

# Influence of Glycemic Index/Load on Glycemic Response, Appetite, and Food Intake in Healthy Humans

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**OBJECTIVE** — High glycemic index (GI)/load (GL) diets reportedly enhance appetite and promote positive energy balance. Support for this hypothesis stems largely from acute feeding trials and longer-term studies lacking control over the macronutrient composition and palatability of test foods. This study evaluated the effects of consuming high- and low-GI/GL meals, matched on macronutrient composition and palatability, plasma glucose and insulin, appetite, and food intake.

**RESEARCH DESIGN AND METHODS** — Thirty-nine healthy adults consumed only low- or only high-GI foods ad libitum in the laboratory for 8 days in either high (three foods per meal)- or low (one food per meal)-variety conditions. Glucose and insulin concentrations as well as appetitive sensations were determined before and for 2 h following breakfast and lunch on days 1 and 8. Energy intake was monitored daily.

**RESULTS** — There were no significant differences in plasma glucose or insulin responses, appetitive ratings, or food intake between treatments.

**CONCLUSIONS** — These data indicate that the differential glycemic response of foods tested in isolation under fixed time are not preserved under conditions of chronic ad libitum consumption of mixed meals.

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The glycemic index (GI) is a property of carbohydrate-containing foods that provides a basis for predicting their postprandial blood glucose response (1). The glycemic load (GL) is the product of a food's GI and carbohydrate content divided by 100 (2). The GL of the average diet of the U.S. rose 22% from 1980 to 1990 (3). Several preload studies (4–6) suggest that ingestion of high-GI meals increases hunger and promotes overeating in a subsequent meal relative to low-GI meals. In trials demonstrating GI effects on appetite, a given amount of food

has been ingested within a predefined period of time. However, discrepant biochemical and appetitive responses may be observed under more natural feeding conditions. The glycemic response (GR) is modulated by multiple meal properties including duration (7), nutrient composition (8,9), energy density (10), volume/weight (7), rheology (11), and palatability (12). The first aim of the present study was to control these potential confounders to isolate and quantify the GI/GL effect on appetite and intake.

In most published studies, responses

to single high- or low-GI foods were contrasted. However, several, but not all, studies (13,14) indicate that when foods are mixed in a meal, the GR is unpredictable. Interactions among different types of carbohydrate, fiber, protein, and fat in the foods also affect the GR to a meal (8). A second aim of this study was to monitor the effects of mixing foods on the GR. Responses were monitored after ingestion of one or three foods per meal, with all foods being either high or low GI.

Most research on GI influences on appetite and intake focused on acute events occurring postprandially. The nutritional significance of this approach is limited due to potential subsequent dietary compensation (15). Fewer studies have explored the consequences of ingesting low- or high-GI foods over multiple days or weeks. Some reveal an adaptation effect (16) and lack of impact on energy intake and body weight (17). Longer-term trials provide information of greater ecological relevance, but, because of their reliance on free-living participants, they have limited experimental control. A third aim of the present study was to evaluate the nutritional implications of ingesting low- or high-GI diets over a longer time period with strict experimental control.

## RESEARCH DESIGN AND METHODS

### Prestudy determination of the GI of test foods

Seventy-nine foods were selected based on their similar macronutrient composition (50–54% of energy as carbohydrate, 15–19% protein, and 30–34% fat) and their published GI values (2). The veracity of the published ratings was confirmed using the particular food brands and preparation methods employed in this study through a pretest with 13 nonstudy adults. After a 10-h overnight fast, participants consumed a food portion containing 50 g of available carbohydrate and 200 ml of water within 15 min (13). Capillary finger-stick blood samples were taken in the fasting state (0 min) and 30,

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**Abbreviations:** AUC, area under the curve; GI, glycemic index; GL, glycemic load; GR, glycemic response.

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

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60, and 120 min after the start of the test meal. Glucose levels were measured using a SureStep glucometer (Lifescan, Milpitas, CA). The positive area under the curve (AUC) changes in blood glucose were computed by the trapezoidal method (8). The AUC for each food's GR was then expressed as a percentage of the mean response to 5 g available carbohydrate portions from white bread consumed by the same subject (8). The mean GI value was determined in three participants for each of the 79 foods. Forty-eight foods that resulted in consistent (range <13 units) GRs were selected as test foods.

