Original Article

Glycaemic glucose equivalent: combining carbohydrate content, quantity and glycaemic index of foods for precision in glycaemia management

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The glycaemic index (GI) is the blood glucose response to carbohydrate in a food as a percentage of the response to an equal weight of glucose. Because GI is a percentage, it is not related quantitatively to food intakes, and because it is based on equi-carbohydrate comparisons, GI-based exchanges for control of glycaemia should be restricted to foods providing equal carbohydrate doses. To overcome these limitations of GI, the glycaemic glucose equivalent (GGE), the weight of glucose having the same glycaemic impact as a given weight of food, is proposed as a practical measure of relative glycaemic impact. To illustrate the differences between GGE and GI in quantitative management of postprandial glycaemia, published values for carbohydrate content, GI and serving size of foods in the food groupings, breads, breakfast cereals, pulses, fruit and vegetables, were used to determine the GGE content per equal weight and per serving of foods. Food rankings and classifications for exchanges based on GGE content were compared with those based on GI. In all of the food groupings analysed, values for relative glycaemic impact (as GGE per 100 g food and per serving) within each of the categories, low, medium and high GI, were too scattered for GI to be a reliable indicator of the glycaemic impact of any given food. Correlations between GI and GGE content per serving were highest in food groupings of similar carbohydrate content and serving size, including breads ($r = 0.73$) and breakfast cereals ($r = 0.8$), but low in more varied groups including pulses ($r = 0.66$), fruit ($r = 0.48$) and vegetables ($r = 0.28$). Because of the non-correspondence of GI and GGE content, food rankings by GI did not agree with rankings by GGE content, and placement of foods in GI-based food exchange categories was often not appropriate for managing glycaemia. Effects of meal composition and food intake on relative glycaemic impact could be represented by GGE content, but not by GI. Because GGE is not restricted to equicarbohydrate comparisons, and is a function of food quantity, GGE may be applied, irrespective of food or meal composition and weight, and in a number of approaches to the management of glycaemia. Accurate control of postprandial glycaemia should therefore be achievable using GGE because they address the need to combine GI with carbohydrate dose in diets of varying composition and intake, to obtain a realistic indication of relative glycaemic impact.

Key words: carbohydrate, diabetes mellitus, food intake, glycaemia, glycaemic glucose equivalents, glycaemic index, relative glycaemic impact.

Introduction

Management of postprandial glycaemia in diabetes care has been imprecise because neither the available carbohydrate content nor the glycaemic index (GI) can provide an accurate guide to the glycaemic impact of a food. GI was originally developed as a physiological basis for food exchanges to account for differences in the glycaemic potency of carbohydrates in foods.[1] It has been the subject of much recent debate,[2–5] as well as a good deal of promotion.[6]

Glycaemic index is defined as the incremental effect of carbohydrate in a food on blood glucose, as a percentage of the effect of an equal weight of glucose. It is usually based on the glycaemic effect of enough food to provide a 50 g dose of carbohydrate, compared with the effect of 50 g glucose or its equivalent in white bread as the reference.

GI = Blood glucose increment due to 50 g carbohydrate in a food × 100/Blood glucose increment due to 50 g glucose

Two intrinsic characteristics of GI severely limit its usefulness as a guide to glycaemic impact in most diets:[7]

1. Glycaemic index is based on equicarbohydrate comparisons, so direct use of it in food exchanges and comparisons should be restricted to food quantities providing equal carbohydrate doses. Although it is stated frequently that GI ranks foods according to their impact on blood glucose,[6] such statements should be qualified with the clause, ‘as long as the foods contain the same amount of carbohydrate’ to be strictly correct.

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2. Being a percentage, GI does not respond to food quantity and so cannot be used to quantitatively link glycaemic response to food intake.

