Prediction of postprandial glycemia and insulinemia in lean, young, healthy adults: glycemic load compared with carbohydrate content alone[1–4]

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ABSTRACT

Background: Dietary glycemic load (GL; defined as the mathematical product of the glycemic index and carbohydrate content) is increasingly used in nutritional epidemiology. Its ability to predict postprandial glycemia and insulinemia for a wide range of foods or mixed meals is unclear.

Objective: Our objective was to assess the degree of association between calculated GL and observed glucose and insulin responses in healthy subjects consuming isoenergetic portions of single foods and mixed meals.

Design: In study 1, groups of healthy subjects consumed 1000-kJ portions of 121 single foods in 10 food categories. In study 2, healthy subjects consumed 2000-kJ servings of 13 mixed meals. Foods and meals varied widely in macronutrient content, fiber, and GL. Glycemia and insulinemia were quantified as area under the curve relative to a reference food (= 100).

Results: Among the single foods, GL was a more powerful predictor of postprandial glycemia and insulinemia than was the available carbohydrate content, explaining 85% and 59% of the observed variation, respectively ($P < 0.001$). Similarly, for mixed meals, GL was also the strongest predictor of postprandial glucose and insulin responses, explaining 58% ($P = 0.003$) and 46% ($P = 0.01$) of the variation, respectively. Carbohydrate content alone predicted the glucose and insulin responses to single foods ($P < 0.001$) but not to mixed meals.

Conclusion: These findings provide the first large-scale, systematic evidence of the physiologic validity and superiority of dietary GL over carbohydrate content alone to estimate postprandial glycemia and insulin demand in healthy individuals. This trial was registered at ANZCTR.org as ACTRN12610000484044. *Am J Clin Nutr* 2011;93:984–96.

INTRODUCTION

Postprandial hyperglycemia and compensatory hyperinsulinemia are factors linked to the development of lifestyle-related chronic diseases, including type 2 diabetes (1) and coronary heart disease (2). Carbohydrates are the only food constituents that directly increase blood glucose and are the main determinant of insulin secretion, yet the proportion of dietary energy consumed as carbohydrate is not clearly linked either positively or negatively to disease risk (3, 4). In contrast, a large body of evidence suggests that dietary fiber and carbohydrate sources (eg, bread, potatoes, and soft drinks) are important influences (5–9). In 1997, the concept of "dietary glycemic load" (GL) was introduced as an indicator of the glucose response and insulin demand induced by a serving of food (1). Since then, many long-term, prospective, observational studies have reported that energy-adjusted total GL from all dietary sources is an independent risk factor for type 2 diabetes in men and women (1, 10); cardiovascular morbidity and mortality, including stroke, in women (2, 11); and certain types of cancers in both sexes (12–14). Biochemical risk factors such as HDL-cholesterol, fasting triacylglycerols (15), and C-reactive protein concentrations (16) have also been found to be independently correlated with dietary GL.

Nonetheless, the physiologic validity of the GL has been questioned because it is a mathematical concept with little direct evidence that it truly represents the magnitude of blood glucose and insulin responses evoked by a specific type of diet. Brand-Miller et al (17) provided confirmation that stepwise increases in GL produced proportionate increases in glycemia and insulinemia in lean, young, healthy subjects. However, the foods studied were all high in carbohydrate and low in fat and protein. The use of the glycemic index (GI) and GL in predicting either glycemic or insulin responses when combined and consumed with added fat and protein as part a mixed meal continues to be challenged (18–20).

To validate the GL concept more broadly, the current study explored the degree of association between calculated GL, carbohydrate content alone, and physiologic responses to 121 single foods (study 1) and 13 mixed meals (study 2) as part of the systematic study of insulin responses in healthy subjects to isoenergetic portions of a wide range of foods. For both studies,

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[2] The abstract of this study was accepted as a "Hot Topic" abstract in the International Congress on Obesity 2010, Stockholm, Sweden, 11–15 July 2010.

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macronutrients, GI, and fiber were deliberately designed to vary over a wide range, with energy content being the only constant. Our hypothesis was that GL, the mathematical product of the published GI and available carbohydrate content of the food, as derived from published sources, would be superior to carbohydrate content alone and dietary fiber in predicting relative postprandial glycemia and insulinemia in lean, young, healthy subjects.

SUBJECTS AND METHODS

Subjects

Healthy subjects were recruited among the GI testing volunteers at the University of Sydney. Their mean (±SD) age was 24 ± 5 y, body mass index (BMI; in kg/m^2) was 22.3 ± 2.3, and fasting plasma glucose was 5.11 ± 0.36 mmol/L. The subjects were divided into separate groups (n = 10–13 per group) to test different categories of foods or meals. The inclusion criteria were as follows: nonsmoking, 18–40 y of age, stable body weight, BMI of 19 to 25, normal glucose tolerance, no food allergy, and no eating disorders. The protocol was approved by the Human Research Ethics Committee of the University of Sydney, and subjects gave informed consent. Subject recruitment took place between 1995 and 2008, and data were routinely added to a database that permitted systematic analysis. Data derived from the first 38 foods tests were published in 1997 (21) before the concept of GL had been introduced.

Study design

Study 1

Subjects (n = 10 for each test food) consumed a 1000-kJ portion of the test food or the reference food (white bread or glucose) in random order after a 10-h overnight fast. Each subject acted as their own control, testing the reference food (either white bread or glucose sugar) on 2 separate occasions; the average response was used as the basis for comparison with all other foods. Any one group of foods was tested within an 8-wk period.

In total, 121 single foods were selected, tested, and grouped into 10 food categories: *1*) dairy products, *2*) breakfast cereals, *3*) bakery products *4*) fruit and fruit juices, *5*) vegetables, *6*) snack foods, *7*) protein-rich foods, *8*) fat-rich foods, *9*) carbohydrate-rich foods, and *10*) beverages and alcoholic drinks. The foods were chosen to represent a broad range of energy sources, including the top 120 sources of energy in the Nurses' Health Study (2) and the male Health Professionals Follow-Up Study (22). Carbohydrate ranged from 0 to 59 g (0–100% of energy), fat from 0 to 27 g (0–100% of energy), protein from 0 to 56 g (0–95% of energy), and fiber from 0 to 24 g. The calculated GL (%GI × available carbohydrate content per 1000-kJ portion) varied from 0 to 46. A reliable GI was assigned to each food on the basis of published GI tables (23) or unpublished data from our laboratory. Nutrients, GI and GL values, and other details of the foods are listed in **Table 1**.

The observed blood glucose response for each portion of food relative to the reference food was described as a glucose score (GS) to distinguish the resulting value from the food's GI, which is based on a standard amount of available carbohydrate. Specifically, for each subject, the glucose incremental area under the 120-min response curve (AUC) was calculated according to the trapezoidal method (24) and compared with the average AUC (n = 2) for the reference glucose. Hence, an individual GS was obtained by dividing the glucose AUC value for 1000 kJ of the test food by his or her average glucose AUC value for the reference glucose and was expressed as follows:

$$\mathrm{GS} = \frac{120\ \mathrm{min\ AUC_{glucose}\ for\ 1000\ kJ\ test\ food}}{120\ \mathrm{min\ AUC_{glucose}\ for\ 1000\ kJ\ reference\ glucose}} \times 100 \quad (1)$$

The mean (±SEM) for a group of subjects was the reported observed GS to the test food.

Similarly, the observed blood insulin response for each food was determined as the insulin response relative to reference glucose on an isoenergetic basis and calculated as follows:

$$\mathrm{Food\ insulin\ index\ (FII)} = \frac{120\ \mathrm{min\ AUC_{Insulin}\ for\ 1000\ kJ\ test\ food}}{120\ \mathrm{min\ AUC_{Insulin}\ for\ 1000\ kJ\ reference\ glucose}} \times 100 \quad (2)$$

The mean (±SEM) for a group of subjects was reported as the FII of the test food.