### **Experimental design of study**

This controlled clinical trial study involved two experimental 8-day sessions separated by a washout period of at least 15 days. Participants were randomized (by coin flip) to either high- or low-GI groups. There were no statistically significant group baseline characteristic differences. Within groups, participants received only high- or low-GI items. Each group first participated in a variety session where a combination of three different foods was served for each of the three daily meals: breakfast, lunch, and dinner. Participants could eat as much as they wanted of any of the foods served. Upon completion of this first session, participants selected their three most preferred foods. These were the only foods eaten, one per meal, during the entire 8 days of the monotony session.

Meals were served restaurant style in the laboratory ad libitum during days 1–7 of each session and through lunch on day 8. A choice of two types of evening snack foods was provided at dinnertime, for consumption at home. Participants returned unconsumed snacks daily. Consumption of nonstudy foods or beverages was prohibited. From days 2 to 7 of each session, blood glucose concentrations were assessed (SureStep; Lifescan, Milpitas, CA) immediately before each meal to confirm participants had not recently eaten. Food intake was measured by covertly preweighing all foods served and reweighing leftover foods. Participants were asked to maintain a constant level of physical activity during the study.

The GI/GL effects on appetite and on glycemic and insulinemic responses were determined on days 1 and 8 of each session. Participants reported to the labora-

tory after a 10-h overnight fast and had an indwelling catheter placed in their forearm. Blood sampling and completion of appetitive questionnaires were completed before and at 30, 60, and 120 min after breakfast and lunch. The study protocol was approved by the human subjects review committee of Purdue University, and written informed consent was obtained before testing began.

Nineteen female and 20 male healthy adults, aged  $24.9 \pm 0.8$  years, with mean BMI  $22.9 \pm 0.5$  kg/m<sup>2</sup>, and with mean body fat  $23.5 \pm 1.0\%$  were recruited through public advertisements. BMI and body fat were analyzed by bioelectrical impedance analysis (bodyfat analyzer model TBF-105; Tanita, Skokie, IL). Participants were nonsmokers, not using medication (except birth control pills), not pregnant or lactating, not on a therapeutic diet, had no recent weight loss or gain >3 kg over the previous 3 months, had regular eating habits (daily breakfast, lunch, and dinner consumption), fasting blood glucose between 70 and 110 mg/dl, no family history of diabetes, no celiac disease, and had dietary restraint  $\leq 14$  (18).

### **Appetite and food preference ratings**

Appetite was assessed by ratings of hunger, desire to eat, and fullness at stipulated times (19). Food pleasantness was rated after initial tasting. All ratings were made on general labeled magnitude scales (20,21).

### **Blood glucose and insulin concentration analyses**

The glucose and insulin responses after ingestion of the test foods were determined using capillary rather than venous blood because glucose changes are greater and more reliable in the former (13). Blood samples were centrifuged at 3,000 rpm for 10 min immediately after collection, and plasma was stored at  $-70^{\circ}\text{C}$  for later batch analysis. Serum insulin was determined by a solid-phase two-site enzyme immunoassay (ALPCO insulin ELISA, catalog no. 008-10-1113-01; American Laboratory Products Company Windham, NH).

### **Test meals**

Milk or yogurt and cereal or pancakes or waffles were provided for breakfast. Pizzas, sandwiches, quiche, pasta, soup, salads, lentils, casseroles, egg rolls, taquitos, tortillas, burritos, chips and dip, potatoes,

bagels, hot pockets, lasagna, spaghetti, noodles, and frittata were provided for lunch, dinner, and evening snack (Table 1).

The low- and high-GI foods had mean GI values of  $43.81 \pm 0.99$  (range 30.09–49.62) and  $105.26 \pm 5.74$  (68.70–169.30), respectively. There were no significant differences for pleasantness ratings (means [range]; low GI = 39 [23–58], high GI = 42 [22–55]), calorie density (low GI = 1.52 kcal/g, high GI = 1.62 kcal/g), or percentage of carbohydrate (low GI = 51.3, high GI 51.1), protein (low GI = 16.8, high GI = 17.5), or fat (low GI = 31.8, high GI = 31.4) between the low- and high-GI foods during the full study.