To overcome these limitations of GI, a food-based 'GI', termed Relative Glycaemic Potency (RGP), was recently proposed and defined as the theoretical glycaemic response to 50 g of a food as a percentage of the response to 50 g glucose.[7] RGP is simply GI adjusted for the carbohydrate content of a food (%CHO) and, because it is expressed as a percentage of the effect of glucose, the RGP of a food can be regarded as the amount of glucose that would be equivalent to 100 g of the food in its glycaemic impact. Thus:

$$\text{RGP} = (\%\text{CHO}/100) \times \text{GI} = \text{GGE}/100\text{ g food}$$

where GGE is the glycaemic glucose equivalent, defined as the weight of glucose that would be equivalent to a given weight of food in its glycaemic impact. One can therefore obtain from RGP a value for the relative glycaemic impact of any weight of a food as its content of GGE. As a number that represents the conjoint role of quality (GI), content (%CHO) and intake in determining glycaemic response, GGE also allows one to treat relative glycaemic potency in much the same way as a nutrient.[8]

The relative glycaemic impact of a given weight of food, as GGE content or intake, is similar to the concept of glycaemic loading,[9] except that it refers specifically to the acute glycaemic effect of a single food intake event and is designed for use in glycaemia management, whereas glycaemic load is a measure of cumulative exposure to glycaemia as a risk factor in disease. Relative glycaemic impact (RGI) is defined as the number of GGE donated by a food item or by a meal:

$$\begin{aligned}\text{RGI} &= \text{GGE intake}\\ &= \text{Food weight} \times \text{GGE/g food}\\ &= \Sigma(\text{Servings of food} \times \text{Food weight/serving} \times (\%\text{CHO} \times \text{GI})/10\,000)\end{aligned}$$

Deriving GGE is simple, but it has important implications:

1. Glycaemic glucose equivalents are based on the glycaemic impact of entire foods rather than solely on the carbohydrate component, so, in contrast to GI, use of GGE need not be restricted to equicarbohydrate comparisons.
2. As GGE intake is a function of food intake, it can be used quantitatively to give a direct measure of the relative glycaemic impact of a food quantity.

Because GGE give a quantitative measure of relative glycaemic impact in response to the composition and quantity of foods eaten, they could greatly extend the usefulness of GI and improve the precision of glycaemia management by diet, insulin and medication. This paper introduces the concept of GGE, comparing it with GI.

Methods

Sources of data

GI values and corresponding values for carbohydrate composition, and serving sizes, for calculating GGE content, were obtained from published sources.[6,10,11]

Tables of relative glycaemic impact were based on common standard measure (CSM) sizes from the New Zealand Food Composition Database[12] and GI values were from a number of sources. Foods were included only if their GI values had been determined and closely matched those for which food composition data were provided.

Calculating glycaemic glucose equivalents content

The relative glycaemic impact of 100 g and of servings of foods was calculated as:

$$\begin{aligned}\text{RGI} &= \text{GGE intake a single intake event}\\ &= \text{Food weight} \times \text{GGE/g food}\\ &= \Sigma(\text{Servings of food} \times \text{Food weight/serving} \times (\%\text{CHO} \times \text{GI})/10\,000)\end{aligned}$$

Data for analysis were selected for foods from the major food groupings, that is, breads, breakfast cereals, pulses, fruit and vegetables.

Relationship of GI to GGE content

The relationship of GI to GGE content was tested using GGE values calculated from data in published tables of GI values, serving sizes and carbohydrate (CHO) per serving.[6] Linear correlations of RGI with GI, per 100 g and per serving, were determined for each food grouping.

Comparison of food rankings by GI and RGI

The GI values within each food group were ranked and compared with corresponding GGE contents for 100 g and for common standard measures in the New Zealand Food Composition Database.

Comparison of food classifications based on GI, GGE/100 g and GGE/CSM

Foods were classified into the GI classes suggested by Brand Miller *et al*.:[6] low GI, <55; medium GI, 55–70; and high GI, > 70. In this paper, categories for GGE/100 g were based on the correspondence between the distributions of GGE/100 g and GI values, and were taken as: low, <15 GGE/100 g; medium, 15–30 GGE/100 g; and high, >30 GGE/100 g. Categories for GGE/CSM were similarly created as: low, <10 GGE/CSM; medium, 10–17 GGE/CSM; and high, >17 GGE/CSM. As with GI categories, these are otherwise arbitrary.

Comparison of meal GI and GGE intake

To compare the effects of changing meal composition on the meal GI and on relative glycaemic impact (as GGE intake), a meal GI was calculated as the average GI of the components of the meal, weighted by the proportions of total carbohydrate that they supply.[12] The meal GGE intake was calculated as the sum of the GGE contributions of each food within the meal.

Statistical analysis

All plots and statistical analyses were carried out using the Microsoft Excel system.