Because the reference food was switched from white bread to glucose during the course of the study, those foods tested against white bread were converted by using a formula to the glucose scale. The conversion factor was based on the testing of white bread by using glucose as the reference food in a group of 20 subjects. For the GS, the conversion factor was 100/70, or 1.43; for FII, the conversion factor was 100/73, or 1.37.

Study 2

Two groups of healthy subjects were recruited to test 13 isoenergetic mixed meals in 2000-kJ portions. One group (n = 11) consumed 6 meals and the other group (n = 10) consumed 7 meals, as previously described (25). The test meals were intended to be representative of normal breakfasts, lunches, dinners, and snacks in Western diets. The meals were consumed in random order, and the reference white bread (2000-kJ portion) was tested at the beginning and end of the study. Test sessions were separated by ≥1 d and finished within a 2-mo period for each group of subjects.

All the component foods in the mixed meals were chosen from the single-food database (n = 121) with known FII values. The 13 isoenergetic meals varied widely in macronutrient composition and calculated GI and GL values (**Table 2**). Carbohydrate ranged from 29 to 92 g (25–78% of energy), protein from 7 to 52 g (6–44% of energy), fat from 3 to 30 g (6–56% of energy), and fiber from 0 to 21 g. The GL varied over a 5-fold range, from 10 to 51. The GL of each test meal was calculated as the sum of the GL of the component foods as follows:

$$\mathrm{GL} = \frac{1}{100}\sum_{a=1}^{n} \mathrm{GI_a} \times \mathrm{CHO_a} \quad (3)$$

where n is the number of foods in the meal, $\mathrm{GI_a}$ is the GI of the ath food, and $\mathrm{CHO_a}$ is the available carbohydrate (g) in the ath food. The observed glucose and insulin responses (relative to white bread) for each meal were described as a GS or FII, respectively, of the test meal and calculated according to the same

TABLE 1
Macronutrient composition, glycemic index (GI), glycemic load (GL), actual glucose score (GS), and food insulin index (FII) for 1000-kJ portions of the reference glucose and test foods[1]

No.	Food categories and items	Test date	Weight	Protein	Fat	AvCHO	Sugars	Fiber	GI	GL	GS[2]	FII[2]
			g/1 MJ	*g*	*g*	*g*	*g*	*g*			%	%
1	Glucose (Glucodin Energy Powder; HomePharmacy, Kuraby, Australia)	2005	59	0	0	59	59	0	100	59	100	100
	Dairy products											
2	Low-fat vanilla ice cream (Coles Farmland; Coles Supermarkets, Sydney, Australia)	2004	185	6	7	44	37	0	43	19	50 ± 2	69 ± 6
3	Vanilla ice cream (Dairy Bell, Camperdown, Australia)	1997	120	5	13	26	26	0	50	13	49 ± 13	65 ± 9
4	Yogurt, strawberry low-fat (Dairy Farmers, Lidcombe, Australia)	1997	260	12	5	38	38	1	31	12	43 ± 11	84 ± 9
5	Frozen yogurt, peach-mango (Streets Blue Ribbon; Unilever Pty Ltd, Epping, Australia)	2004	181	9	5	38	36	0	51	19	41 ± 6	64 ± 6
6	Cheddar cheese (Grocery-Wholesalers; Coles Supermarkets)	1997	59	15	21	0	0	0	0	0	39 ± 13	33 ± 9
7	Skim-fat milk (Dairy Farmers)	2001	690	25	1	33	33	0	29	9	25 ± 6	60 ± 13
8	1%-Fat milk (Dairy Farmers)	2005	558	20	6	27	27	0	29	8	16 ± 3	34 ± 4
9	Low-fat processed cheese (Kraft free singles; Kraft Foods Ltd, South Wharf, Australia)	2003	154	36	4	15	15	0	10	2	14 ± 3	42 ± 6
10	Milk (Dairy Farmers)	1999	368	11	14	17	17	0	31	5	12 ± 1	24 ± 3
11	Reduced-fat cottage cheese (Dairy Farmers)	2006	234	29	10	7	7	0	10	1	9 ± 2	40 ± 7
12	93% Fat-free cheddar cheese (Dairy Farmers)	2003	119	41	8	1	1	0	0	0	6 ± 1	20 ± 6
13	Low-fat cottage cheese (Bulla original; Bulla Dairy Foods, Derrimut, Australia)	2007	264	30	6	16	14	0	10	2	4 ± 1	52 ± 7
14	Cream cheese (Coles Farmland)	2003	68	6	24	3	2	0	0	0	4 ± 1	18 ± 6
	Breakfast cereals[3]											
15	Cornflakes (Kellogg Foods Inc, USA, Wells Fargo Bank, MN)	2004	67	5	0	55	4	2	81	45	100 ± 8	82 ± 7
16	Rice Krispies/Bubbles (Kellogg Foods Inc, Collingwood, Australia)	2007	62	4	0	54	6	1	88	48	99 ± 3	94 ± 4
17	Original Shredded Wheat (Post Healthy Classics; Post Foods Inc, St Louis, MO)	2004	68	7	2	45	0	9	75	34	92 ± 8	91 ± 11
18	Lucky Charms cereal (General Mills Inc, Minneapolis, MN)	2004	59	4	2	48	26	2	69	33	85 ± 7	69 ± 9
19	Post Grapenuts (Post Foods Inc, USA)	1999	69	9	1	48	8	6	75	36	79 ± 6	110 ± 12
20	Wheaties (General Mills Inc)	2008	67	7	1	46	10	7	75	35	78 ± 7	78 ± 4
21	Frosted Flakes (Kellogg Foods Inc, USA)	2002	62	2	0	54	24	2	55	30	70 ± 7	72 ± 8
22	Special K cereal (Kellogg Foods Inc, USA)	1999	63	13	1	44	8	2	69	30	69 ± 5	86 ± 10
23	Post Honey Bunches of Oats (Post Foods Inc, USA)	2008	61	6	5	42	11	4	63	26	63 ± 6	61 ± 4
24	7 Whole Grain Puffs (Kashi, La Jolla, CA)	2007	63	7	2	51	0	3	65	33	64 ± 7	59 ± 7
25	Cheerios (General Mills Inc, USA)	2004	65	7	4	43	3	7	74	32	62 ± 6	63 ± 7
26	All-Bran Complete Wheat Flakes (Kellogg Foods Inc, USA)	2007	76	7	2	47	11	9	60	28	60 ± 6	55 ± 7
27	Raisin Bran cereal (Kellogg Foods Inc, USA)	1999	74	6	2	49	22	8	61	30	58 ± 5	69 ± 6
28	Post Great Grains (Kraft Foods Inc, USA)	2008	59	6	7	39	10	5	74	29	54 ± 6	57 ± 7
29	Cornflakes (Kellogg Foods Inc, Australia)	1997	64	5	0	53	10	2	77	41	53 ± 8	55 ± 6
30	Special K cereal (Kellogg Foods Inc, Australia)	1997	63	15	2	41	14	1	54	22	49 ± 6	48 ± 4

(Continued)

TABLE 1 (*Continued*)