Participants also received 200 ml of noncaloric fruit-flavored drink, ice tea (Crystal Light; Kraft, Rye Brook, NY), water, decaffeinated tea (Celestial Seasonings, Boulder, CO), or decaffeinated coffee (Folgers, Cincinnati, OH) at each meal. After lunch and dinner, participants had two options for a 50-kcal dessert. These included Jell-O (Kraft, Glenview, IL) and fat-free Reddi-whip cream (Con-Agra Foods, Downer Grove, IL) or low-calorie candies and gums.

### **Food intake analyses**

A single dietitian analyzed the dietary intake data using the Food Processor Nutrition Analysis Software package (version 7.60, released 2000; ESHA Research, Salem, OR).

### **Determination of the GL of the test foods**

The GL values of the 48 test foods were calculated by multiplying the total amount of carbohydrate (grams) ingested by the GI value of each food and dividing by 100 (2).

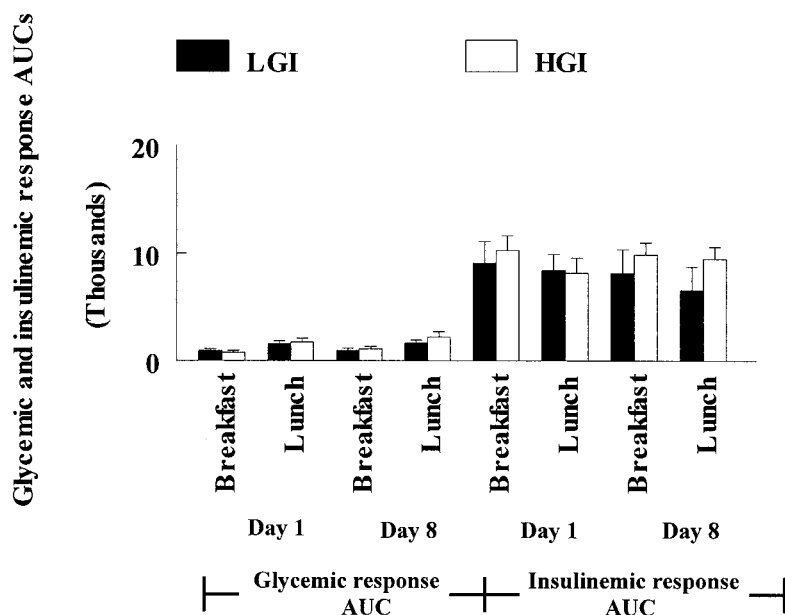
### **Statistics**

GR, insulin response, appetite, and intake analyses were conducted by repeated-measures ANOVA. Day (day 1 and 8), meal (breakfast and lunch), and time (0, 30, 60, and 120 min) were within-subjects factors, while GI group was a between-subjects factor. Pearson bivariate correlation coefficients were calculated to evaluate the relationship between GR (AUC), insulin response (AUC), and appetitive ratings (AUC) on days 1 and 8 of each study session. Analyses were conducted using the SPSS software package

Table 1—Macronutrient composition, GI, and load and fiber content of the test foods