Results

Relative glycaemic impact as GGE/100 g, and as GGE/serving, for foods within each food grouping were plotted against their GI (Figs 1,2). Considering all foods together, the range of RGI within each GI category (low, <55; medium, 55–70; high, >70) was extremely large, reflecting the very different carbohydrate contents of the foods. However, the three GI categories each contained foods of relatively low, medium and high GGE content, even within each food grouping. That is, the GI-based classification did not discriminate well between foods of low, medium and high relative glycaemic impact.

The correlation of GGE content with GI depended on the uniformity of foods within a food grouping. Thus, for breads and breakfast cereals, within which groups serving sizes and carbohydrate contents are relatively similar, the correlation between GI and GGE content was closer than for pulses, fruit and vegetables, in which serving size is often determined by natural morphology (Table 1). It is clear from Figs 1 and 2 that even though fruit and vegetables exhibit a full range of GI values, they generally have less glycaemic impact per unit weight than breads, breakfast cereals and pulses, and a slightly lower RGI per serving.

Ranking of foods by GGE compared with GI

The range of GGE contents within each GI category for each food grouping (Figs 1,2) suggested that food rankings by GI would not match the rankings by GGE, either on an equal weight (GGE/100 g) or on a per serving (GGE/serving) basis. The ranked GI values corresponding most closely with GGE content values were those for breads and breakfast cereals, but the correspondence was poor for fruit and vegetables (Tables 2,3). A detailed example is given for the food category 'fruit' in Table 2, which shows that rankings by GI do not correspond at all well with relative glycaemic impact, either as GGE/100 g or as GGE/CSM. Space does not permit the data for all groups to be shown, but a sampling of foods taken from several food categories in the New Zealand Food Composition Database shows that whether RGI is expressed on an equal weight basis, per serving, or per megajoule, the GI of a food may be a poor guide to glycaemic impact (Table 3). As a corollary, the sensitivity of GGE content and insensitivity of GI to food quantity are shown, because the differences in the three relative glycaemic impact values for each food are the result of the different quantities (mJ, 100 g, CSM) involved.

Table 1. Correlations of GI with GGE content as a measure of relative glycaemic impact within food groupings

Food group	Relative glycaemic impact	
	GGE/100 g	GGE/serving
Breads	0.83	0.73
Breakfast cereals	0.86	0.80
Pulses	0.51	0.66
Fruit	0.20	0.48
Vegetables	0.24	0.28

GGE, glycaemic glucose equivalents; GI, glycaemic index.

Food classifications based on GI and RGI

The non-correspondence of GI and RGI in food classifications can have significant consequences for glycaemic control (Table 4). Food categories based on low (< 55),

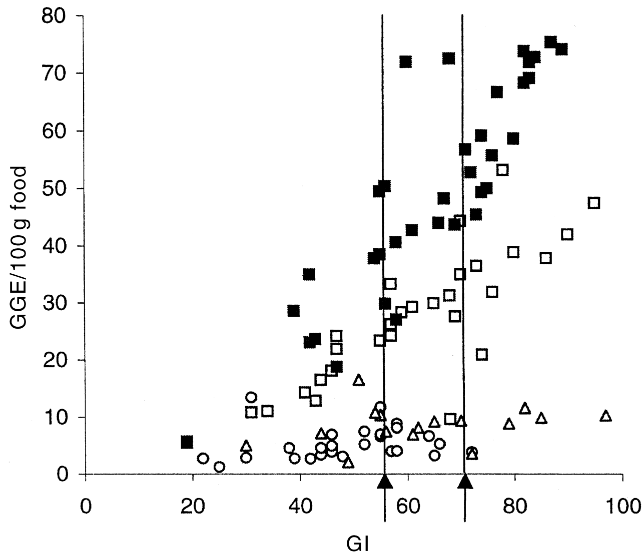

Figure 1. Glycaemic glucose equivalents (GGE) per 100 g of foods relative to their glycaemic indices (GI). Low, medium and high GI categories are shown by arrows at GI 55 and GI 70 (calculated from data in reference 6). □, Breads; ■, breakfast cereals; ○, fruit; △, vegetables.

