An insulin index of foods: the insulin demand generated by 1000-kJ portions of common foods[1–3]

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ABSTRACT The aim of this study was to systematically compare postprandial insulin responses to isoenergetic 1000-kJ (240-kcal) portions of several common foods. Correlations with nutrient content were determined. Thirty-eight foods separated into six food categories (fruit, bakery products, snacks, carbohydrate-rich foods, protein-rich foods, and breakfast cereals) were fed to groups of 11–13 healthy subjects. Finger-prick blood samples were obtained every 15 min over 120 min. An insulin score was calculated from the area under the insulin response curve for each food with use of white bread as the reference food (score = 100%). Significant differences in insulin score were found both within and among the food categories and also among foods containing a similar amount of carbohydrate. Overall, glucose and insulin scores were highly correlated ($r = 0.70$, $P < 0.001$, $n = 38$). However, protein-rich foods and bakery products (rich in fat and refined carbohydrate) elicited insulin responses that were disproportionately higher than their glycemic responses. Total carbohydrate ($r = 0.39$, $P < 0.05$, $n = 36$) and sugar ($r = 0.36$, $P < 0.05$, $n = 36$) contents were positively related to the mean insulin scores, whereas fat ($r = -0.27$, NS, $n = 36$) and protein ($r = -0.24$, NS, $n = 38$) contents were negatively related. Consideration of insulin scores may be relevant to the dietary management and pathogenesis of non-insulin-dependent diabetes mellitus and hyperlipidemia and may help increase the accuracy of estimating preprandial insulin requirements. *Am J Clin Nutr* 1997;66:1264–76.

KEY WORDS Insulin, glycemic index, NIDDM, non-insulin-dependent diabetes mellitus, diabetic diet, hyperlipidemia, carbohydrate, insulin score, glucose score, area under the curve, humans

INTRODUCTION

The insulinemic effects of foods may be relevant to the treatment and prevention of weight gain, non-insulin-dependent diabetes mellitus (NIDDM), and associated complications. Recent studies have shown that carbohydrate-rich diets, which result in high postprandial glucose and insulin responses, are associated with undesirable lipid profiles (1, 2), greater body fat (3–5), and the development of insulin resistance in rats (6) and humans (7, 8). Both obesity and NIDDM are associated with varying degrees of insulin resistance and fasting hyperinsulinemia. Prolonged or high degrees of postprandial insulinemia are thought to contribute to the development of insulin resistance and associated diseases (9–17). Therefore, the classification of the relative insulinemic effects of different foods is of both theoretical and practical significance.

Postprandial blood glucose responses have been the focus of much research because of their importance for glycemic control in patients with diabetes. It is now well accepted that different foods containing equal amounts of carbohydrate can produce a wide range of blood glucose responses. The glycemic index (GI) method was developed to rank foods according to the extent to which they increase blood glucose concentrations (18). Tables of GI values of common carbohydrate-containing foods are a useful guide to help people with diabetes choose foods that produce smaller glycemic responses. However, the GI concept does not consider concurrent insulin responses and few studies have reported GI values and their accompanying insulin responses.

The extent to which different dietary factors affect postprandial insulinemia has not been well researched because insulin secretion is largely assumed to be proportional to postprandial glycemia. Furthermore, hyperglycemia is thought to be more relevant to the secondary complications of NIDDM because the abnormal insulin secretion or action in people with diabetes is controlled with exogenous insulin or medications that counteract insulin resistance. However, knowledge of factors that influence both postprandial glycemia and insulin secretion in nondiabetic persons is required to devise treatment strategies that will completely normalize meal-related glycemia (19).

To explore the importance of dietary habits and postprandial insulinemia in the etiology and treatment of NIDDM, we need to be able to systematically rate insulin responses to common foods. If we are to compare insulin responses to foods, what is the best basis of comparison? Should we compare insulin responses to portions of food representing a normal serving size, portions containing an equal amount of carbohydrate, or portions containing an equal amount of energy? GI tables represent the glycemic effects of equal-carbohydrate portions

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TABLE 1
Description and preparation of the test foods

Food	Variety, manufacturer, or place of purchase	Preparation
Fruit		
Black grapes	Waltham cross	Fresh, stem removed, served whole
Apples	Red delicious	Fresh, unpeeled, cut into eight segments
Oranges	Navel	Fresh, peeled, cut into eight segments
Bananas	Cavendish	Fresh, peeled, cut into quarters
Bakery products		
Croissants	Purchased in bulk from supermarket and stored frozen	Defrosted, reheated at 180 °C for 6 min, and served warm
Chocolate cake with frosting	White Wings Foods, Smithfield, Sydney, Australia	Prepared according to manufacturer's directions, stored at 4 °C up to 2 d before serving at room temperature
Doughnuts with cinnamon sugar	Purchased in bulk from supermarket and stored frozen	Prepared by supermarket from standard recipe, defrosted overnight, reheated at 180 °C for 5 min, and served warm
Chocolate chip cookies	Arnott's Biscuits Ltd, Homebush, Sydney, Australia	Served crisp at room temperature, stored in airtight container
Water crackers	Grocery Wholesalers Ltd, Yennora, Australia	Served crisp at room temperature
Snack foods and confectionery		
Mars Bar	Mars Confectionary Australia, Ballarat, Australia	Cut into four standard pieces and served at room temperature
Yogurt	Strawberry fruit yogurt; Australian Co-operative Foods,[1] Wetherill Park, Sydney, Australia	Stored at 4 °C, served cold
Ice cream	Vanilla ice cream; Dairy Bell, Camperdown, Sydney, Australia	Stored frozen and served cold
Jellybeans (assorted colors)	Grocery Wholesalers Ltd	Served at room temperature, stored in airtight container
Peanuts	Salted roasted peanuts; Grocery Wholesalers Ltd	Served at room temperature, stored in airtight container
Potato chips	Crinkle cut chips; Smith's Snackfood Company, Chatswood, Sydney, Australia	Served from freshly opened packet
Popcorn	Microwave cooked popcorn; Uncle Toby's Company Ltd, Wahgunyah, Australia	Prepared according to manufacturer's directions immediately before serving
Protein-rich foods		
Cheese	Mature cheddar cheese; Grocery Wholesalers Ltd	All servings cut from same large block, stored at 4 °C, served cold
Eggs	Poached hens eggs	Poached the day before serving, stored at 4 °C overnight, reheated in microwave oven for 1.5 min immediately before serving
Lentils	Served in tomato sauce[2]	Prepared in bulk according to recipe, stored at 4 °C for up to 2 d, reheated in a microwave oven for 2 min immediately before serving
Baked beans	Canned navy beans in tomato sauce; Franklins, Chullora, Sydney, Australia	Heated on stove for 5 min immediately before serving
Beef steak	Lean topside beef fillets bought in bulk from supermarket, trimmed and stored frozen	Grilled the day before serving, cut into standard bite-sized pieces, and stored at 4 °C overnight; reheated in microwave oven for 2 min immediately before serving
White fish	Ling fish fillets bought in bulk from Sydney fish markets, trimmed and stored frozen	Steamed the day before serving, stored at 4 °C overnight, cut into bite-sized pieces, and reheated in microwave oven for 2 min immediately before serving
Carbohydrate-rich foods		
White bread	Fresh sliced wheat-flour bread; Quality Bakers Australia Ltd, Eastwood, Sydney, Australia	Served fresh and plain at room temperature
Whole-meal bread	Fresh sliced bread made from whole-meal wheat flour; Riga Bakeries, Moorebank, Sydney, Australia	Served fresh and plain at room temperature
Grain bread	Fresh sliced rye bread containing 47% kibbled rye; Tip Top Bakeries, Chatswood, Sydney, Australia	Served fresh and plain at room temperature
White rice	Calrose rice (Sunwhite), Ricegrowers' Co-operative Ltd, Leeton, Australia	Boiled 12 min and stored overnight at 4 °C, reheated in microwave oven for 1.5 min immediately before serving
Brown rice	Calrose rice (Sunbrown), Ricegrowers' Co-operative Ltd	Boiled 12 min and stored overnight at 4 °C, reheated in microwave oven for 1.5 min immediately before serving
White pasta	Spirals	Boiled 8 min and stored overnight at 4 °C
Brown pasta	Whole-meal spirals; San Remo Pasta Company, Auburn, Sydney, Australia	Reheated in microwave oven for 1.5 min immediately before serving
Potatoes	Russet potatoes	Peeled, boiled for 20 min, and stored at 4 °C overnight; reheated in a microwave oven for 2 min immediately before serving