No.	Food categories and items	Test date	Weight	Protein	Fat	AvCHO	Sugars	Fiber	GI	GL	GS[2]	FII[2]
			g/1 MJ	*g*	*g*	*g*	*g*	*g*			%	%
31	Sustain (Kellogg Foods Inc, Australia)	1997	62	10	3	43	14	4	55	24	46 ± 4	52 ± 4
32	Cracklin' Oat Bran (Kellogg Foods Inc, USA)	2004	58	5	8	36	21	6	55	20	46 ± 5	48 ± 3
33	Honeysmacks (Kellogg Foods Inc, Australia)	1997	63	9	2	48	31	3	71	34	42 ± 5	49 ± 4
34	Porridge (Uncle Toby's Inc; Nestle Pty Ltd, Sydney, Australia)	1997	60	11	5	37	8	5	57	21	42 ± 8	29 ± 3
35	100% Natural Granola Oats, Honey & Raisins (Quaker Oats Inc, Chicago, IL)	2004	55	6	9	35	16	3	44	15	35 ± 5	41 ± 7
36	Muesli bar (Uncle Toby's Inc)	1997	63	11	5	37	17	7	56	21	30 ± 5	34 ± 4
37	All-Bran original (Kellogg Foods Inc, Australia)	1997	74	12	3	43	14	14	30	13	28 ± 5	23 ± 3
	Bakery products											
38	Water crackers (Grocery Wholesalers Ltd, Yennora, Australia)	1997	58	6	5	42	1	2	78	33	83 ± 17	64 ± 9
39	The Original Pancake & Waffle Mix (Aunt Jemima; Quaker Oats Inc, USA)	2004	132	6	1	51	9	1	67	34	71 ± 8	110 ± 10
40	Panjacks (White Wings Shaker; White Wings Pty Ltd, North Ryde, Australia)	2003	121	5	3	48	17	2	67	32	67 ± 10	58 ± 6
41	Fat-free blueberry muffin (Krusteaz Wild Blueberry; Continental Mills Pty Ltd, Seattle, WA)	2004	101	3	1	51	28	3	71	36	67 ± 6	69 ± 6
42	Blueberry Streusel Muffin (Duncan Hines Blueberry; Pinnacle Foods Group LLC, Peoria, IL)	2004	79	4	7	41	22	1	55	22	62 ± 7	69 ± 11
43	Chocolate chip cookies (Arnotts Biscuits Ltd, Virginia, Australia)	1997	51	2	11	35	19	1	62	22	52 ± 8	67 ± 11
44	Croissants (Woolworth Supermarket Inc, Sydney, Australia)	1997	66	6	12	29	3	2	67	19	52 ± 6	58 ± 10
45	Fat-free oatmeal raisin cookie (Archway Inc, Archway Cookies Inc, Battle Creek, MI)	2004	67	2	0	53	30	2	54	29	50 ± 6	54 ± 9
46	Reduced-fat chocolate chip cookie (Chips Ahoy; Kraft Foods Inc, USA)	2004	53	3	9	36	15	2	50	18	47 ± 6	49 ± 5
47	Doughnuts with cinnamon sugar (Woolworth Supermarket Inc, Australia)	1997	65	4	13	26	9	1	76	20	44 ± 8	54 ± 7
48	Chocolate cake brownie with frosting (White Wings Pty Ltd, Australia)	1997	64	4	12	30	20	1	38	11	39 ± 10	60 ± 9
49	Apple pie baked at 190°C for 35 min (Sara Lee, Pymble, NSW, Australia)	2002	85	3	11	32	16	1	41	13	39 ± 5	47 ± 4
50	Cinnamon swirl pastry (Entenmanns Cinnamon Swirl Bun; Bimbo Bakeries USA, Horsham, PA)	2004	63	4	10	31	14	2	40	12	39 ± 4	42 ± 4
51	Jatz crackers (Arnott's Jatz, Virginia, Australia)	2007	51	4	9	34	2	2	55	18	37 ± 4	45 ± 8
52	Super Moist Yellow Cake with chocolate frosting (Betty Crocker; General Mills Inc)	2004	73	2	11	32	21	1	42	13	33 ± 4	53 ± 6
53	Honey-Raisin Bran muffin (Sun Maid, Kingsburg, CA)	2004	64	3	8	38	23	3	56	21	32 ± 4	37 ± 4
54	Regular Chocolate Chip Cookies (Chips Ahoy)	2004	49	3	12	30	15	2	50	15	21 ± 4	33 ± 3

(Continued)

TABLE 1 (*Continued*)

No.	Food categories and items	Test date	Weight	Protein	Fat	AvCHO	Sugars	Fiber	GI	GL	GS[2]	FII[2]
			g/1 MJ	*g*	*g*	*g*	*g*	*g*			%	%
	Fruit and fruit juice											
55	Peaches, canned in syrup (SPC; SPC Ardmona, Northmead, Australia)	2007	346	1	2	56	53	4	58	32	67 ± 5	65 ± 8
56	Honeydew melon (raw, Australia)	2006	714	5	2	46	46	1	62	29	62 ± 8	93 ± 15
57	Raspberry jam (Cottees; Cottee Inc, Southbank, Australia)	2005	88	0	0	59	59	1	51	30	58 ± 8	62 ± 9
58	Bananas, raw, peeled (Australia)	1997	279	3	0	56	47	6	52	29	55 ± 7	59 ± 4
59	Seedless raisins (Sunbeam; Sunbeam Food Inc, Irymple, Australia)	2006	72	2	1	56	55	4	64	36	54 ± 7	31 ± 5
60	Orange juice, concentrate (Mr Juicy, Bulimba, Australia)	2007	625	3	0	53	53	1	53	28	53 ± 6	55 ± 7
61	Apple juice (Berrivale Orchards Inc, Berrimah, Australia)	1999	588	0	0	59	59	0	39	23	53 ± 5	47 ± 2
62	Black grapes, raw, fresh (Australia)	1997	395	1	0	57	57	4	50	28	52 ± 6	60 ± 4
63	Peaches, canned in juice (SPC Ardmona, Australia)	2007	485	2	1	55	42	6	40	22	50 ± 6	54 ± 10
64	Apples, Red Delicious, raw (Australia)	1997	435	1	0	58	57	9	36	21	35 ± 4	43 ± 3
65	Oranges, raw, peeled (Australia)	1997	625	7	1	51	51	13	42	21	27 ± 5	44 ± 2
66	Avocado, raw, peeled (USA)	2002	112	2	25	0	0	2	0	0	1 ± 1	4 ± 1
	Vegetables											
67	Carrot juice, freshly extracted (Australia)	2006	762	6	1	41	41	24	43	18	44 ± 5	41 ± 8
68	Frozen corn (McCain Super; McCain Foods Pty Ltd, Baulkham Hills, Australia)	2006	222	6	3	43	10	7	47	20	36 ± 4	39 ± 7
69	Tomato pasta sauce (Paul Newman, Sydney, Australia)	2006	445	6	8	38	34	0	31	12	34 ± 2	41 ± 8
70	Coleslaw, commercial (Coles Supermarkets Ltd, Australia)	2002	252	5	10	34	33	7	39	13	20 ± 5	20 ± 2
	Snack foods											
71	97% Fat-free pretzels (Parkers; The Smith's Snackfood Company, Chatswood, Australia)	2004	63	6	2	50	2	3	84	42	85 ± 7	74 ± 12
72	Jellybeans (Grocery Wholesalers Inc, Australia)	1997	88	3	0	56	45	0	78	44	83 ± 13	117 ± 12
73	Sherbet (Frosty Fruits orange mango splits; Nestle Pty Ltd, Australia)	2007	217	3	3	50	48	0	59	30	61 ± 7	76 ± 8
74	Mars Bar (Mars Confectionary Inc, Auburn, Australia)	1997	54	3	9	38	37	2	62	23	55 ± 9	89 ± 11
75	French fries (McCain's Foods Inc, Australia)	1997	93	4	9	37	2	4	70	26	50 ± 11	54 ± 9
76	Popcorn (Uncle Toby's Inc, Australia)	1997	52	5	13	27	2	6	66	18	43 ± 11	39 ± 7
77	40% Reduced-fat potato chips (Cape Cod Potato Chip Company, Hyannis, MA)	2004	51	4	11	31	2	2	60	19	40 ± 5	51 ± 6
78	McDonald's French fries (McDonald's Inc, Australia)	2002	76	3	13	26	1	3	70	18	39 ± 5	57 ± 6
79	Potato chips (The Smith's Snackfood Company, Australia)	1997	44	3	16	22	0	2	60	13	36 ± 6	45 ± 10
80	Corn chips (The Smith's Snackfood Company, Australia)	1999	46	3	13	24	1	5	42	10	32 ± 4	45 ± 5
81	Snickers bar (Masterfoods, Hackettstown, NJ)	2004	50	3	12	29	25	1	42	12	27 ± 4	37 ± 3
82	Hershey's milk, chocolate (Hershey Foods Inc, Hershey, PA)	2004	45	3	14	25	23	1	43	11	27 ± 2	34 ± 3
	Carbohydrate-rich foods											
83	Potatoes (russet boiled, peeled; Australia)	1997	368	10	1	49	3	9	78	38	99 ± 25	88 ± 8
84	White rice (Sunwhite; Rice-growers Inc, Leeton, Australia)	1997	203	5	1	56	0	0	72	40	77 ± 11	58 ± 9
85	Brown rice (Sunbrown; Ricegrowers Inc)	1997	148	5	2	53	1	1	72	38	73 ± 13	45 ± 8
86	White bread (Sunblest; Tiptop Pty Ltd, Enfield, Australia)	2005	97	9	2	44	3	3	70	31	70 ± 6	73 ± 5