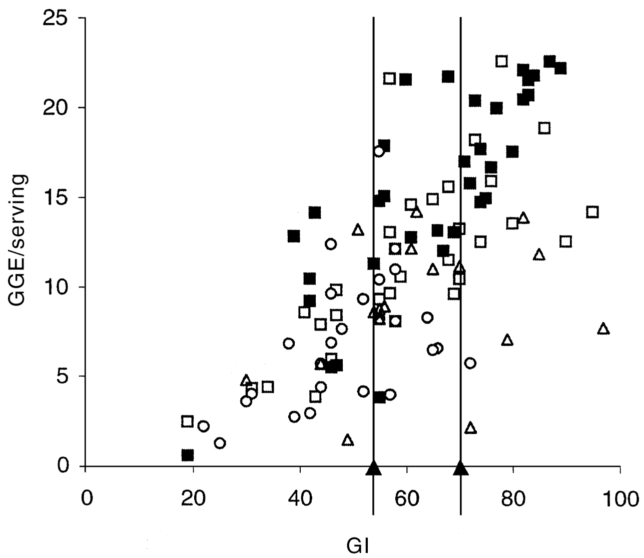

Figure 2. Glycaemic glucose equivalents (GGE) per serving of foods relative to their glycaemic indices (GI). Low, medium and high GI categories are shown by arrows at GI 55 and GI 70. (Calculated from data in reference 6.) □, Breads; ■, breakfast cereals; ○, fruit; △, vegetables.

Table 2. Correspondence between rankings by GI, and by relative glycaemic impact as GGE per 100 g or per common standard measure (GGE/CSM) in a food group: Fruit ranked by GI

Fruit	CSM	GI		GGE/100 g		GGE/CSM	
		Data	Rank by GI	Data	Rank by GGE/ 100 g	Data	Rank by GGE/CSM
Watermelon, raw	Cup	72	1	4	19	7.8	10
Pineapple, raw	Slice	66	2	8	9	8.3	9
Melon, rock, raw	Cup	65	3	4	16	6.9	12
Apricot, syrup, canned	Cup	64	4	17	3	47.0	3
Raisins	Cup	64	5	41	2	63.1	2
Pawpaw, Australian	Slice	58	7	4	18	5.6	13
Banana, raw	Banana	58	6	14	7	17.8	7
Apricot, raw	Apricot	57	8	5	12	2.9	20
Sultanas	Cup	56	9	42	1	64.3	1
Mango, raw	Mango	55	10	8	8	14.1	6
Kiwifruit, raw	Kiwifruit	52	11	5	14	4.8	16
Orange juice, fresh	Cup	50	12	5	15	11.9	8
Peaches, canned	Cup slices	47	13	10	6	26.9	4
Grapes, black or white	Grape	46	14	7	10	0.4	22
Orange, raw	Orange	44	15	3	20	4.3	18
Pear, flesh, raw	Pear	42	16	5	13	7.2	11
Plums, raw	Plum	39	17	5	11	2.7	21
Apple, dessert, flesh, raw	Apple	38	18	4	17	4.9	15
Banana, green, raw	Banana	38	19	10	5	12.6	5
Apricot, dried	10 halves	31	20	15	4	5.3	14
Grapefruit, flesh, raw	Grapefruit	25	21	3	22	4.3	19
Cherries, raw	Cup	22	22	3	21	4.6	17

CSM, common standard measure; GGE, glycaemic glucose equivalents; GI, glycaemic index.

medium (55–70), and high (> 70) GI, on which the GI exchange system is based, did not contain the same foods as corresponding categories based on GGE/100 g and GGE/serving. Foods whose GGE content did not match their classification by GI included watermelon, which is classed as a high GI food, in contrast to apples and oranges, classed as low GI. When carbohydrate content was taken into account, watermelon (4 GGE/100 g), apple (4 GGE/100 g) and orange (3 GGE/100 g) had about the same GGE content per unit weight. Similarly, broad beans are classed as high GI (GI = 79) and spaghetti as low GI (GI = 41), but the GGE content for broad beans (7 GGE/100 g) was less than that of spaghetti (8 GGE/100 g), and the GGE dose per common standard measure (1 cup) was 11.5 GGE/CSM for broad beans, and 12.1 GGE/CSM for spaghetti. Similarly, broad beans and haricot beans are classed as high and low GI, respectively, yet broad beans deliver about the same GGE dose per 100 g and per serving as haricot beans. Therefore, a food classed as highly glycaemic by its GI factor may, in fact, have as low a relative glycaemic impact as a food of low GI. Other examples of the discrepancy between categories based on GI and GGE content are shown in Table 4.