TABLE 1
Continued

Food	Variety, manufacturer, or place of purchase	Preparation
French fries	Prefried oven-baked French fries; McCain's Foods (Australia), Castle Hill, Sydney, Australia	Stored frozen, cooked in conventional oven for 15 min immediately before serving
Breakfast cereals[3]		
Cornflakes	Kellogg's Australia Pty Ltd, Pagewood, Sydney, Australia	—
Special K	Toasted flakes made from wheat and rice flour, high in protein; Kellogg's Australia Pty Ltd	—
Honeysmacks	Puffed whole-wheat grains with a honey-based coating; Kellogg's Australia Pty Ltd	—
Sustain	A mixture of wheat, corn, and rice flakes; rolled oats; dried fruit; and flaked almonds; Kellogg's Australia Pty Ltd	—
All-Bran	A high-fiber cereal made from wheat bran; Kellogg's Australia Pty Ltd	—
Natural muesli	Based on raw rolled oats, wheat bran, dried fruit, nuts, and sunflower seeds; Uncle Toby's Company Ltd, Wahgunyah, Australia	—
Porridge	Uncle Toby's Company Ltd, Wahgunyah, Australia	Raw rolled oats cooked in a microwave oven according to manufacturer's directions and served without sweetener

[1] Now Dairy Farmer's.
[2] Recipe: 15 mL olive oil, 350 g dried green lentils, 410 g canned tomatoes, 120 g onion, 1 clove garlic, and 1 tsp pepper.
[3] All cereals were served fresh with 125 mL fat-reduced (1.5% fat) milk.

of foods. However, carbohydrate is not the only stimulus for insulin secretion. Protein-rich foods or the addition of protein to a carbohydrate-rich meal can stimulate a modest rise in insulin secretion without increasing blood glucose concentrations, particularly in subjects with diabetes (20–22). Similarly, adding a large amount of fat to a carbohydrate-rich meal increases insulin secretion even though plasma glucose responses are reduced (23, 24).

Thus, postprandial insulin responses are not always proportional to blood glucose concentrations or to a meal's total carbohydrate content. Several insulinotropic factors are known to potentiate the stimulatory effect of glucose and mediate postprandial insulin secretion. These include fructose, certain amino acids and fatty acids, and gastrointestinal hormones such as gastric inhibitory peptide, glucagon, and cholecystokinin (25, 26). Thus, protein- and fat-rich foods may induce substantial insulin secretion despite producing relatively small blood glucose responses. We therefore decided that comparing the insulinemic effects of foods on an isoenergetic basis was a logical and practical approach.

The aim of this study was to systematically compare postprandial insulin responses to isoenergetic portions of a range of common foods. An insulin score (IS) was calculated for each food on the basis of its insulinemic effect relative to a reference food. Thirty-eight foods, categorized into six different food groups, were studied to determine which foods within the same food group were most insulinogenic. We hypothesized that postprandial insulin responses are not closely related to the carbohydrate content or glycemic effects of some foods.

SUBJECTS AND METHODS

Test foods

Thirty-eight foods were tested and were grouped into six food categories: *1*) fruit: grapes, bananas, apples, and oranges; *2*) bakery products: croissants, chocolate cake with icing, doughnuts with cinnamon sugar, chocolate chip cookies, and water crackers; *3*) snack foods and confectionery: Mars Bar candy bar (Mars Confectionary Australia, Ballarat, Australia), strawberry yogurt, vanilla ice cream, jellybeans, salted roasted peanuts, plain potato chips, and plain popcorn; *4*) protein-rich foods: cheddar cheese, poached eggs, boiled lentils in a tomato sauce, baked beans in a tomato sauce, grilled beef steak, and steamed white fish; *5*) carbohydrate-rich foods: white bread, whole-meal bread, rye-grain bread, white rice, brown rice, white pasta, brown pasta, boiled potatoes, and oven-baked French fries; and *6*) breakfast cereals: Cornflakes (Kellogg's Australia Pty Ltd, Pagewood, Australia), Special K (Kellogg's Australia Pty Ltd), Honeysmacks (Kellogg's Australia Pty Ltd), Sustain (Kellogg's Australia Pty Ltd), All-Bran (Kellogg's Australia Pty Ltd), natural muesli, and oatmeal porridge.

Each food was served plain as a 1000-kJ portion with 220 mL water. White bread was used as the reference food for each food group. The foods were selected to represent a range of natural and processed foods commonly eaten in industrialized societies. Details of the foods and their preparation methods are listed in **Table 1**. Foods were bought in bulk to minimize variations in composition and were served in standard-sized pieces. The nutritional composition of each food per 1000 kJ as calculated from Australian food tables or manufacturers' data is shown in **Table 2**.

Subjects

Separate groups of healthy subjects (n = 11–13) were recruited to test each category of foods. Volunteers were excluded if they were smokers or taking prescription medications, had a family history of diabetes or obesity, were dieting, or had irregular eating habits. In total, 41 subjects participated. One subject consumed all of the test foods and 15 other subjects

TABLE 2
Nutritional composition of the test foods per 1000-kJ serving as calculated from Australian food tables or manufacturers' data[1]

Food	Serving weight	Fat	Protein	Carbohydrate		Fiber	Water	Energy density
				Sugar	Starch			
	g	*g*	*g*	*g*		*g*	*g*	*kJ/g*
Fruit								
Grapes	395	0.4	3.2	56.9	0.0	3.6	317.0	2.5
Bananas	279	0.3	4.7	47.2	8.4	6.1	210.1	3.6
Apples	435	0.0	1.3	56.5	2.2	9.1	360.9	2.3
Oranges	625	0.6	6.9	50.6	0.0	12.5	539.4	1.6
Bakery products								
Croissants	61	14.4	6.1	3.1	18.6	1.8	13.5	16.4
Cake[2]	64	11.9	4.3	20.1	10.5	0.7	10.7	15.6
Doughnuts	65	13.4	4.3	8.9	17.0	1.4	16.1	15.4
Cookies[2]	51	10.9	2.4	18.7	16.2	1.0	2.1	19.6
Crackers	58	5.4	5.8	1.3	40.2	1.6	2.2	17.2
Snacks and confectionery								
Mars Bar[2]	54	9.4	2.9	36.7	1.1	1.7	3.5	18.5
Yogurt[2]	241	5.3	11.8	37.6	0.0	0.5	187.0	4.2
Ice cream	120	13.4	5.2	25.8	0.0	0.0	74.2	8.3
Jellybeans	88	0.0	5.3	44.6	11.5	0.0	12.2	11.4
Peanuts	38	20.1	9.6	1.7	3.7	2.4	0.6	26.3
Potato chips[2]	44	16.2	2.7	0.2	22.1	2.4	1.1	22.7
Popcorn[2]	47	13.0	4.6	2.1	25.3	6.2	1.7	21.3
Protein-rich foods								
Cheese	59	20.0	15.0	0.1	0.0	0.0	20.9	16.9
Eggs	159	17.9	19.6	0.5	0.0	0.0	119.4	6.3
Lentils	253	4.6	19.4	4.2	24.9	11.4	222.0	3.9
Baked beans	351	1.7	16.1	16.1	23.2	16.8	267.1	2.8
Beef steak	158	7.7	42.0	0.0	0.0	0.0	104.3	6.3
Fish	333	1.0	56.3	0.0	0.0	0.0	250.0	3.0
Carbohydrate-rich foods								
White bread[2]	94	2.1	8.5	1.8	44.1	3.3	36.1	10.6
Whole-meal bread[2]	101	2.6	7.6	1.7	43.7	6.6	40.3	9.9
Grain bread[2]	108	5.4	9.4	2.4	37.6	6.5	41.4	9.3
White rice[2]	203	0.5	5.0	0.1	56.0	0.4	140.0	4.9
Brown rice[2]	148	2.1	5.2	0.5	52.6	1.4	93.9	6.8
White pasta	201	0.8	7.8	2.0	47.1	3.5	134.8	5.0
Brown pasta[2]	218	1.6	11.3	0.7	47.8	10.9	132.6	4.6
Potatoes	368	1.0	10.0	3.1	45.9	9.2	290.8	2.7
French fries[2]	93	8.7	3.9	1.1	35.4	3.5	33.8	10.7
Breakfast cereals								
Cornflakes[2]	170	2.1	8.4	10.2	36.1	1.5	110.9	5.9
Special K[2]	172	2.1	15.3	14.0	27.2	1.4	111.2	5.8
Honeysmacks[2]	172	2.2	8.7	31.1	17.0	2.6	115.0	5.8
Sustain[2]	168	3.1	9.7	13.7	29.1	3.2	119.1	5.9
Muesli[2]	175	6.1	10.7	17.1	19.8	6.6	114.1	5.7
Porridge[2]	383	6.2	10.9	7.5	29.0	4.7	333.7	2.6
All-Bran[2]	174	2.9	11.7	13.9	29.4	14.1	111.0	5.7