(Continued)

TABLE 1 (*Continued*)

No.	Food categories and items	Test date	Weight	Protein	Fat	AvCHO	Sugars	Fiber	GI	GL	GS[2]	FII[2]
			g/1 MJ	*g*	*g*	*g*	*g*	*g*			*%*	*%*
87	Whole-meal bread (Riga Bakeries Inc, Sydney, Australia)	1997	101	8	3	45	2	7	74	34	68 ± 12	70 ± 9
88	Brown pasta (Sam Remo Pasta Inc, Wetherill Park, Australia)	1997	218	11	2	49	1	11	42	20	48 ± 7	29 ± 4
89	Tortillas, white corn (DieGo; San Diego Tortilla Factory, Burleigh Heads, Australia)	2007	104	6	2	47	1	4	49	23	43 ± 7	36 ± 8
90	Grain bread (Tiptop Bakeries Inc, Australia)	1997	108	9	5	40	2	7	50	20	42 ± 8	41 ± 4
91	Pizza[4] (McCains, Australia)	1999	90	12	8	30	2	0	60	18	41 ± 5	47 ± 4
92	Grain bread (Burgen, Soy-Lin, Chatswood, Australia)	2006	99	15	7	29	2	5	36	11	34 ± 5	52 ± 9
93	White pasta, spirals (Sam Remo, Australia)	1997	201	8	1	49	2	4	46	23	32 ± 7	29 ± 4
94	Beef lasagna (Sara Lee Bakery Pty Ltd, Pymble, Australia)	2002	164	12	10	25	3	1	38	10	15 ± 2	34 ± 5
	Protein-rich foods											
95	Baked beans[5] (Franklins; Franklins Supermarket, Rockdale, NSW, Australia)	1997	351	16	2	39	16	17	44	17	80 ± 13	88 ± 14
96	Lentils, served with tomato sauce[6] (Australia)	1997	253	19	5	29	4	11	37	11	43 ± 15	42 ± 9
97	Eggs, poached (Australia)	1997	160	21	18	1	1	0	0	0	29 ± 11	23 ± 4
98	Battered fish fillets (Coles Supermarkets Inc, Australia)	2002	110	13	15	14	0	1	38	5	29 ± 2	54 ± 4
99	Canned navy beans (Eden Organic Navy Beans, Clinton, MI)	2005	281	19	5	28	0	24	31	9	20 ± 4	23 ± 4
100	White fish (Ling fish fillet, Australia)	1997	333	56	1	0	0	0	0	0	20 ± 9	43 ± 13
101	Beef steak[7] (Australia)	1997	158	42	8	0	0	0	0	0	15 ± 6	37 ± 12
102	Taco[8] (Casa Fiesta Beef Taco; Bruce Foods Corporation, New Iberia, LA)	2004	138	20	13	9	1	2	39	4	11 ± 1	24 ± 2
103	Tuna, canned in water (Coles Supermarkets Inc, Australia)	2001	239	48	5	0	0	0	0	0	8 ± 2	26 ± 4
104	Frankfurter/hot dog (Australia)	2001	95	14	19	3	0	2	28	1	8 ± 2	16 ± 3
105	Peanuts, salted and roasted (Grocery Wholesalers Inc, Australia)	1997	38	10	20	5	2	2	14	1	8 ± 3	15 ± 2
106	Bologna (Australia)	2001	111	24	9	13	3	3	0	0	6 ± 2	11 ± 2
107	Peanut butter (Kraft Foods Inc, Australia)	2001	41	9	20	7	2	5	14	1	6 ± 1	11 ± 2
108	Tofu (Soyco, Sydney, Australia)	2003	227	27	11	7	1	3	15	1	5 ± 1	21 ± 4
109	Peeled prawns, boiled (Findus Seafood Deli, Australia)	2003	235	48	4	2	1	0	0	0	5 ± 1	21 ± 4
110	Chicken, fried in olive oil, with skin, cooked (Australia)	2001	94	23	17	0	0	0	0	0	5 ± 1	19 ± 4
111	Tuna, canned in oil, drained (Coles Farmland)	2003	135	24	15	2	1	0	0	0	4 ± 1	16 ± 2
112	Bacon (Premium Short Cut Bacon; Primo Smallgoods, Chullora, Australia)	2007	106	16	19	1	1	0	0	0	3 ± 1	9 ± 2
113	Roast chicken without skin (Woolworth Inc, Australia)	2005	113	31	13	0	0	0	0	0	1 ± 1	17 ± 4
	Fat-rich foods											
114	Walnuts (Lucky California, Sydney, Australia)	2003	35	6	23	1	1	3	0	0	4 ± 1	5 ± 1
115	Butter (Western Star Original; Mt Waverley, Australia)	2007	33	0	27	0	0	0	0	0	2 ± 1	2 ± 1
116	Olive oil (Australia)	2005	27	0	27	0	0	0	0	0	1 ± 0	3 ± 1

(Continued)

TABLE 1 (*Continued*)

No.	Food categories and items	Test date	Weight	Protein	Fat	AvCHO	Sugars	Fiber	GI	GL	GS[2]	FII[2]
			g/1 MJ	*g*	*g*	*g*	*g*	*g*			%	%
	Beverages											
117	Fruit punch (Fruity Flavorits Orange Mango Fruit drink; Frosts Food & Beverage Pty Ltd, Singapore)	2007	833	1	0	58	58	0	67	39	67 ± 7	76 ± 10
118	Ice tea (Narkena Ltd, Sefton, Australia)	2006	622	0	0	59	59	0	59	35	59 ± 7	69 ± 9
119	Coca-Cola (Coca-Cola Amatil Inc, Sefton, Australia)	1999	595	0	0	59	59	0	53	31	50 ± 5	44 ± 3
120	Beer, 4.9% alcohol (Budweiser, Pyrmont, NSW, Australia)	2001	671	2	0	13	0	0	66	9	41 ± 8	20 ± 4
121	Gin, 40% alcohol (Australia)	2001	111	0	0	0	0	0	0	0	7 ± 4	1 ± 1
122	White wine, 11% alcohol (Australia)	2001	362	1	0	1	0	0	0	0	5 ± 2	3 ± 1

[1] AvCHO, available carbohydrate. GI values were derived from the published international GI table (23).

[2] Mean (±SEM) values represent average glucose and insulin responses to 1000-kJ portions of the food relative to a 1000-kJ portion of glucose sugar in a group of 10 to 13 healthy individuals. Because the reference food was switched from white bread to glucose sugar during the course of the study, those foods tested against white bread were converted by using a formula to the glucose scale. The conversion factor was based on the testing of white bread by using glucose as the reference food in a group of 20 subjects. For the GS, the conversion factor was 100/70 or 1.43; for FII, the conversion factor was 100/73 or 1.37.

[3] Cereals were served fresh with 125 mL 1.5%-fat milk.