GGE content of individual food items compared with GI

The utility of GGE content compared with GI as a guide to the glycaemic impact of foods that are eaten as individual items, such as snacks and fruits, is demonstrated with a few examples in Table 5. GI values for food items are often not a guide to glycaemic impact because carbohydrate food items with similar GI scores may differ in size and carbohydrate content, and therefore deliver quite different GGE doses.

GGE content of meals compared with meal GI

Table 6 shows a hypothetical meal for which the meal GI was calculated, as an average GI weighted by the proportions of carbohydrate provided by each food,[13] and compared with the relative glycaemic impact of the meal, calculated as the sum of the GGE contributions of the individual foods. In addition, the effect of an additional serving of carbohydrate food is shown. The results show that glycaemic index is not an effective guide to the glycaemic impact of meals in which the carbohydrate dose changes. In fact, an additional cup of porridge slightly decreased the glycaemic index of the meal, even though the GGE dose of the meal increased greatly.

Discussion

The difference between relative glycaemic impact as GGE intake and GI is very simple; GGE intake is GI adjusted for the carbohydrate content of the food and the amount of food consumed. Simple though such an adjustment is, it has important implications because it allows the dietary management of postprandial glycaemia to be made quantitative

Table 3. Abbreviated table of GI and relative glycaemic impact as GGE per 100 g, per common standard measure and per megajoule of food

Food	Nature of CSM	Weight (g)	%CHO	GI	Relative glycaemic impact		
					GGE/MJ	GGE/100 g	GGE/CSM
Bakery products							
Bagels, plain	Bagel	74	47	72	36	33.8	25
Bread roll, white, soft	Roll	51	49	70	34	34.3	17.5
Bread, white, sliced	Medium slice	26	43	70	35	30.1	7.8
Bread, wholemeal	Medium slice	28	37	69	32	25.5	7.1
Croissants	Small	57	39	67	16	26.1	14.9
Crispbread, rye	Biscuit	6	64	65	32	41.6	2.5
Bread, multigrain, heavy	Medium slice	28	37	52	21	19.2	5.4
Beverages, non-alcohol							
Juice, orange, unsweetened	Cup	256	7.7	52	28	4	10.3
Breakfast cereals							
Corn flakes, Kelloggs	Serving	30	85	84	46	71.4	21.4
Wheat, puffed	Cup	14	64	74	35	47.4	6.6
Wheat biscuit, Weet-Bix	Biscuit	15	62	70	33	43.4	6.5
Porridge, milk/water	Cup	260	10.5	61	19	6.4	16.7
Muesli, non-toasted	Cup	107	57	56	23	32	31.9
Muesli, toasted, sweetened	Cup	110	53	43	14	22.8	25.1
Cereals, pseudo-cereals							
Rice, white, boiled	Cup	216	27	58	50	15.7	33.8
Rice, brown, boiled	Cup	206	29	55	28	16	32.9
Spaghetti, boiled	Cup	148	20	41	14	8.2	12.1
Dairy							
Ice cream, vanilla	Cup	143	22	61	16	13.4	19.2
Milk, fluid, standard	Cup	258	4.5	27	5	1.2	3.1
Fruit							
Watermelon, raw	Cup	213	5.1	72	37	3.7	7.8
Pineapple, raw	Slice	110	11.4	66	33	7.5	8.3
Melon, rock, raw	Cup	168	6.3	65	33	4.1	6.9
Raisins	Cup	154	64	64	33	41	63.1
Banana, raw	Banana	128	24	58	32	13.9	17.8
Apricot, raw	Apricot	54	9.3	57	6	5.3	2.9
Kiwifruit, raw	Kiwifruit	100	9.3	52	24	4.8	4.8
Peaches, canned	Cup slices	260	22	47	27	10.3	26.9
Orange, raw	Orange	128	7.7	44	20	3.4	4.3
Pear, flesh, raw	Pear	148	11.6	42	22	4.9	7.2
Plums, raw	Plum	49	13.9	39	20	5.4	2.7
Apple, dessert, flesh, raw	Apple	121	10.7	38	20	4.1	4.9
Grapefruit, flesh, raw	Grapefruit	170	10.1	25	14	2.5	4.3
Vegetables							
Parsnip, boiled	Parsnip	160	12.3	97	51	11.9	19.1
Potato, microwaved	Potato	90	21	81	43	17.1	15.4
Beans, broad, boiled	Cup	170	8.6	79	28	6.8	11.5
Pumpkin, boiled, drained	Cup	220	4	75	16	3	6.6
Carrots, boiled, drained	Carrot	49	5.5	71	35	3.9	1.9
Potato, mashed, milk/butter	Cup	209	14.5	70	30	10.2	21.2
Corn, sweet, boiled	Cob	128	21	55	23	11.6	14.8
Peas, green, boiled	Cup	165	7.1	48	16	3.4	5.6
Beans, haricot, boiled	Cup	180	15	38	15	5.7	10.3

