RS	5.95	7.87‡§	7.28†	6.44	6.22*	5.91
Mid RS	6.11	7.75‡§	6.67‡	6.43	6.24*	5.82
High RS	5.65	7.33§	6.50‡	6.34	5.86*†	5.68
SE by time	±0.24	±0.40	±0.54	±0.32	±0.23	±0.17
ANOVA by time	$P = 0.83$	$P < 0.008$	$P < 0.028$	$P = 0.76$	$P < 0.003$	$P = 0.23$

Data are mean SE of 9 normal and 9 overweight women. Overall ANOVA: group, $P = 0.8690$; treatment, $P = 0.248$; group by treatment, $P < 0.089$; time, $P < 0.0001$; group by time $P = 0.746$; treatment by time, $P < 0.016$; group by treatment by time, $P = 0.999$. Means with different symbols within a column are significantly different ($P < 0.05$). Low, medium, and high β-glucan intake averaged 0.3, 0.9, and 3.7 g/meal, respectively. Low, mid, and high resistant starch averaged 0.9, 3.4, and 6.5 g/meal, respectively. RS, resistant starch.

resistant starch muffins, glucose AUC decreased when β-glucan (17%) or resistant starch (24%) content was increased. High β-glucan/high resistant starch reduced AUC by 33% compared with the low β-glucan/low resistant starch.

Insulin AUC was also significantly affected by treatment ($P = 0.0001$) but not by group ($P = 0.165$) or group by treatment ($P = 0.531$) (Fig. 1). The high–β-glucan/high–resistant starch meal resulted in the lowest insulin AUC. Compared with the low–β-glucan/low–resistant starch meal, insulin AUC decreased when β-glucan (33%) or resistant starch (38%) content was increased. High β-glucan/high resistant starch reduced AUC by 59% compared with the low–β-glucan/low– resistant starch meal.

Insulin resistance calculations resulted in a significant difference between groups with the MFFM method (overweight group 8.1 ± 0.14, control group 8.5 ± 0.15; $P < 0.05$) but not HOMA ($P = 0.11$). Values calculated by the MFFM method were above the value (6.3) suggested by McAuley et al. (16), indicating insulin resistance. HOMA calculations based on grouped fasting insulin rather than weight or BMI resulted in a

Table 2—*Insulin response (pmol/l) after glucose and nine meals containing three levels of resistant starch and three levels of β-glucan*

	Time						Group	
Treatment	Fasting	30 min	1 h	2 h	3 h	4 h	Control	Overweight
Glucose	72	318*†	314*	163†‡	106	68	168	178‡
Low β-glucan								
Low RS	63	401*	393*†	225*†	105	126	156*	282*
Mid RS	69	321*†	347*†	164†‡	91	109	159*	208†‡
High RS	82	352*†	292*†	129‡	94	73	171*	169‡§
Medium β-glucan								
Low RS	67	346*†	345*†	191*	120	101	160*	229†
Mid RS	77	340*†	303*†	176†‡	107	104	157*	212†‡
High RS	64	319*†	297*†	150‡	103	122	149*	202†‡
High β-glucan								
Low RS	96	322†‡	302*†	148†‡	105	108	130*	229†
Mid RS	77	328*†	258†	140‡	100	111	146*	192†‡
High RS	68	234‡	170‡	105§	97	125	122*	144§
SE by time	±8	±46	±65	±33	±19	±28	±25	±24
ANOVA	$P = 0.22$	$P < 0.048$	$P < 0.003$	$P < 0.012$	$P = 0.99$	$P = 0.73$		

Data are mean SE of 9 normal and 9 overweight women. Overall ANOVA: group, $P < 0.017$; treatment, $P < 0.01$; group by treatment $P < 0.001$; time, $P < 0.0001$; treatment by time, $P < 0.040$; group by time, $P = 0.274$; group by treatment by time, $P = 0.875$. Means with different symbols within a column are significantly different based on log-transformed evaluation ($P < 0.05$). Means within the group (control and overweight) columns with different symbols are significantly different. Low, medium, and high β-glucan intake averaged 0.3, 0.9, and 3.7 g/meal, respectively. Low, mid, and high resistant starch (RS) averaged 0.9, 3.4, and 6.5 g/meal, respectively. RS, resistant starch.