[4] Pizza base: white-flour pizza base (McCain Foods), tomato paste (Leggo tomato paste; JR Simplot, Mentone, Australia), and shredded mozzarella cheese (Perfect Italiano; Fonterra Pty Ltd, Australia).

[5] Canned navy beans in tomato sauce (Franklins, Australia); heated on stove for 5 min immediately before serving.

[6] Lentils: served in a basic tomato sauce. Ingredients: 15 mL olive oil, 350 g dried green lentils, 410 g canned tomatoes, 120 g onion, 1 clove garlic, and 1 teaspoon pepper.

[7] Lean top-side beef fillets. Grilled the day before serving, cut into standard bite-sized pieces, stored at 4°C overnight, and reheated in a microwave oven for 2 min immediately before serving.

[8] Ingredients: seasoned beef mince, lettuce, tomato, and Kraft-Coon-Light & Tasty cheese (Kraft Inc, USA).

formula as described above. The mean (±SEM) GS or FII for each group of subjects was determined.

Experimental procedures

Subjects were instructed to refrain from unusual physical activity, alcohol, and legumes and to eat a high-carbohydrate, low-fat dinner meal on the day before a test. On the test morning, subjects presented to the metabolic kitchen after a 10–12-h fast. After warming the hand in hot water, 2 baseline finger-prick blood samples (≈0.7 mL each) were obtained 5 min apart. Subjects then consumed the test food or meal at a comfortable pace within 14 min. Additional finger-prick capillary blood was collected 15, 30, 45, 60, 90, and 120 min after eating commenced. The subjects remained seated throughout and were not permitted to eat or drink until the end of the session.

Blood samples were collected into anticoagulant-coated tubes (Eppendorf tubes, grade II; Sigma Chemical Company, Castle Hill, Australia) containing 10 IU heparin sodium salt and centrifuged immediately (1 min at 10,000 × *g* at room temperature). The plasma layer was pipetted into a labeled tube and stored at −20°C until analyzed. Plasma glucose was analyzed with the glucose hexokinase enzymatic assay on a centrifugal analyzer (model HITACHI 912; Hitachi, Tokyo, Japan). The mean within-assay and between-assay precisions (CVs) were both <6%. Plasma insulin was measured with an antibody-coated tube radioimmunoassay (Diagnostic Products Corporation, Los Angeles, CA). The within- and between-assay CVs were 3.0% and 3.5%, respectively.

Statistical analysis of data

To determine the ability of GL to predict postprandial glycemia and insulinemia, GL was correlated against the observed glucose and insulin responses. Linear regression analysis was used to test associations between glucose and insulin responses and GL, GI, available carbohydrate, starch, sugars, protein, fat, and fiber, and stepwise regression was used to examine the extent to which the different predictors accounted for the variability of the observed postprandial responses. All statistical analyses were carried out by using the PASW statistical package (version 18.0; SPSS Inc, Chicago, IL). Differences and correlation coefficients were considered statistically significant if the *P* value was <0.05 and was highly significant if the *P* value was <0.01 (2-tailed).

RESULTS

Study 1

The observed glucose responses to 121 single foods varied over a wide range, from 1 ± 1 for avocado to as high as 100 ± 8 for cornflakes, relative to the reference 1000-kJ glucose challenge (= 100). Glucose responses were more strongly correlated with GL and GI than with available carbohydrate ($r = 0.92$, 0.87, and 0.81, respectively; $P < 0.001$ for all; **Figure 1**). GL explained 85%, GI 76%, and available carbohydrate 66% of the variation in glucose response to single foods. On their own, starch, fat, and protein contents were also significant predictors of postprandial glycemia, although less powerfully than GL (starch: $r = 0.64$; fat: $r = -0.61$; protein: $r = -0.45$; $P < 0.001$

TABLE 2
Macronutrient composition, calculated glycemic index (GI), glycemic load (GL), actual glucose score (GS), and food insulin index (FII) values for 2000-kJ portions of the reference white bread and test mixed meals (M)[1]

No.	Meal ingredients and portion sizes	Year of test	Weight	Protein	Fat	AvCHO	Fiber	GI	GL	GS[2]	FII[2]
			g/2 MJ	*g*	*g*	*g*	*g*			*%*	*%*
Group 1											
Ref	193 g White bread[3]	2006	193	19	5	93	4	70	65	100	100
M1	78 g Grain bread, 25 g peanut butter, 200 mL full-fat milk	2006	303	25	26	37	7	32	12	23 ± 3	44 ± 7
M2	100 g honeydew-melon, 98 g banana, 300 g 99% fat-free strawberry yogurt, 200 mL apple juice	2006	698	19	3	90	3	40	36	47 ± 6	116 ± 26
M3	44 g Walnuts, 28 g raisins, 250 g carrot juice	2006	322	10	30	38	6	55	21	35 ± 4	35 ± 5
M4	30 g Raspberry jam, 85 g croissant, 214 mL iced tea	2006	329	7	15	77	0	61	47	74 ± 8	113 ± 19
M5	75 g Roast chicken, 40 g avocado, 97 g grain bread	2006	212	36	24	29	6	36	10	23 ± 2	51 ± 6
M6	110 g Tuna, 222 g white rice, 45 g corn	2006	377	25	13	63	0	69	43	49 ± 10	68 ± 9
Group 2											
Ref	193 g White bread[3]	2005	193	19	5	93	4	70	65	100	100
M7	245 g All-Bran cereal[4], 294 g apple juice	2005	539	18	5	91	21	33	30	47 ± 4	47 ± 6
M8	159 g Poached eggs, 101 g whole-meal bread	2005	260	27	20	39	7	67	26	58 ± 10	53 ± 5
M9	279 g Banana, 352 g full-fat milk	2005	631	17	14	72	6	47	34	41 ± 4	58 ± 3
M10	49 g Cookies, 123 g ice cream	2005	172	9	23	44	0	55	24	64 ± 5	54 ± 3
M11	90 g Pizza, 583 g Coca-Cola[5]	2005	673	13	8	92	0	55	51	120 ± 15	85 ± 10
M12	201 g Pasta, 253 g lentils	2005	454	27	13	63	15	42	27	49 ± 5	45 ± 3
M13	158 g Beef steak, 368 g potatoes	2005	526	52	9	40	9	77	31	72 ± 6	88 ± 7

[1] The GI and GL values of the mixed meals were calculated by using the GI of the individual food components and the available carbohydrate content. All of the component foods were selected from the single-food database generated in study 1 (n = 121). AvCHO, available carbohydrate; Ref, reference food.
[2] Mean (±SEM) values of each test meal represent the observed glucose and insulin responses to 2000-kJ servings relative to 2000-kJ portions of white bread (n = 10–11). The details of meal composition were previously described (25).
[3] White bread: Sunblest (Tip Top Bakeries Pty Ltd, Australia).
[4] Kellogg's All-Bran, Sydney, Australia.
[5] Coca-Cola Amatil, Sydney, Australia

for all; n = 121; Figure 1). Sugar showed a weak, although still significant, relation with observed glucose responses (r = 0.25, P = 0.005), whereas fiber was not significantly correlated (r = 0.17, P = 0.07) (Figure 1). Even when considered separately, the fiber content of cereals or fruit and vegetables showed no relation to glycemia (data not shown).

When all predictors were entered into a stepwise multiple linear regression model, only GL, GI, and sugar were selected as significant predictors (carbohydrate alone was not significant): $P < 0.001$, $P = 0.03$, and $P = 0.04$, respectively. Removing sugar from the model left both GL and GI as significant predictors: $P < 0.001$ and $P = 0.005$, respectively. Even in this model, GL was the more significant predictor and explained 85% of the variability in glucose response, as opposed to 88% from a full regression.