[1] Mars Bar, Mars Confectionary Australia, Ballarat, Australia; Cornflakes, Special K, Honeysmacks, Sustain, and All-Bran: Kellogg's Australia Pty Ltd, Pagewood, Australia.
[2] Nutrient composition calculated from manufacturer's data.

completed two or more food categories. All of the subjects were university students; relevant characteristics of the subjects are listed in **Table 3**. The mean body mass index (BMI, in kg/m^2) of the 41 subjects was 22.7 ± 0.4 (range: 19–29). Three subjects had a BMI > 25 but two of these were short, stocky males who had excess muscle rather than fat. Female subjects did not participate during their menstrual period or if they experienced adverse premenstrual symptoms. Informed consent was obtained from all of the subjects and the study was approved by the Medical Ethical Review Committee of the University of Sydney.

Protocol

Each subject first consumed a 1000-kJ portion of white bread (45.9 g carbohydrate) to confirm normal glucose tolerance. White bread was also used as the reference food (IS = 100%) against which all other foods were compared, similar to the method used for calculating GI values of foods (18). The use of

TABLE 3
Characteristics of each group of subjects[1]

Food group	Age	BMI[2]
	y	
Fruit (n = 5 F, 6 M)	22.9 ± 3.9	22.9 ± 1.4
Bakery products (n = 6 F, 6 M)	22.2 ± 3.7	23.1 ± 2.7
Snacks and confectionery (n = 5 F, 7 M)	21.0 ± 1.2	22.9 ± 3.5
Protein-rich foods (n = 5 F, 6 M)	22.4 ± 2.8	24.3 ± 3.1
Carbohydrate-rich foods (n = 5 F, 8 M)	21.0 ± 1.9	23.0 ± 1.9
Breakfast cereals (n = 5 F, 6 M)	22.8 ± 3.9	22.8 ± 1.4

[1] $\bar{x}$ ± SD.
[2] In kg/m^2.

a reference food controls for inherent differences between individuals that affect insulin sensitivity, such as body weight and activity levels.

Subjects were fed 1000-kJ portions of the test foods in a random order on separate mornings after a 10-h overnight fast. Within each food group, each subject acted as his or her own control, being tested at the same time of day and under as similar conditions as possible. Subjects were asked to refrain from unusual activity and food intake patterns, to abstain from alcohol and legumes the day before a test, and to eat a similar meal the night before each test. When subjects arrived at the lab in the morning, they completed a short questionnaire assessing recent food intake and activity patterns. A fasting finger-prick blood sample was collected and subjects were then given a test food and 220 mL water (0 min). When possible, foods were presented under a large opaque plastic hood with a hole through which volunteers pulled out pieces of the test food one at a time. This was an attempt to minimize between-subject variation in cephalic-phase insulin secretion arising from the sensory stimulation associated with the anticipation and act of eating (27). However, this was not feasible for the liquid foods (yogurt and ice cream), foods served in a sauce (baked beans and lentils), or with milk (all of the breakfast cereals), which were presented in standard bowls without the hood.

Subjects were asked to eat and drink at a comfortable rate. Immediately after finishing the test food, subjects recorded the time taken to eat the food and completed a questionnaire assessing various appetite responses and the food's palatability. [These results are reported in a separate paper (28).] Subjects remained seated at tables in a quiet environment and were not permitted to eat or drink until the end of the session (120 min).

Finger-prick blood samples (1.5–2.5 mL) were collected from warmed hands immediately before the meal (0 min) and 15, 30, 45, 60, 75, 90, 105, and 120 min after the start of the meal (into plastic tubes that had been kept on ice) with use of an automatic lancet device (Autoclix; Boehringer Mannheim Australia, Castle Hill, Australia). Blood samples were centrifuged immediately after collection (1 min at 12 500 × g at room temperature) and plasma was pipetted into chilled tubes and immediately stored at −20 °C until analyzed (< 1 mo). Plasma glucose concentrations were analyzed in duplicate with a Cobas Fara automatic spectrophotometric analyzer (Roche Diagnostica, Basel, Switzerland) and the glucose hexokinase enzymatic assay. The mean within-assay and between-assay precisions (CVs) were both < 6%. Plasma insulin concentrations were measured in duplicate by using an antibody-coated-tube radioimmunoassay kit (Coat-A-Count; Diagnostic Products Corporation, Los Angeles). For both plasma glucose and insulin analysis, all nine plasma samples for a particular subject's test were analyzed within the same run to reduce any error introduced by interassay variation. When possible, all plasma samples for a particular subject were analyzed for insulin within the same run. For the insulin analysis, the mean within-assay CV was 5% and the mean between-assay CV was 7%.

Statistical analysis

Cumulative changes in postprandial plasma glucose and insulin responses for each food were quantified as the incremental area under the 120-min response curve (AUC), which was calculated by using the trapezoidal rule with fasting concentrations as the baseline and truncated at zero. Any negative areas tended to be small and were ignored. For each subject, an IS (%) was calculated for each test food by dividing the insulin AUC value for the test food by the insulin AUC value for white bread (the reference food), and expressed as a percentage as follows:

$$\text{IS (\%)} = \frac{\text{Area under the 120-min insulin response curve for 1000 kJ test food}}{\text{Area under the 120-min insulin response curve for 1000 kJ white bread}} \times 100 \quad (1)$$

This equation is similar to that developed by Wolever and Jenkins (29) for calculating GI values. A glucose score (GS) (not the same as a GI score, which is based on a 50-g carbohydrate portion) for each food was also calculated by using the same equation with the corresponding plasma glucose results.

Analysis of variance (ANOVA) and Fisher's probable least-significant-difference test for multiple comparisons were used to determine statistical differences among the foods within each food group (STATVIEW STUDENT SOFTWARE; Abacus Concepts Inc, Berkley, CA). Linear-regression analysis was used to test associations between glucose and insulin responses and nutritional indexes (MINITAB DATA ANALYSIS SOFTWARE, version 7.0; Minitab Inc, State College, PA). Test foods not containing a particular nutrient were excluded from these analyses. Therefore, sample sizes for the correlations between individual nutrients and the mean GSs and ISs varied from 32 to 36. Mean results for white bread for each food group were included in some statistical analyses, so these correlations were made with 43 values. One subject from the protein-rich food group did not complete the fish test and one subject from the breakfast cereal group did not complete the Sustain test. Therefore, in total, 503 individual tests were fully completed.