Foods (serving size [g])	GI	GL	Caloric density (kcal/g)	Carbohydrate (%en)	Protein (%en)	Lipids (%en)	Fiber (g)
Low-GI test foods							
Quick pizza (190)*	43 ± 3	22.07	1.10	51	16	33	45.3
Barley feta toss (208)*	42 ± 5	22.15	1.10	53	16	32	40.9
Chicken barley salad (276)*	36 ± 2	18.71	0.87	52	17	31	18.0
Ham and cheddar cheese pizza (185)*	43 ± 3	21.44	2.20	50	17	33	27.6
Quiche (118)*	47 ± 1	23.45	1.78	50	19	30	13.3
Chicken and lentils (241)*	50 ± 6	25.31	1.99	51	18	30	57.0
Pita sandwich (206)*	49 ± 8	24.70	2.12	50	16	33	4.1
Black bean burritos (306)*	45 ± 1	23.05	1.60	51	19	31	37.4
Lasagna (211)*	48 ± 6	24.14	1.96	50	17	32	34.6
Brown rice casserole (145)*	36 ± 1	18.22	2.32	50	16	34	5.4
Whole-wheat spaghetti (259)*	43 ± 3	21.88	1.60	51	18	31	22.6
Bagel, ham, and cream cheese (115)*	47 ± 9	23.97	2.60	51	15	33	1.6
Michelina's Gravy With Egg Noodles (284)†	49 ± 5	25.77	1.36	53	17	30	2.0
Stouffer's Spaghetti (Stouffer's, Solon, OH) (340)†	41 ± 4	21.09	1.09	51	18	31	5.0
Delimex Chicken Taquitos (140)†	49 ± 3	24.38	2.60	50	16	34	8.0
Broccoli and garbanzo bean pita pizza (120)*	37 ± 11	19.48	2.10	53	16	32	10.9
Creamy oatmeal (112)*	45 ± 5	23.83	0.94	53	17	31	1.5
Oatmeal crisp raisin (119)*	44 ± 5	22.87	1.06	52	16	32	0.8
Bran flakes (117)*	30 ± 3	15.35	0.98	51	17	32	1.8
Wheat puffs (115)*	45 ± 6	22.81	0.96	51	17	32	0.8
Cracklin' Oat Bran (121)*	47 ± 9	24.63	1.13	52	15	32	3.2
Fiber-One (118)*	46 ± 5	24.49	0.87	53	17	30	4.3
Muesli (120)*	43 ± 4	22.36	1.10	52	16	32	2.7
All-Bran (117)*	46 ± 1	23.02	0.93	50	18	32	3.2
Mean values (low GI)	44 ± 1	22.47	1.52	51.3	16.8	31.8	14.7
High-GI test foods							
Chips and dip (223)*	104 ± 3	52.20	1.67	50	19	31	4.0
Tortilla Peru (83)*	156 ± 5	78.15	1.60	50	19	31	0.8
Mashed potatoes (215)*	80 ± 4	39.80	0.98	50	17	33	4.7
Corinna's Potatoes (215)*	108 ± 2	53.93	1.13	50	19	30	5.0
Mark's Potatoes (211)*	85 ± 3	42.65	1.04	50	19	31	3.8
Barley parmesan frittata (122)*	92 ± 1	48.05	2.27	52	18	30	27.0
Chicken breast sandwich (114)*	103 ± 6	51.50	2.04	50	19	31	1.4
White rice casserole (273)*	88 ± 5	47.34	1.25	54	16	31	2.4
Bob Evans Burritos (136)†	88 ± 6	45.71	2.40	52	18	30	2.0
Red Baron 4 Cheese Pizza (120)†	91 ± 3	46.40	2.27	51	19	31	5.0
Chef's Choice Sun-Up Skillet Breakfast (274)†	102 ± 2	52.16	1.17	51	18	31	5.0
Jose Ole Steak Fajita Wrap (151)†	94 ± 1	47.02	1.60	50	18	32	3.0
Pagoda Café Chicken (85)†	135 ± 5	69.92	1.70	52	15	33	5.0
Red Baron Chicken and Broccoli (127)†	163 ± 4	84.85	2.42	52	16	32	1.2
Noodles, vegetables, and beans soup (274)*	103 ± 2	51.36	1.00	50	17	33	4.8
Skillet Sensation (177)†	169 ± 10	84.65	0.99	50	17	33	6.0
Grape Nuts and yogurt (118)*	91 ± 3	47.31	1.03	52	17	31	1.0
Yocrunch (145)*	96 ± 6	48.97	1.75	51	19	31	0.4
Crispix and yogurt (143)*	75 ± 10	39.76	1.60	53	16	31	0.4
Cream of wheat (194)*	73 ± 7	38.55	2.13	53	16	30	1.3
Rice Krispies and yogurt (132)*	137 ± 4	69.62	1.40	51	19	30	0.1
Honey Nut Cheerios and yogurt (112)*	69 ± 2	34.35	0.94	50	19	31	0.5
Pancakes, ham, and cream cheese (220)*	98 ± 6	50.11	2.23	51	15	34	1.8
Waffles, ham, and butter (94)*	127 ± 5	65.80	2.20	52	16	32	3.4
Mean values (high GI)	105 ± 6	57.75	1.62	51.1	17.5	31.4	3.8

Data are means ± SE, unless otherwise indicated. \*Recipes created and prepared in the laboratory. †Frozen ready-to-eat foods.



**Figure 1**—Mean ( $\pm$ SE) glycemic and insulinemic response AUCs obtained on days 1 and 8 of the study. Group values for glycemic ( $P \geq 0.299$ ) and insulinemic ( $P \geq 0.187$ ) AUC for each meal are not significantly different.