A similar situation applied to insulin responses. Relative to a 1000-kJ portion of glucose (= 100), food insulin indexes varied from 1 ± 1 for gin to 117 ± 12 for jellybeans. GL was the strongest individual predictor of the observed insulin response (r = 0.77, $P < 0.001$), followed by GI (r = 0.74, $P < 0.001$), available carbohydrate (r = 0.70, $P < 0.001$), fat ($r = -0.54$, $P < 0.001$), starch (r = 0.43, $P < 0.001$), and sugar (r = 0.34, $P < 0.001$), and protein ($r = -0.26$, P = 0.005) (**Figure 2**). Fiber showed essentially no relation with insulin responses (r = 0.04, P = 0.64) (Figure 2). On its own, GL explained 59% of the variability in postprandial insulinemia, GI explained 55%, and carbohydrates explained 49%. A stepwise regression model selected only GL (P = 0.005), protein ($P < 0.001$), GI ($P < 0.001$), and sugar (P = 0.005) as significant predictors. Together, these 4 variables explained 66% of the variability in insulin response, as opposed to 59% for GL alone and 67% for the full regression.

The findings were similar when foods with little or no carbohydrate (GL < 8, n = 29) were excluded. GL was still the strongest individual predictor of glucose responses (r = 0.84, $P < 0.001$), followed by GI (r = 0.75, $P < 0.001$), available carbohydrate (r = 0.58, $P < 0.001$), and fat ($r = -0.52$, $P < 0.001$). Protein, sugar, and fiber ($r = -0.08$) were not significant predictors. In the stepwise regression model, only GL and sugar were selected as significant contributors to the variation in glycemic responses, explaining 72% in the full regression as opposed to 70% for GL alone. GL also remained the strongest single predictor of insulin responses (r = 0.60, $P < 0.001$), followed by GI (r = 0.53, $P < 0.001$), available carbohydrate (r = 0.40, $P < 0.001$), and fat ($r = -0.32$, $P < 0.001$). Fiber showed a weak, marginally significant correlation with insulin response ($r = -0.22$, P = 0.04). The stepwise regression selected only GL as the significant predictor ($P < 0.001$), which explained 36% of the variability. Carbohydrate alone explained only 16% of the variation in insulin responses, whereas GI explained 29%.

Study 2

The observed glucose responses to the 13 meals varied over a 5-fold range, with significant differences among the meals (**Figure 3**A; $P < 0.001$). Glucose responses (expressed relative to white bread = 100) ranged from 23 ± 3 to 120 ± 15 (Figure 3B) and were strongly correlated with the calculated GL (r = 0.76, P = 0.003; **Figure 4**A). In contrast, in the context of these

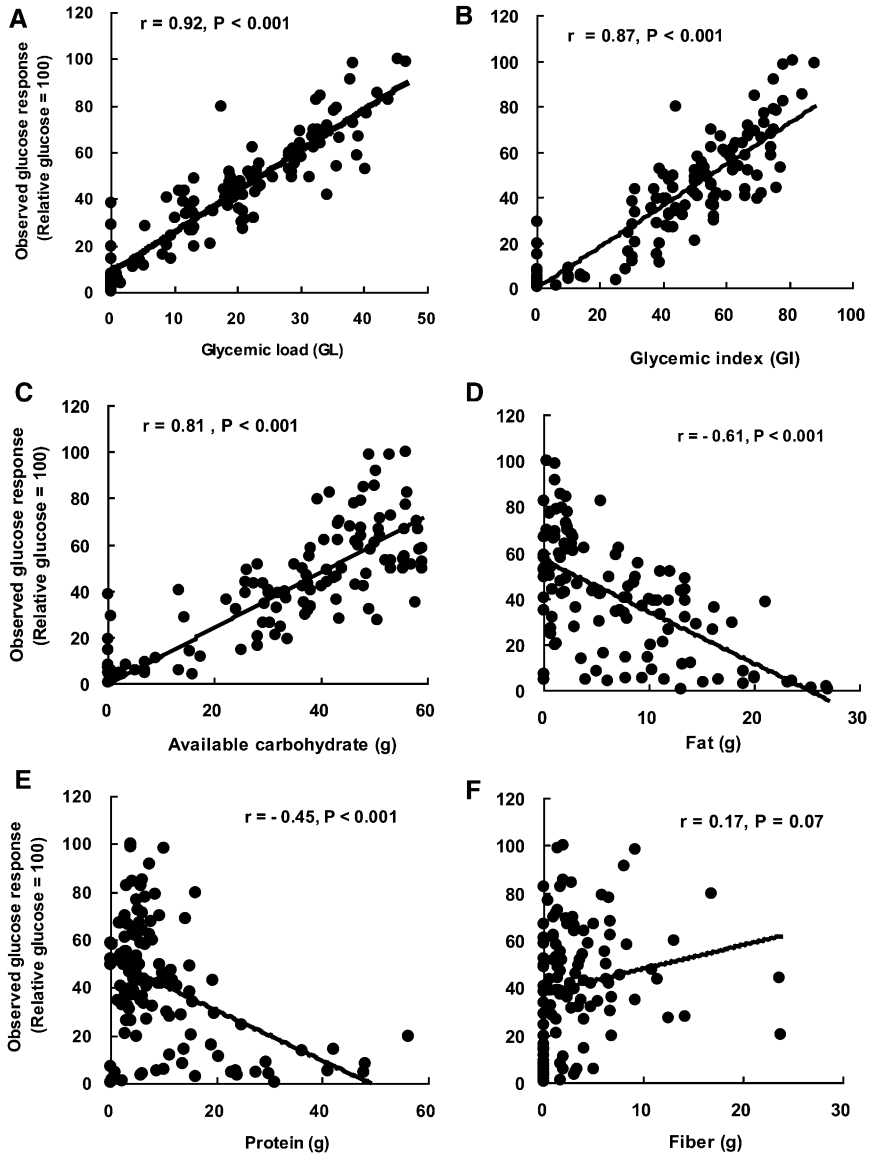

FIGURE 1. A–F: Univariate correlations between observed glucose responses (relative to 1000 kJ glucose = 100), the calculated glycemic load, the glycemic index, and the available carbohydrate, protein, fat, and fiber contents of 121 single test foods. Simple (univariate) analysis was used to test the significance of the associations. Each point on the graph represents the mean result for the test meal (n = 10–13 subjects).

mixed meals, neither available carbohydrate alone ($r = 0.48$, $P = 0.10$) nor GI alone ($r = 0.48$, $P = 0.09$) were significant predictors of postprandial glycemia (Figure 4). Similarly, fat ($P = 0.10$), protein ($P = 0.55$), and fiber ($P = 0.26$) were not significantly correlated.

The insulin responses to the mixed meals in the present study were reported previously as part of a study to test the physiologic validity of an insulin index of foods (25). They varied over a 3-fold range (from 35 ± 5 to 116 ± 26) and were significantly correlated with GL ($r = 0.68$, $P = 0.01$) and fat ($r = -0.60$, $P = 0.03$), only marginally with carbohydrate ($r = 0.53$, $P = 0.06$), and not at all with protein ($r = -0.04$, $P = 0.88$), GI ($r = 0.31$, $P = 0.30$), or fiber ($r = -0.46$, $P = 0.12$) contents.

In a stepwise regression of observed glucose responses on GL, GI, carbohydrate, protein, fat, and fiber, only GL was significant ($P = 0.003$), which accounted for 58% of the variation. Similarly, the stepwise regression analysis on the insulin data also found only GL to be a significant predictor, responsible for 46% of the variation ($P = 0.01$).