Stepwise-multiple-regression analysis was used to examine the extent to which the different macronutrients and GSs accounted for the variability of the ISs (MINITAB DATA ANALYSIS SOFTWARE). For this analysis, the individual white bread GS and IS results were included for the carbohydrate-rich food group only; therefore, this analysis was performed with 446 individual observations for 38 foods. Including the white bread results for each food group (n = 503) suggests that independent repeat tests were done for white

TABLE 4
Areas under the 120-min plasma glucose and insulin response curves (AUCs), ratio of insulin AUC to glucose AUC, the insulin AUC per g carbohydrate and per g serving weight, and mean glucose and insulin scores[1]

Food	Glucose AUC	Insulin AUC	Insulin AUC: glucose AUC	Insulin AUC per g carbohydrate	Insulin AUC per g serving weight	Glucose score	Insulin score
	mol · min/L	*pmol · min/L*		*pmol · min · L^{-1} · g^{-1}*	*pmol · min · L^{-1} · g^{-1}*	%	%
Breakfast cereals							
White bread	156 ± 21	13 557 ± 1756	108 ± 19	295 ± 38	144 ± 19	100 ± 0	100 ± 0
All-Bran	59 ± 9	4299 ± 612	87 ± 15	99 ± 14	25 ± 3	40 ± 7	32 ± 4
Porridge	80 ± 9	5093 ± 493	74 ± 11	139 ± 13	13 ± 1	60 ± 12	40 ± 4
Muesli	65 ± 12	6034 ± 813	118 ± 18	163 ± 22	34 ± 5	43 ± 7	46 ± 5
Special K	106 ± 14	8038 ± 635	95 ± 14	195 ± 15	47 ± 4	70 ± 9	66 ± 5
Honeysmacks	91 ± 10	9102 ± 1506	108 ± 12	189 ± 31	53 ± 9	60 ± 7	67 ± 6
Sustain	93 ± 8	8938 ± 757	102 ± 9	209 ± 18	53 ± 4	66 ± 6	71 ± 6
Cornflakes	110 ± 11	8768 ± 623	88 ± 5	189 ± 13	52 ± 4	76 ± 11	75 ± 8
Group mean	—	7183 ± 357	92 ± 5	169 ± 8	39 ± 2	59 ± 3	57 ± 3
Carbohydrate-rich foods							
White bread	120 ± 13	12 882 ± 1901	112 ± 15	281 ± 41	137 ± 20	100 ± 0	100 ± 0
White pasta	50 ± 11	4456 ± 453	156 ± 48	91 ± 9	22 ± 2	46 ± 10	40 ± 5
Brown pasta	74 ± 7	4535 ± 574	67 ± 10	93 ± 12	21 ± 3	68 ± 10	40 ± 5
Grain bread	68 ± 9	6659 ± 837	106 ± 12	166 ± 21	62 ± 8	60 ± 12	56 ± 6
Brown rice	113 ± 13	6240 ± 616	58 ± 5	117 ± 11	42 ± 4	104 ± 18	62 ± 11
French fries	70 ± 11	7643 ± 713	146 ± 29	209 ± 19	82 ± 8	71 ± 16	74 ± 12
White rice	129 ± 16	8143 ± 683	69 ± 5	145 ± 12	40 ± 3	110 ± 15	79 ± 12
Whole-meal bread	106 ± 14	11 203 ± 1420	122 ± 20	247 ± 31	111 ± 14	97 ± 17	96 ± 12
Potatoes	148 ± 24	13 930 ± 1467	120 ± 19	284 ± 30	38 ± 4	141 ± 35	121 ± 11
Group mean	—	8410 ± 461	106 ± 8	182 ± 10	62 ± 5	88 ± 6	74 ± 8
Protein-rich foods							
White bread	121 ± 19	17 438 ± 3154	177 ± 35	387 ± 63	185 ± 33	100 ± 0	100 ± 0
Eggs	36 ± 11	4744 ± 1017	135 ± 92	9340 ± 1845	30 ± 6	42 ± 16	31 ± 6
Cheese	42 ± 10	5994 ± 1590	268 ± 153	64 257 ± 15 013	106 ± 27	55 ± 18	45 ± 13
Beef	18 ± 6	7910 ± 2193	1583 ± 939	—	50 ± 14	21 ± 8	51 ± 16
Lentils	63 ± 17	9268 ± 2174	307 ± 103	325 ± 68	37 ± 9	62 ± 22	58 ± 12
Fish	29 ± 14	9350 ± 2055	775 ± 502	—	28 ± 6	28 ± 13	59 ± 18
Baked beans	110 ± 14	20 106 ± 3776	183 ± 44	504 ± 87	57 ± 11	114 ± 18	120 ± 19
Group mean	—	9983 ± 1032	585 ± 61	18 607 ± 5456	53 ± 6	54 ± 7	61 ± 7
Fruit							
White bread	171 ± 19	15 563 ± 1632	105 ± 18	339 ± 36	166 ± 17	100 ± 0	100 ± 0
Apples	83 ± 7	8919 ± 910	118 ± 18	152 ± 15	20 ± 2	50 ± 6	59 ± 4
Oranges	66 ± 11	9345 ± 1074	166 ± 23	185 ± 21	15 ± 2	39 ± 7	60 ± 3
Bananas	133 ± 12	12 445 ± 1353	108 ± 22	224 ± 24	45 ± 5	79 ± 10	81 ± 5
Grapes	126 ± 14	12 293 ± 1190	113 ± 19	216 ± 21	31 ± 3	74 ± 9	82 ± 6
Group mean	—	10 751 ± 605	124 ± 10	194 ± 11	28 ± 2	61 ± 5	71 ± 3
Snacks and confectionery							
White bread	159 ± 29	15 592 ± 2376	104 ± 24	340 ± 52	166 ± 25	100 ± 0	100 ± 0
Peanuts	20 ± 7	3047 ± 828	214 ± 88	564 ± 153	80 ± 22	12 ± 4	20 ± 5
Popcorn	71 ± 12	6537 ± 679	109 ± 32	239 ± 25	139 ± 14	62 ± 16	54 ± 9
Potato chips	77 ± 15	8195 ± 1577	169 ± 78	367 ± 71	186 ± 36	52 ± 9	61 ± 14
Ice cream	93 ± 17	12 348 ± 1867	172 ± 38	479 ± 72	103 ± 16	70 ± 19	89 ± 13
Yogurt	88 ± 23	15 611 ± 1808	167 ± 33	415 ± 48	65 ± 7	62 ± 15	115 ± 13
Mars Bar	98 ± 10	16 682 ± 1896	218 ± 65	441 ± 50	309 ± 35	79 ± 13	122 ± 15
Jellybeans	161 ± 18	22 860 ± 368	133 ± 27	407 ± 64	260 ± 41	118 ± 18	160 ± 16
Group mean	—	12 183 ± 994	191 ± 20	416 ± 30	163 ± 14	65 ± 6	89 ± 7
Bakery products							
White bread	129 ± 15	17 599 ± 3058	188 ± 64	383 ± 67	187 ± 33	100 ± 0	100 ± 0
Doughnuts	78 ± 14	12 445 ± 2402	113 ± 21	480 ± 93	191 ± 37	63 ± 12	74 ± 9
Croissants	89 ± 6	13 097 ± 2978	483 ± 244	604 ± 137	215 ± 49	74 ± 9	79 ± 14
Cake	61 ± 11	14 305 ± 3472	178 ± 54	467 ± 113	223 ± 54	56 ± 14	82 ± 12
Crackers	139 ± 26	14 673 ± 2686	331 ± 104	354 ± 65	253 ± 46	118 ± 24	87 ± 12
Cookies	92 ± 12	15 223 ± 382	200 ± 57	436 ± 110	298 ± 75	74 ± 11	92 ± 15
Group mean	—	12 681 ± 1325	261 ± 56	468 ± 47	236 ± 24	77 ± 7	83 ± 5

[1] $\bar{x}$ ± SEM. Mars Bar, Mars Confectionary Australia, Ballarat, Australia; All-Bran, Special K, Honeysmacks, Sustain, and Cornflakes: Kellogg's Australia Pty Ltd, Pagewood, Australia.

bread, which artificially increases the accuracy of any calculation involving white bread.