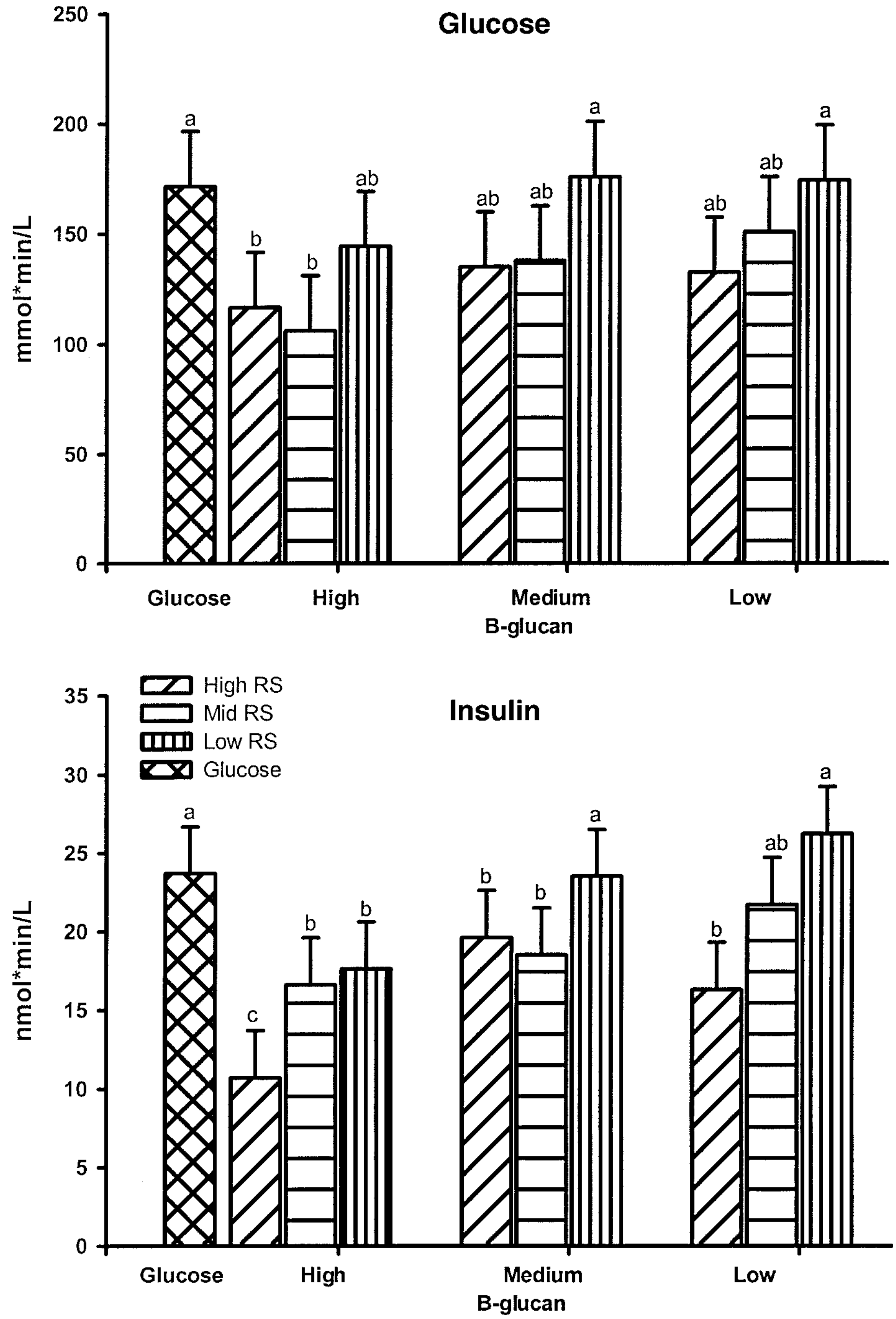

Figure 1—*AUCs for glucose and insulin by treatment after glucose and nine meals containing three levels of resistant starch and three levels of β-glucan. Data are least-square means ± SE. AUC based on 0- to 2-h plasma glucose or insulin concentrations. Bars with different superscripts are significantly different* ($P < 0.05$). *Glucose ANOVA: group,* $P = 0.465$; *treatment,* $P < 0.038$; *group by treatment,* $P = 0.631$. *Insulin ANOVA: group,* $P = 0.165$; *treatment,* $P < 0.0003$; *group by treatment,* $P = 0.532$.

distinct separation ($P < 0.0001$) in insulin resistance; the lower average fasting insulin (62.4 mmol/l) had a value of 2.3, whereas the higher average insulin (125.4 mmol/l) had a value of 4.9.

CONCLUSIONS — This study demonstrates that consumption of a moderate amount of either resistant starch or β-glucan can improve (lower) the glucose and insulin responses of both normal and overweight women. Results of this study can be used in the control of glucose responses in both normal and insulin-resistant subjects. The amount of β-glucan or resistant starch required to effect this improvement can be achieved through diet (Table 3).

Although a variety of fiber components, especially soluble fibers, have generally been reported to decrease glucose and insulin responses (1–4,6–8) in normoglycemic and diabetic subjects, none has compared both sources used in this study. Soluble fibers (found in oats, barley, and citrus fruits) are more effective in controlling glucose and insulin than predominantly insoluble fibers such as wheat (1,2). Glucose and insulin responses were significantly lower after barley pasta containing 12 g β-glucan (17) or barley bread (18) than after wheat pasta or bread, respectively. This level of soluble fiber is higher than that consumed in our study (averaging 3.7 g/meal). Numerous studies have reported inverse relationships between β-glucan and glucose and/or insulin responses after subjects consumed amounts comparable to those consumed in our study (19–21). Suggested mechanisms for these results include viscosity of the soluble fibers resulting in delayed or reduced carbohydrate absorption from the gut (22).