(release 10.0.5; SPSS, Chicago, IL). The criterion for statistical significance was  $P < 0.05$ , two tailed. The results are reported as means  $\pm$  SE.

## RESULTS

### Glycemic and insulinemic responses

Group GRs did not significantly differ following breakfast or lunch on day 1 or 8 of either session (Fig. 1). The group insulinemic responses also did not significantly differ after breakfast or lunch on these same days (Fig. 1).

### Appetite

There were no significant group differences for hunger, fullness, or desire-to-eat ratings (Fig. 2). No significant correlation between any appetite index rating and glycemic or insulinemic responses were observed on days 1 or 8.

### Total energy and macronutrient intake

There was no group difference in energy (Fig. 3) or macronutrient intake from days 1 through 7 or on day 8 of the variety or monotony sessions.

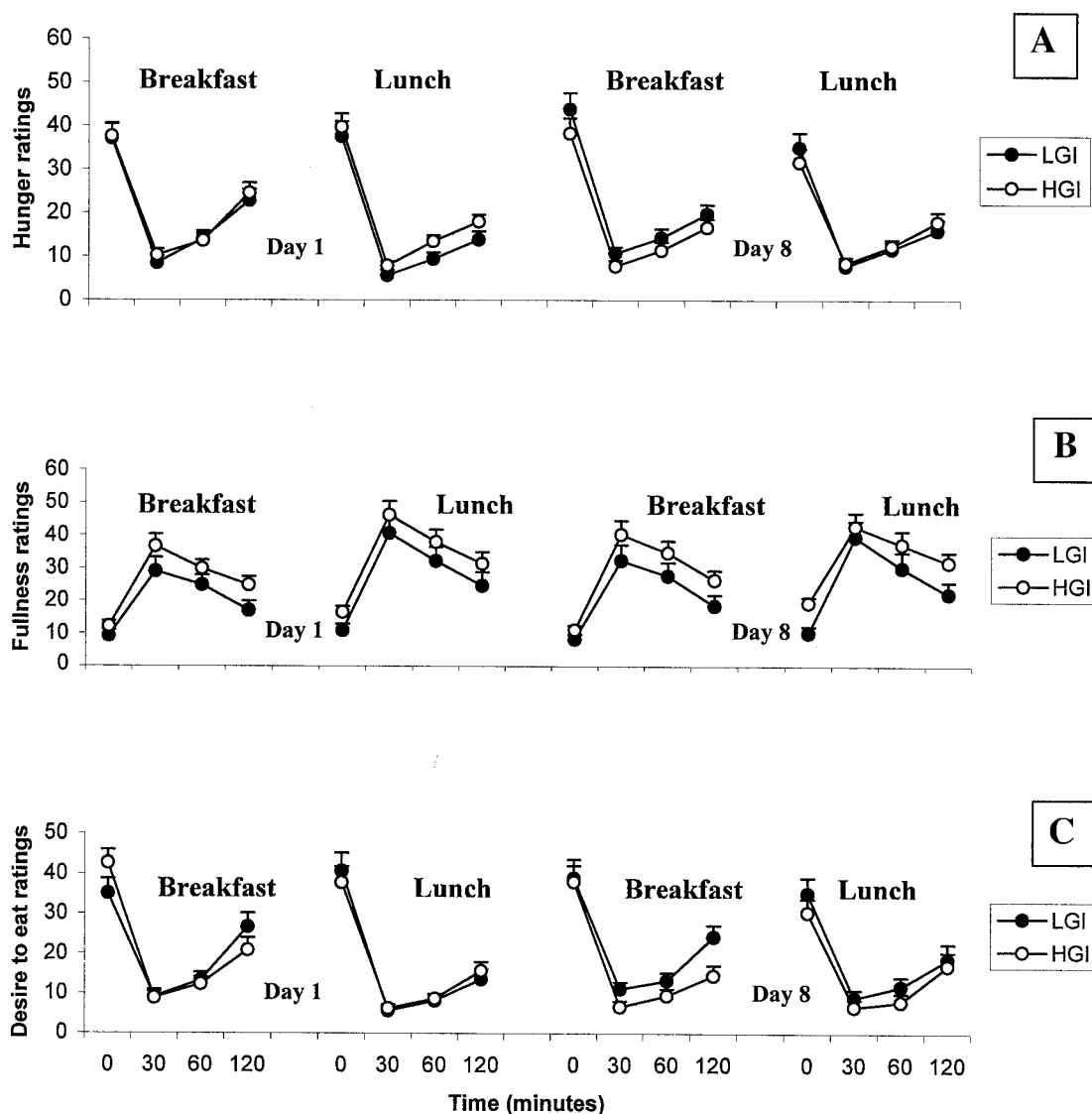
**CONCLUSIONS**— There is a lack of consensus regarding the utility of the GI/GL to predict appetite and food intake. This is due, in part, to assumptions about