RESULTS

Fasting glucose and insulin concentrations

Within each food group, the subjects' average fasting plasma glucose and insulin concentrations were not significantly different among the foods. Mean fasting plasma glucose concentrations did not vary significantly among the six food groups, whereas mean fasting insulin concentrations were more variable, ranging from ≈42 to 120 pmol/L. Fasting insulin concentrations were not more variable in females than in males and there were no significant differences at various stages of the menstrual cycle. A significant correlation was found between mean fasting insulin concentrations and mean BMI values for the six groups of subjects ($r = 0.81$, $P < 0.05$, $n = 6$).

Postprandial glucose and insulin responses

As with any biological response, there was between-subject variation in the glucose and insulin responses to the same food. Two-way ANOVA was used to examine the ranking of each subject's responses to the different test foods within a food group (ie, interindividual variation). There were significant differences among the subjects in the rank order of their glucose AUC responses except within the fruit and protein-rich food groups. There were also significant differences among the subjects' rank order of insulin AUC responses within all food groups. However, individual subjects within each food group consistently produced relatively low, medium, or high insulin responses. Furthermore, subjects produced their lowest insulin responses for the least insulinogenic foods and their highest insulin responses for the most insulinogenic foods within each food group.

There were large differences in mean glycemic and insulin responses to the foods, both within and between food groups. Mean glucose and insulin AUC results, mean GSs and ISs, and the mean ratios of insulin to glucose AUCs (the amount of insulin secretion in relation to the blood glucose response) are listed in **Table 4**. Mean GSs and ISs were calculated for each food group by averaging the scores for all test foods within the food group. On average, the snack food group produced the highest food group IS (89%), followed by bakery products (83%), carbohydrate-rich foods (74%), fruit (71%), protein-rich foods (61%), and breakfast cereals (57%). Average GSs for the food groups did not follow the same rank order (**Figure 1**). The carbohydrate-rich food group produced the highest average GS (88%), followed by bakery products (77%), snack foods (65%), fruit (61%), breakfast cereals (59%), and protein-rich foods (54%). Interestingly, the GS rank order is not proportional to the average total carbohydrate content of each food group, which highlights the influence of other food factors (eg, fiber and processing) in determining the rate of carbohydrate digestion and absorption.

Overall, among the 38 test foods, jellybeans produced the highest mean IS (160 ± 16%), eightfold higher than the lowest IS (for peanuts: 20 ± 5%) (**Figure 2**). White bread, the standard food, consistently produced one of the highest glucose and insulin responses (peak and AUC) and had a higher IS than most of the other foods (84%). All of the breakfast cereals were significantly less insulinogenic than white bread ($P < 0.001$). All-Bran and porridge both produced a significantly lower IS than the other cereals ($P < 0.001$), except muesli. Despite containing more carbohydrate than porridge and muesli, All-Bran produced the lowest GS. Baked beans, which contain considerably more carbohydrate than the other protein-rich foods, produced a significantly higher GS and IS ($P < 0.001$). On average, fish elicited twice as much insulin secretion as did the equivalent portion of eggs. Within the fruit group, oranges and apples produced a significantly lower GS and IS than

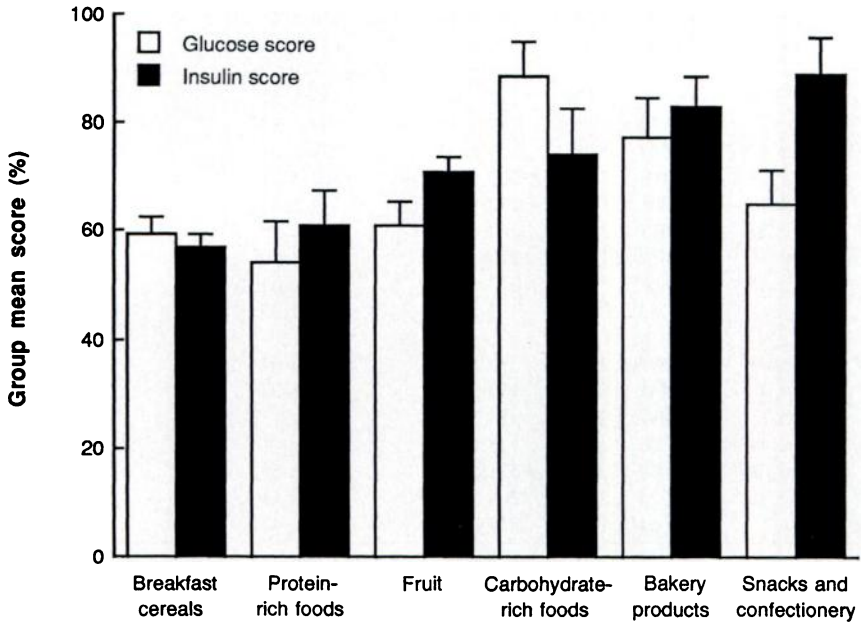

FIGURE 1. Mean (± SEM) glucose and insulin scores for each food group.

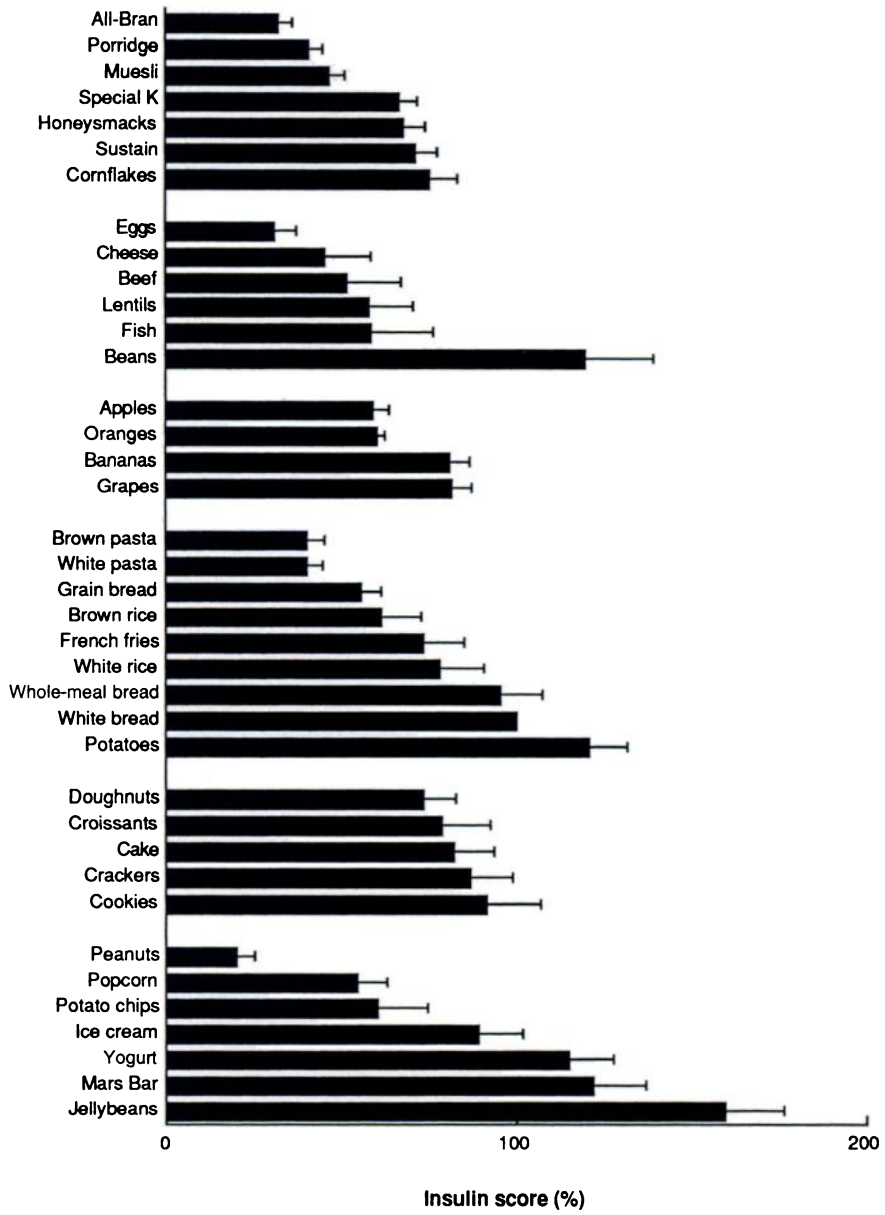

FIGURE 2. Mean (± SEM) insulin scores for 1000-kJ portions of the test foods. White bread was the reference food (insulin score = 100%). All-Bran cereal, Special K cereal, Honeysmacks cereal, Sustain cereal, and Cornflakes, Kellogg's Australia Pty Ltd, Pagewood, Australia; Mars Bar candy bar, Mars Confectionary Australia, Ballarat, Australia.

grapes and bananas ($P < 0.05$ to $P < 0.001$), despite containing a similar amount of carbohydrate.