A few studies have not found glucose and insulin concentrations to be significantly lowered (1,18) with soluble fiber, but these studies used lower amounts than consumed by subjects in our study. Studies that reported little or no decrease in glucose or insulin response to the meal may have had soluble fiber contents near or below the threshold needed to reduce glycemic response. None of these studies combined β-glucan with resistant starch.

High-amylose starches are less digestible than standard starches in part because of the presence or development of resistant starch. Similar to soluble fibers, resistant starch is digested by colonic bacteria. Improvement in glycemic response after foods containing high-amylose starch or resistant starch has been reported in a few studies (5–8,23,24). Krezowski et al. (6) reported significantly lower postprandial glucose and insulin responses of subjects with type 2 diabetes after high-amylose muffins compared with concentrations after corn flakes or low-amylose muffins. Significantly lower insulin and AUC has been reported in normal, hyperinsulinemic, and overweight hypertriglyceridemic subjects after high-amylose than after low-amylose cornstarch muffins or bread averaging 5.8 vs. 1.3 g resistant starch (23), 13 vs. <1.0 g resistant starch (5), or 18.4 vs. 2.4 g resistant starch (24). Behall et al. (8) re-

Table 3—*Approximate fiber* and resistant starch† of some food sources as eaten*

	Amount	Total fiber (g)	Soluble fiber (g)	Resistant starch (g)
Cereals				
Oatmeal	2 c cooked	2	1	0.15
Barley	2 c cooked	4	1	2.25
Corn flakes	1 c	1	0	0.3
Wheat bran flakes	3/4 c	5.5	0.5	0.2
Grain Products				
Whole wheat bread	1 slice	2.5	0.5	0.1
English muffin	1 muffin	2	0.5	0.6
Spaghetti	1 c	2	0.5	0.3
White rice	1/2 c	0.5	0	0.6
Other starch sources				
Potato, baked	Medium	3	1	0.3
Potatoes, mashed	1/2 c	1.4	0.5	2.4
Legumes (beans)	2 c cooked	6–7	1–3	2–3.5
Lentils	2 c cooked	7	1	2.8
Fruit (1 medium fruit)				
Apple		4	1	0
Bananas (varies with ripeness)		3	1	4.9
Citrus fruits		2–3	2	0
Peaches		2	1	0
Plums		1.5	1	0

*Total fiber (26–28), *†soluble fiber (26–28), and †resistant starch (27–29).

ported a significant reduction of glucose and insulin responses after the consumption of breads containing 8–13.4 g resistant starch. Subjects consuming 12.2–18.9 g resistant starch also had significant reductions in glucose and insulin responses (7). Our highest level of resistant starch was ~8–10 g. Responses after two different levels of total and available carbohydrate were not significantly different (7). In the current study, the β-glucan combined with resistant starch, especially both high β-glucan and resistant starch, resulted in a greater reduction in glucose and insulin concentrations than might have been expected with only the resistant starch.

Similar to soluble fiber, a minimum intake of resistant starch (~5–6 g) appears to be needed in order for beneficial reductions in insulin response to be observed. Estimates of daily intake of resistant starch range from 3–6 g/day (averaging 4.1 g/day) in Europe and Australia with similar but inconsistent data for the U.S. (25). It appears that more resistant starch than currently is consumed should be included in the diet for the health benefits related to diabetes and cardiovascular disease. Consumption of at least one serving each of cooked barley flakes, lentils, English muffin, and a citrus fruit in a day would contain ~4.5 g soluble fiber and 5.65 g resistant starch (Table 3).

Our study found the overweight women to be somewhat more insulin resistant than the normal-weight women, as would be expected. Overweight subjects in this study had higher fasting insulin concentrations. Insulin resistance is associated with obesity, hypertension, dyslipidemia, glucose intolerance, and hyperinsulinemia (9,12). It has been estimated that occurrence of insulin resistance increases nearly 20% for each 5% increase in weight over the reported weight at age 20 years. Insulin resistance occurs in 4% of a nonobese population but up to 46% in obese subjects and may be the initiating step in the development of type 2 diabetes (12). McAuley et al. (16) reported that fasting insulin of >87.5 mmol/l (12.2 μU/dl) was as accurate at predicting insulin resistance in a normoglycemic population as was HOMA, insulin-to-glucose ratio, or the Bennett index.

Increased incidences of abnormal carbohydrate metabolism, especially with respect to elevated glucose or insulin concentrations in the blood, are reported with increasing age and weight. Our study used a simple food to provide a combination of levels of soluble fiber and resistant starch. The combination of resistant starch with β-glucan resulted in a greater decrease in glucose and insulin than the same amounts consumed individually and as great a decrease as that reported elsewhere with larger amounts of resistant starch or β-glucan consumed alone. Beneficial reductions in glucose and insulin can result if sufficient soluble fiber, resistant starch, or both are consumed. Consumption of foods containing moderate amounts of these fibers may improve glucose metabolism in both normal and overweight women.

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