the role of blood glucose as a determinant of appetite, the use of different outcome variables, and incomplete control over variables that may confound an assessment of the association. Data inconsistent with the view that blood glucose is causally related to appetite within the normal physiological range have been reported (22,23). Euglycemic clamp studies reveal that independent manipulation of glucose and insulin is not associated with alterations of appetite (23). It has been predicted that appetite and food intake will be suppressed by high-GI foods over the period when blood glucose is elevated (23). This has been observed in several trials using simple stimuli (solutions of sugars with different GIs or sugar solutions with added fiber) (24). However, augmented hunger or increased intake have also been reported during this time (6) and taken as evidence for an effect of high-GI foods on these measures. The present study explored the association between appetite and the glycemic and insulinemic responses after breakfast and lunch on days 1 and 8 of a controlled feeding period. No difference between the low- and high-GI foods was observed. The magnitude of the glycemic and insulin responses did not differ between lunch and breakfast or between days 1 and 8. However, hunger ratings were higher after breakfast than lunch and on day 1 than

day 8. Thus, the present data do not support a close association between plasma glucose or insulin and self-reported appetite or a difference due to the ingestion of low- or high-GI foods.

Self-reported appetite ratings and measured food intake have been the principle dependent variables in work on GI and diet. Appetite ratings are an imperfect proxy for the more nutritionally relevant outcome of food intake (25). Thus, reports of appetite alone are of uncertain value. A concern with intake as an outcome variable is the timing of data collection. Effects noted at an early time point may be compensated for later (16). It is questionable whether studies measuring intake at one meal subsequent to loading with a food or meal of known GI value can be equated to studies monitoring intake over longer time points. Meal duration is another potential confounder. A slower rate of eating moderates glycemic and insulinemic responses (9). Most trials have controlled this variable but by doing so have compromised the ecological relevance of the outcome. Meal duration varies under free-living conditions. The present study evaluated appetite and food intake after two meals on 2 days a week apart. Intake was assessed over the entire treatment day as well as over nearly 8 days. While the composition of the diet was tightly controlled, eating was ad libitum and the duration was self-determined. Participants ingested  $\sim 396 \pm 32$  g of food per meal on test days, representing an  $\sim 37\%$  higher weight of food ingested compared with the load provided for initial standardized GI determination ( $290 \pm 24.04$  g of food). Meal duration was not recorded but was commonly  $>15$  min. Appetitive and intake data were consistent and failed to reveal differential effects of the low- or high-GI diets. This was true despite the fact that participants were restricted to ingestion of only low- or high-GI foods, conditions designed to maximize observation of GI effects. This would not be true under free-living conditions and raises questions about the ecological significance of such a classification.

Because appetite and intake are governed by a large array of food properties, attribution of treatment effects to the GI value of foods is extremely difficult. One trial (5) involving seven foods differing in GI revealed an inverse association between GI and satiety. However, no con-