DISCUSSION

This study provides the first large-scale, systematic evidence of the physiologic validity of the concept of dietary GL as a measure of postprandial glycemia and insulin demand in healthy subjects. Among the 121 single foods tested, GL explained ≈85% of the variation in postprandial glycemia and 59% of the variation in insulinemia, which correlated more strongly than did the available carbohydrate content alone. Similarly, among the 13 realistic mixed meals, GL was still the strongest predictor of glycemia and insulinemia, although it explained less of the observed variation (58% and 46%, respectively). In contrast, neither available carbohydrate content alone nor GI alone was a significant predictor of metabolic

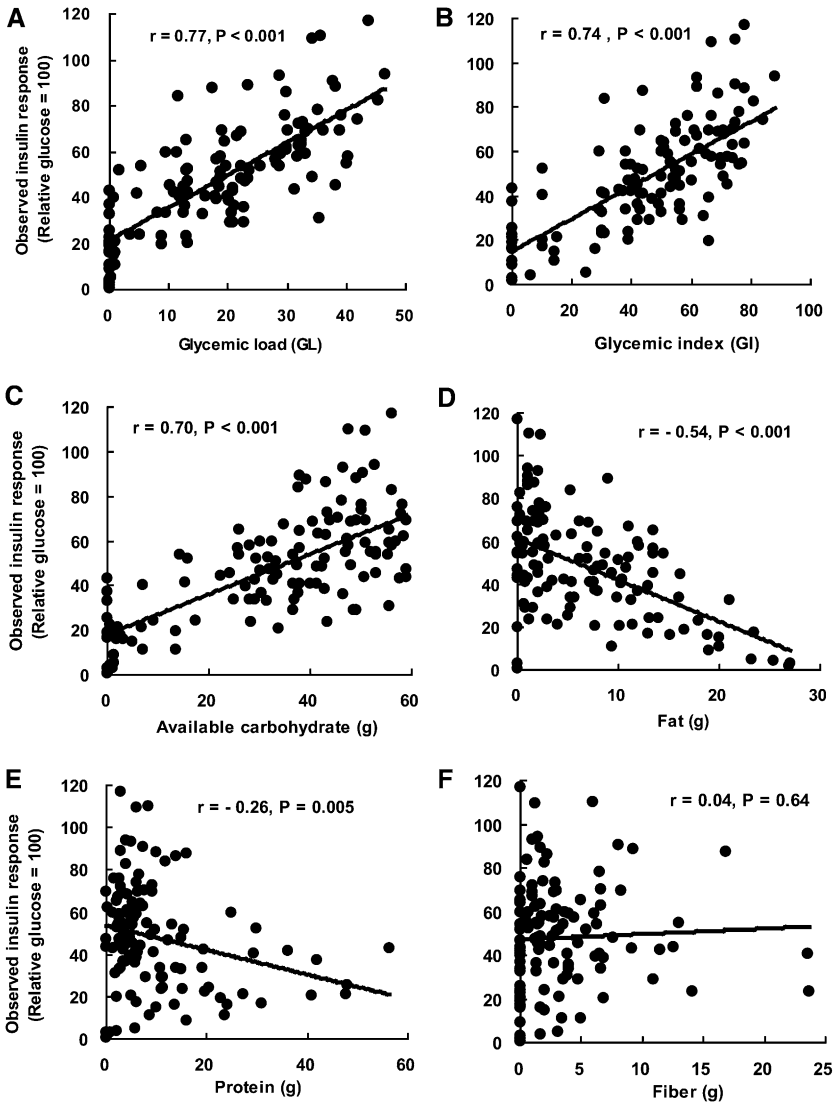

FIGURE 2. A–F: Univariate correlations between observed insulin responses (relative to glucose = 100), the calculated glycemic load, the glycemic index, and the available carbohydrate, protein, fat, and fiber contents of 121 single test foods. Simple (univariate) analysis was used to test the significance of the associations. Each point on the graph represents the mean result for each test meal (n = 10–13 subjects).

responses to these mixed meals. In addition, we found that fiber showed little or no relation to glycemia or insulinemia in either study. Taken together, the findings support the hypothesis that calculated dietary GL is superior to carbohydrate content alone as a surrogate measure of postprandial glycemia and insulin demand in healthy subjects.

Salmeron et al (10) first introduced the concept of GL in 1997 and found that the risk of type 2 diabetes in women was significantly related to overall dietary GL but not to the carbohydrate content of the diet. Subsequently, we showed that progressive increases in GL, irrespective of food source, produced insulin responses that were directly proportional to GL (17). Because excessive insulin demand has been hypothesized to lead to β cell exhaustion in susceptible individuals (26), high-GL diets could therefore have a true physiologic basis for increasing the risk of type 2 diabetes. Nonetheless, it is important to recognize that in the meal study, GL explained less than half (46%) of the observed variability in insulin responses, which implies that unknown factors could be more important.

Traditionally, the carbohydrate content (positively) and dietary fiber (inversely) have been considered major nutrient influences on glucose responses in healthy and diabetic subjects. Thus, carbohydrate counting continues to be the basis of insulin dose adjustment in diabetes management (27), with reductions recommended for high-fiber foods (28). Surprisingly, however, in the meal study, neither carbohydrate alone nor fiber was a significant predictor of postprandial responses. The 2-fold variation in GI among the meals (from 32 to 77) was the likely explanation for why carbohydrate content alone was not predictive. In nutritional epidemiology, carbohydrate energy has seldom been related to the relative risk of chronic disease (3, 4). In contrast, GL has been increasingly shown to be a significant independent predictor of risk (2, 3, 6, 10, 29).

A higher consumption of dietary fiber and whole-grain foods was shown to improve insulin sensitivity in controlled trials (30) and to be associated with a reduced risk of cardiovascular disease and type 2 diabetes in prospective cohort studies (31). In the present study, however, fiber was not a predictor of either glycemia or insulinemia

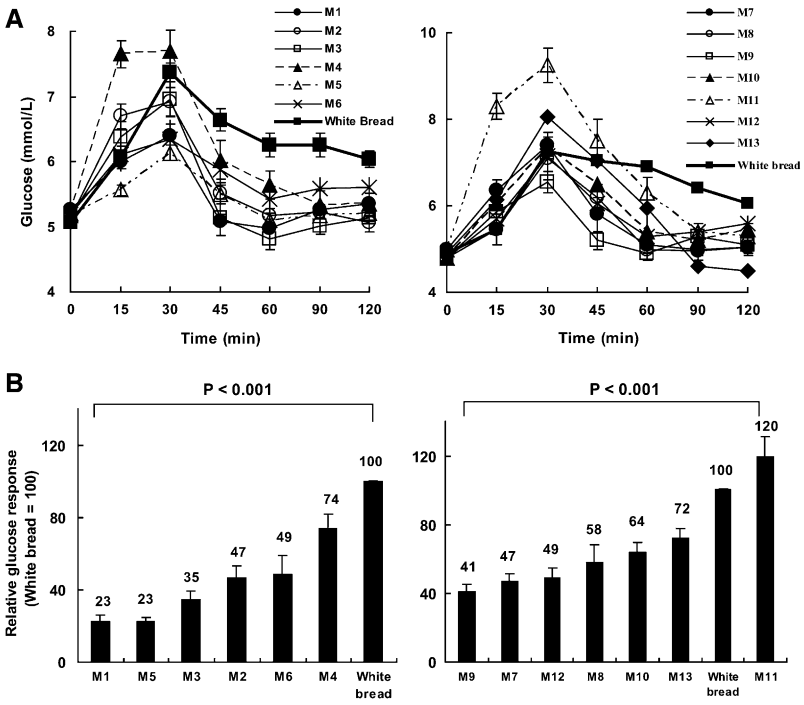

FIGURE 3. Mean (±SEM) glucose responses (area under the glucose curve) (A) and relative glucose responses (assessed as the glucose score) (B) evoked by 13 mixed meals (2000-kJ portions) compared with an isoenergetic white bread reference meal (= 100). Because of the large number of meals, 6 meals were tested by 11 subjects in group 1, and 7 meals were tested by 10 subjects in group 2. Repeated-measures ANOVA was used to determine the significance of differences. M, meal.

among the single foods or mixed meals. Whereas fiber itself is not digested and absorbed, the ability of intact cell walls and viscous fiber to slow digestion is used to justify the claim that whole grains and other high-fiber foods will produce less glycemia and insulinemia than other foods (32). Our finding of little or no relation between fiber content and glycemia/insulinemia is therefore remarkable. One implication is that the mechanism underlying the beneficial effects of fiber is not a reduction in acute glycemia or insulinemia per se. Instead, the health effects of fiber could be ascribed to second- meal effects, accompanying micronutrients, or antioxidants or to fermentation in the large intestine (33).