Potatoes produced significantly higher GSs and ISs than all of the other carbohydrate-rich foods. White bread produced a higher GS and IS than grain bread ($P < 0.05$ and $P < 0.001$ respectively), but whole-meal bread and white bread had similar scores. White and brown rice had similar GSs and ISs, as did white and brown pasta. Among the bakery products, crackers produced a significantly higher GS than the other test foods, but there were no significant differences in ISs within this group (all tended to be high). Among the snack foods, jellybeans produced a significantly higher GS and IS than the other foods in this group. Despite containing similar amounts of carbohydrate, jellybeans induced twice as much insulin secretion as any of the four fruits. The candy bar and yogurt, which both contained large amounts of sugar in combination with fat or protein, produced relatively high ISs. Popcorn and potato chips elicited twice as much insulin secretion as peanuts ($P < 0.05$ and $P < 0.01$, respectively).

Significant differences were found both within and among the food groups when the insulin AUC responses were examined as a function of the food's carbohydrate content (Table 4). On average, protein-rich foods produced the highest insulin secretion per gram of carbohydrate (food group mean: 18 607 pmol · min · L^{-1} · g^{-1}) (because of their mostly low carbohydrate contents), followed by bakery products (468 pmol · min · L^{-1} · g^{-1}), snack foods (416 pmol · min · L^{-1} · g^{-1}), fruit (194 pmol · min · L^{-1} · g^{-1}), carbohydrate-rich foods (182 pmol · min · L^{-1} · g^{-1}), and breakfast cereals (169 pmol · min · L^{-1} · g^{-1}). When the

insulin AUC response was examined in relation to the food's serving size (g), the bakery products were the most insulinogenic (food group mean: 236 pmol · min · L^{-1} · g^{-1}), followed by snack foods (163 pmol · min · L^{-1} · g^{-1}), carbohydrate-rich foods (62 pmol · min · L^{-1} · g^{-1}), protein-rich foods (53 pmol · min · L^{-1} · g^{-1}), breakfast cereals (39 pmol · min · L^{-1} · g^{-1}), and fruit (28 pmol · min · L^{-1} · g^{-1}). These results reflect the insulinogenic effects of protein and fat.

Insulin responses in relation to glucose responses

Overall, mean glucose and insulin AUC values were positively correlated ($r = 0.67$, $P < 0.001$, $n = 43$), as were the peak glucose and insulin values ($r = 0.57$, $P < 0.001$, $n = 43$). Hence, the mean GSs and ISs were highly correlated ($r = 0.70$, $P < 0.001$, $n = 38$) (**Figure 3**). The peak glucose concentration (change from fasting) correlated positively with glucose AUC values ($r = 0.74$, $P < 0.001$, $n = 43$) and peak insulin concentrations were proportional to the insulin AUC values ($r = 0.95$, $P < 0.001$, $n = 43$). In addition, the observed GSs for 1000-kJ portions of the foods correlated with previously published GI values based on portions of foods containing 50 g carbohydrate ($r = 0.65$, $P < 0.001$, $n = 32$). Six test foods (chocolate chip cookies, eggs, cheese, beef, fish, and Honeysmacks cereal) were not included in this analysis because GI values were not available.

Insulin AUC values were divided by glucose AUC values to determine which foods were markedly insulinogenic relative to their glycemic effect (Table 4 and **Figure 4**). On average, the protein-rich foods stimulated a large amount of insulin secretion relative to their glycemic response, followed by the bakery products, snack foods, fruit, carbohydrate-rich foods, and breakfast cereals.

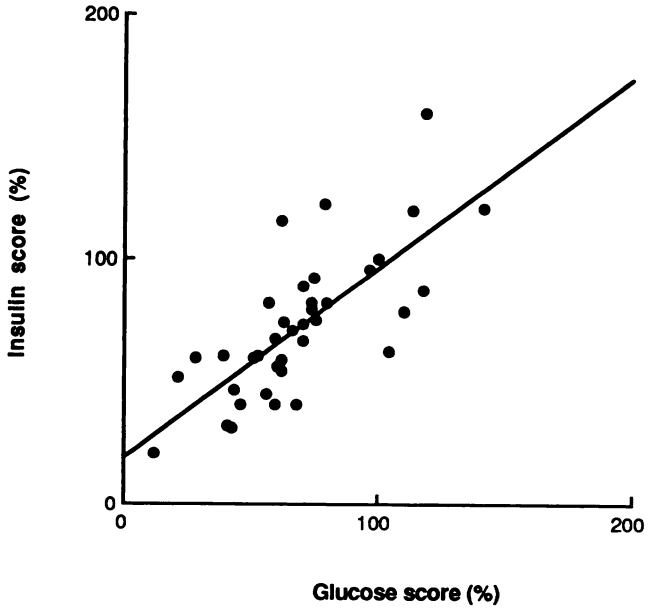

FIGURE 3. Relation between the mean glucose and insulin scores ($r = 0.74$, $P < 0.001$, $n = 38$).

Relations between metabolic responses and nutrient contents of the foods

Correlations between the macronutrient compositions of the test foods and the mean ISs are shown in **Figure 5**. The portion size (energy density: kJ/g), water, and fiber contents of the foods were not significantly related to the mean ISs. The relation between protein contents and ISs was negative but not significant ($r = -0.24$, $n = 38$). The mean ISs were positively related to total carbohydrate content ($r = 0.39$, $P < 0.05$, $n = 36$) and sugar content ($r = 0.36$, $P < 0.05$, $n = 36$), but were not significantly related to starch content ($r = -0.09$, $n = 30$). Fat content was negatively related to the mean IS ($r = -0.27$, NS, $n = 36$). When expressed as a percentage of total energy, fat ($r = -0.27$, NS, $n = 36$) and protein ($r = -0.24$, NS, $n = 38$) were negatively associated with the mean IS, whereas total carbohydrate was positively related ($r = 0.37$, $P < 0.05$, $n = 36$).

Relations between the GSs and the nutrients largely followed the same directions as the IS correlations. Mean GSs were not significantly related to the foods' serving sizes or water or fiber contents. Mean GSs correlated negatively with fat ($r = -0.38$, $P < 0.05$, $n = 36$) and protein ($r = -0.38$, $P < 0.05$, $n = 38$) contents, and positively with total carbohydrate content ($r = 0.32$, NS, $n = 36$). Unlike the ISs, the GSs were significantly related to starch content ($r = 0.43$, $P < 0.05$, $n = 30$) but not sugar content ($r = -0.07$, NS, $n = 36$). When expressed as a percentage of total energy, fat ($r = -0.38$, $P < 0.05$, $n = 36$) and protein ($r = -0.39$, $P < 0.05$, $n = 38$) were negatively associated with mean GSs, whereas total carbohydrate content was positively related ($r = 0.46$, $P < 0.01$, $n = 36$).