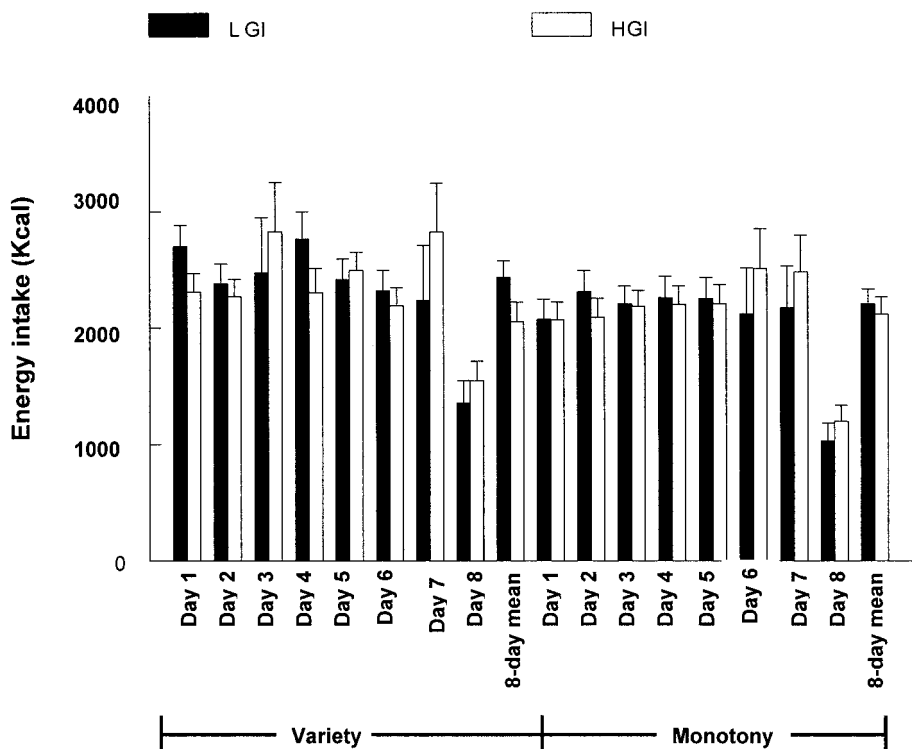
**Figure 2**—Mean ( $\pm$ SE) breakfast and lunch self-reported hunger (A), fullness (B), and desire-to-eat (C) ratings obtained on a general labeled magnitude scale by 39 participants on days 1 and 8. Group breakfast and lunch hunger [ $F(1,38) = 0.46$ ,  $P = 0.525$ ], fullness [ $F(1,38) = 0.10$ ,  $P = 0.750$ ], and desire-to-eat [ $F(1,38) = 0.38$ ,  $P = 0.54$ ] ratings are not significantly different.

control subjects were incorporated to exclude contributions of the different macronutrient compositions, caloric contents, and weights of the foods, all of which are reported to modify appetite. In another experiment (4), loading of high-GI foods resulted in greater energy consumption in an ad libitum meal 5 h later compared with a low-GI preload. However, the low-GI preload contained 20% less carbohydrate and almost double the protein. Further, the low GI was comprised of more solid foods than the high GI. Each of these compositional differences cannot be excluded as the basis for the findings (12). The present study sought to address many of these potentially confounding

factors by monitoring the appetitive and dietary responses to foods closely and individually matched on macronutrient composition and palatability. Despite the empirically confirmed marked GI differences of the test foods, the glycemic and insulinemic responses they elicited were comparable when only low- or only high-GI foods were eaten ad libitum. Moreover, whether due to the absence of differential glycemic and insulinemic responses or to the tighter control over other food attributes, no differences of appetite or food intake were observed. Similar results were noted in another free-living crossover study (26), where isoenergetic diets of similar macronutri-

ent composition, but different GI, were ingested for 30 days. In that study, all meals were provided to the participants who consumed them at home. Thus, while it was longer in duration than the present study, it had less experimental control.

It must be acknowledged that purposeful design features of this study also serve as limitations. All feeding occurred in the laboratory to ensure compliance, and this could alter intake relative to free-living behavior. If so, it would likely further moderate treatment effects rather than accentuate them. The 8-day study duration is longer than most studies but is still short in absolute terms. Whether ef-



**Figure 3**—Group mean ( $\pm$ SE) daily energy intake during the variety and monotony sessions. Low- and high-GI group energy intakes did not differ over the first 7 days ( $P \geq 0.3$ ) or on day 8 ( $P = 0.2$ ) of each session. Energy intake did not differ [ $F(1,38) = 0.002$ ,  $P = 0.97$ ] according to study session.

fects would emerge over a longer time frame warrants further study. Some measures (e.g., appetite, palatability) are subjective in nature but not likely to lead to bias because participants were randomized and not aware of the study purpose.

In summary, the present findings reveal that ad libitum ingestion of only empirically documented low- or high-GI foods, served individually or in mixed meals and matched individually for macronutrient composition and palatability, does not elicit a differential glycemic or insulinemic response either acutely or over a multiday period. Further, there were no significant differences of appetite or energy or macronutrient intake on any assessment day or overall. Although there may be important associations between dietary GI and disease risk (17,27), the present findings raise questions about the predictive power of the GI of a specific food or diet for either appetitive or dietary responses.

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