The ability of GI tables to predict glucose and insulin responses to mixed meals has often been questioned (18, 19). Yet, in this study, most GI values were drawn from published tables, helping to justify the case for using GI tables at least in research involving healthy individuals. The intrinsic value of the GI itself has also been challenged because glucose tolerance is highly variable within and between individuals. We managed these sources of variation by using each subject as his or her own control, comparing their response to the test food with a reference food and testing the reference food more than once. These precautions were important because they contributed to more precise measurements of relative glycemia and insulinemia.

Our study had limitations that dictate caution in extrapolating the findings to clinical practice. First, our subjects were a select group of lean glucose-tolerant individuals, with the likelihood of optimal β cell function. The relations between GL and postprandial glycemia seen in this group may or may not apply to obese, insulin-resistant, or type 2 diabetic patients who are the targets of GI/GL therapy. Greater within-day or day-to-day variability in metabolic responses could compromise the ability to detect relative differences among foods and meals. Indeed, in individuals with severe β cell dysfunction and/or low β cell mass, there may be no differences in either glucose or insulin responses among different foods. Second, in the present study, metabolic responses were studied only at breakfast time, which may not necessarily reflect responses to meals eaten at other times of the day. It is likely that GL will explain less of the variability in glucose and insulin responses after evening meals and snacks. Third, among the mixed meals, GL (despite being the strongest predictor) explained less than half the variability in postprandial insulinemia. Hence other factors, unknown and potentially more important than GL, are yet to be discovered. Finally, our ability to measure the available carbohydrate content of foods remains problematic, whether calculated "by difference" or estimated directly. Determining the true amount of carbohydrate available to the circulation will depend on future efforts to more precisely assay sugars and starches, including resistant starch and low-digestibility carbohydrates. These caveats must be recognized in testing the hypothesis that low-GI and/or GL diets reduce insulin demand and therefore the risk of type 2 diabetes.

The strengths of this research include the large number of single foods (n = 121) and mixed meals (n = 13) studied, the adequate sample size (10–13 individuals per food), and repeated testing of a reference food. The single foods were carefully selected on the basis of their contribution to energy in American diets. The use of finger-prick, rather than forearm, blood sampling was also ideal and contributed to lower within-subject variability and a greater ability to detect differences among foods and meals (34). Potentially, because GL appears to be a more accurate predictor of exogenous insulin requirements than carbohydrate content alone, GL may have clinical application in the management of insulin-sensitive individuals with type 1 diabetes. Thus, to adjust the meal-time insulin dose, a GL:insulin

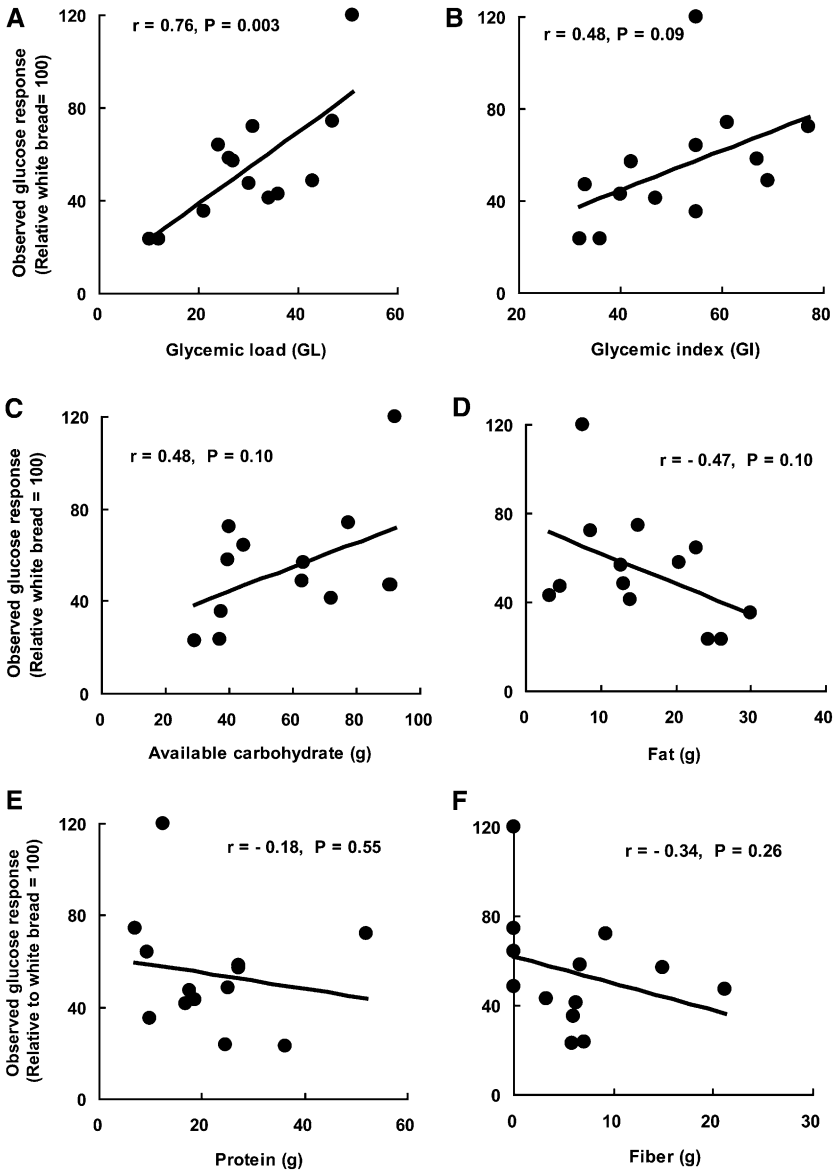

FIGURE 4. A–F: Univariate correlations between observed glucose responses (relative to white bread = 100), the glycemic load, the glycemic index, and macronutrients of the 13 mixed meals. Simple (univariate) analysis was used to test the significance of associations. Each point on the graph represents the mean result for each test meal (n = 10–11 subjects).

ratio could be used in lieu of the carbohydrate:insulin ratio. Comprehensive tables of GI and GL for nominal serving sizes of >2500 different foods are available (23).

In conclusion, the present study provides the first large-scale, systematic evidence of the physiologic validity and superiority of dietary GL over carbohydrate content alone for estimating postprandial glycemia and insulin demand in healthy individuals. The findings support the assumption that the mechanism linking high dietary GL to chronic disease risk may be postprandial hyperglycemia and/or compensatory hyperinsulinemia. Although further studies are needed in obese, insulin-resistant, and type 2 diabetic individuals, the findings provide support for the analysis of dietary GI and GL among other measures of carbohydrate nutrition in nutritional epidemiology.

The authors' responsibilities were as follows—JCB-M, FA, WCW, and JB: conceived the study, selected the test foods and meals, and interpreted the data; FA: created the database and designed the experiment; JB: conducted the study, prepared the meals, and collected the data; PP: analyzed the data and contributed to the interpretation of the findings; JB and JCB-M: wrote the manuscript; and WCW, FA, and PP: reviewed the manuscript and contributed to the discussion. JCB-M is a coauthor of *The New Glucose Revolution* book series (Marlowe and Co, New York, NY), President of the Glycemic Index (GI) Foundation, and Director of a nonprofit GI-based food endorsement program in Australia. JCB-M and FA manage the University of Sydney GI testing service. FA was employed by the University of Sydney for the purposes of commercial GI testing. JB, WCW, and PP had no conflicts of interest to declare.

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