Stepwise-multiple-regression analysis of the 446 individual results for the 38 foods was performed to determine the extent to which the macronutrients and GSs accounted for the variability of the ISs. Unfortunately, it was not possible to generate a single multiple-regression equation that included all of the macronutrients because some pairs of nutrients were highly correlated (eg, fat and protein, fiber and water, total carbohydrate and sugar or starch, and sugar and starch). The regression equation that included all of the macronutrients had unacceptably high variance inflation factors. Therefore, two separate regression equations were generated that were limited to the factors that were measured and not interdependent. Equation *2* includes fat but not protein, whereas equation *3* includes protein but not fat:

$$\text{IS} = 72.4 + 0.383\ \text{GS} - 1.88\ \text{fat} - 0.103\ \text{water} + 0.509\ \text{sugar} - 0.421\ \text{starch} \quad (2)$$

for which SD = 37.34, $R^2 = 33.1\%$, and adjusted $R^2 = 32.4\%$. P values (significance found in the linear-regression analysis for the associations between the individual nutrients and the IS) are as follows: GS and water ($P < 0.000$), fat ($P < 0.001$), sugar ($P < 0.005$), and starch ($P < 0.036$).

$$\text{IS} = 23.2 + 0.383\ \text{GS} + 0.785\ \text{protein} - 0.098\ \text{water} + 1.29\ \text{sugar} + 0.377\ \text{starch} \quad (3)$$

for which SD = 37.42, $R^2 = 32.8\%$, and adjusted $R^2 = 32.1\%$. P values are as follows: GS, water, and sugar ($P < 0.000$); protein ($P < 0.003$); and starch ($P < 0.02$).

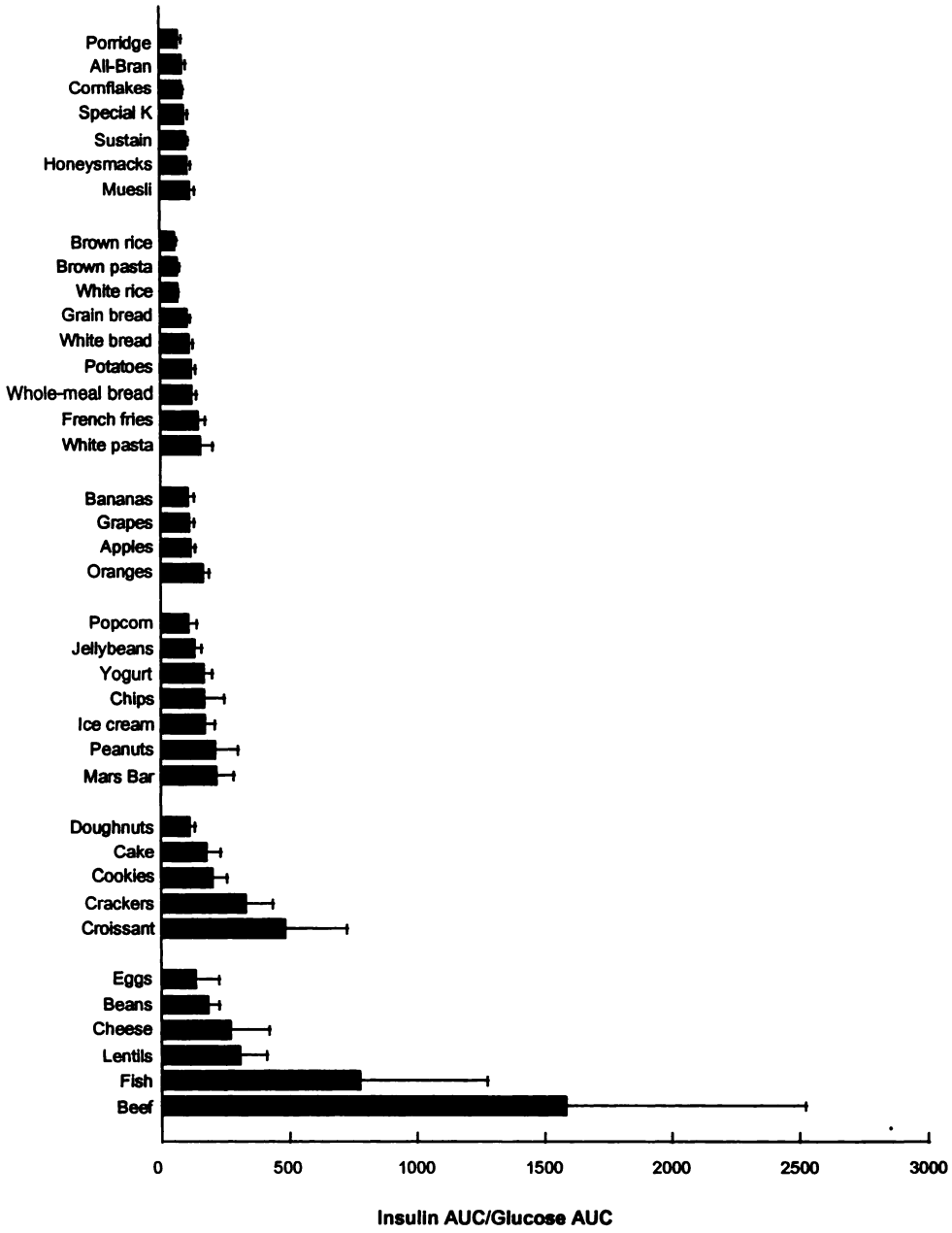

FIGURE 4. Ratio of insulin area under the curve (AUC) to glucose AUC responses. $\bar{x} \pm$ SEM. All-Bran cereal, Special K cereal, Honeysmacks cereal, Sustain cereal, and Cornflakes, Kellogg's Australia Pty Ltd, Pagewood, Australia; Mars Bar candy bar, Mars Confectionary Australia, Ballarat, Australia.

Linear-regression analysis of the individual GS and IS results had an R^2 value of 23%. Therefore, the glycemic response was a significant predictor of the insulin response, but it accounted for only 23% of the variability in insulinemia. The macronutrients (protein or fat, water, sugar, and starch) were also significant predictors but together accounted for only another 10% of the variability of the insulin responses. Thus, we can explain only 33% of the variation of the insulin responses to the 38 foods studied.

DISCUSSION

The results of this study confirm and also challenge some of our basic assumptions about the relation between food intake and insulinemia. Within each food group, there was a wide range of insulin responses, despite similarities in nutrient composition. The important Western staples, bread and potato, were among the most insulinogenic foods. Similarly, the highly refined bakery products and snack foods induced substantially more insulin secretion per kilojoule or per gram of food than did the other test foods. In contrast, pasta, oatmeal porridge, and All-Bran cereal produced relatively low insulin responses, despite their high carbohydrate contents. Carbohydrate was quantitatively the major macronutrient for most foods. Thus, it is not surprising that we observed a strong correlation between GSs and ISs ($r = 0.70$, $P < 0.001$). However, some protein- and fat-rich foods (eggs, beef, fish, lentils, cheese, cake, and doughnuts) induced as much insulin secretion as did some

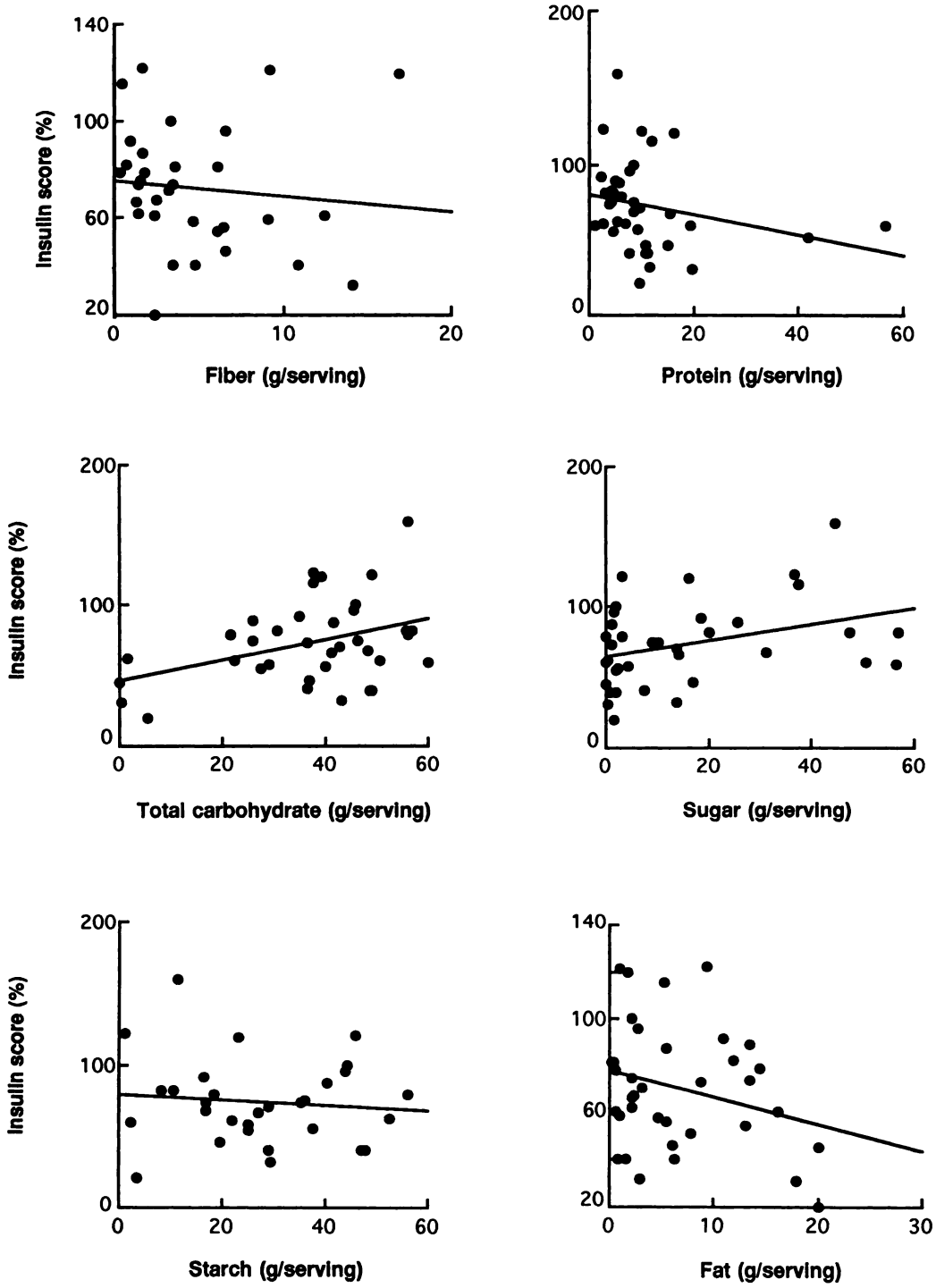

FIGURE 5. Relations between the nutrient contents of the test foods and the mean insulin scores. Fiber: $r = -0.10$, NS, $n = 32$; protein: $r = -0.24$, NS, $n = 38$; total carbohydrate: $r = 0.39$, $P < 0.05$, $n = 36$; sugar: $r = 0.36$, $P < 0.05$, $n = 36$; starch: $r = -0.09$, NS, $n = 30$; fat: $r = -0.27$, $P < 0.05$, $n = 36$.

carbohydrate-rich foods (eg, beef was equal to brown rice and fish was equal to grain bread). As hypothesized, several foods with similar GSs had disparate ISs (eg, ice cream and yogurt, brown rice and baked beans, cake and apples, and doughnuts and brown pasta). Overall, the fiber content did not predict the magnitude of the insulin response. Similar ISs were observed for white and brown pasta, white and brown rice, and white and whole-meal bread. All of these foods are relatively refined compared with their traditional counterparts. Collectively, the findings imply that typical Western diets are likely to be significantly more insulinogenic than more traditional diets based on less refined foods.

In this study, we chose to test isoenergetic portions of foods rather than equal-carbohydrate servings to determine the insu-

lin response to all of the nutrients in the foods as normally consumed. A standard portion size of 1000 kJ was chosen because this resulted in realistic serving sizes for most of the foods except apples, oranges, fish, and potatoes. Although some of the protein-rich foods may normally be eaten in smaller quantities, fish, beef, cheese, and eggs still had larger insulin responses per gram than did many of the foods consisting predominantly of carbohydrate. As observed in previous studies, consumption of protein or fat with carbohydrate increases insulin secretion compared with the insulinogenic effect of these nutrients alone (22, 30–32). This may partly explain the markedly high insulin response to baked beans. Dried haricot beans, which are soaked and boiled, are likely to have a lower IS than commercial baked beans, which are more readily digestible.

The results confirm that increased insulin secretion does not account for the low glycemic responses produced by low-GI foods such as pasta, porridge, and All-Bran cereal (33). Furthermore, equal-carbohydrate servings of foods do not necessarily stimulate insulin secretion to the same extent. For example, isoenergetic servings of pasta and potatoes both contained ≈50 g carbohydrate, yet the IS for potatoes was three times greater than that for pasta. Similarly, porridge and yogurt, and whole-grain bread and baked beans, produced disparate ISs despite their similar carbohydrate contents. These findings, like others, challenge the scientific basis of carbohydrate exchange tables, which assume that portions of different foods containing 10–15 g carbohydrate will have equal physiologic effects and will require equal amounts of exogenous insulin to be metabolized. It is possible that preprandial insulin doses for patients with NIDDM could be more scientifically estimated or matched on the basis of a meal's average insulinemic effect in healthy individuals, rather than on the basis of the meal's carbohydrate content or GI. Further research is required to test this hypothesis. The advent of intensive insulin therapy and the added risk of hypoglycemia increases the urgency of this research (34).

Our study was undertaken to test the hypothesis that the postprandial insulin response was not necessarily proportional to the blood glucose response and that nutrients other than carbohydrate influence the overall level of insulinemia. Multiple-regression analysis of the individual results showed that the glycemic response was a significant predictor of the insulin response, but it accounted for only 23% of the variability in insulinemia. The macronutrients (protein or fat, water, sugar, and starch) were also significant predictors, but together accounted for only another 10% of the variability of the insulin responses. Thus, we can explain only 33% of the variation of the insulin responses to the 38 foods under examination. The low R^2 value indicates that the macronutrient composition of foods has relatively limited power for predicting the extent of postprandial insulinemia. The rate of starch digestion, the amount of rapidly available glucose and resistant starch, the degree of osmolality, the viscosity of the gut's contents, and the rate of gastric emptying must be other important factors influencing the degree of postprandial insulin secretion. Further research is required to examine the relation between postprandial insulinemia, food form, and various digestive factors for a much larger range of foods to produce a regression equation with greater predictive value.

Dietary guidelines for healthy people and persons with NIDDM have undergone considerable change and will continue to be modified as our understanding of the relations between dietary patterns and disease improves. There is concern that high-carbohydrate diets may increase triacylglycerol concentrations and reduce high-density lipoprotein concentrations (35, 36). The use of diets high in monounsaturated fat is an attempt to overcome the undesirable effects of some high-carbohydrate diets on plasma lipids (37–39). However, diets high in monounsaturated fat are unlikely to facilitate weight loss. A low-fat diet based on less-refined, carbohydrate-rich foods with relatively low ISs may help enhance satiety and aid weight loss as well as improve blood glucose and lipid control (4).

The results of this study are preliminary but we hope they stimulate discussion and further research. Additional studies are needed to determine whether the IS concept is useful, reproducible around the world, predictable in a mixed-meal context, and clinically useful in the treatment of diabetes mellitus, hyperlipidemia, and overweight. Studies examining the relation between postprandial insulinemia and the storage and oxidation of fat, protein, and carbohydrate may provide further insight into the relation between fuel metabolism and satiety, and establish whether low-insulinemic diets can facilitate greater body fat loss than isoenergetic high-insulinemic diets.

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