%CHO, carbohydrate content; CSM, common standard measure; GGE, glycaemic glucose equivalents; GI, glycaemic index.

and accurate. Specifically, GGE is a variable that can be used directly in glycaemia management, without the need for prior calculation to account for the effects of food composition.

Ranking and classification of foods by GGE compared with GI

Although correlations between GGE content and GI were quite close for breads and breakfast cereals, the differences

Table 4. Examples of differences in classification of foods based on GI, and on relative glycaemic impact as GGE per 100 g food or as GGE/CSM

Classification	Food	GI	Food	GGE/100 g	Food	GGE/CSM
Low	Muesli	43	Broad beans	7	Carrot	1.9
	Taro	54	Pumpkin boiled	3	Pumpkin boiled	6.6
	Sponge cake	46	Carrot	3.9	Golden fruit biscuit	6.6
	Canned peach	47	Canned peach	10	Swede	4
	Spaghetti	41	Swede	3	Puffed rice	9.7
	Haricot beans	38	Spaghetti	8	Apple	4.9
	Apple	38	Haricot beans	6	Orange	4.3
	Orange	50	Apple	4	Watermelon	7.8
			Orange	3		
			Watermelon	4		
Medium	Oat bran	55	Muesli	23	Broad beans	11.5
	Raisin	64	Taro	15	Spaghetti	12.1
			Oat bran	30	Haricot beans	10.8
			Sponge cake	28		
High	Carrot	71	Golden fruit biscuit	51	Muesli	25.1
	Broad beans	79	Puffed rice	69	Taro	21
	Pumpkin boiled	75	Raisin	41	Oat bran	36
	Golden fruit biscuit	77			Sponge cake	25
	Swede	72			Canned peach	27
	Puffed rice	89			Raisin	63
	Watermelon	72				

Classifications were based on the following ranges: for GI, low <55, medium 55–70, high >70; for GGE/100 g, low <15, medium 15–30, high >30; for GGE/CSM, low <10; medium 10–17, high >17. CSM, common standard measure; GGE, glycaemic glucose equivalents; GI, glycaemic index.

Table 5. The glycaemic index, and corresponding relative glycaemic impact as GGE content per item, of foods consumed as individual items

Food item	CSM	Weight (g)	GI	GGE/CSM
Apricot	1	54	57	3
Banana	1	128	58	18
Ice cream	2 scoops	50	61	6.5
Blueberry muffin	1	80	59	24
Fanta™	1 can	375	68	35
Pineapple	2 slices	125	66	6.6
Orange juice	1 glass	256	46	9.9
Banana cake	1 slice	80	47	22
Dark rye bread	1 slice	70	86	19
Apple muffin	1	80	44	19
Broad beans	1 cup	170	79	11.5
Spaghetti	1 cup	148	41	12.1

CSM, common standard measure; GGE, glycaemic glucose equivalents; GI, glycaemic index.

in GGE content between foods within each GI category showed that, even within food groupings, GI cannot be used to predict glycaemic impact with any certainty. GI-based classification of foods for glycaemic control requires that rankings by GI be the same as rankings by relative glycaemic impact. However, the very large range of GGE contents, within each of the GI categories, for each food grouping (Figs 1,2) demonstrates clearly the need to categorise foods by carbohydrate content and serving size, to achieve carbohydrate equivalence, before GI can be used accurately to select foods for glycaemic control.

Carbohydrate equivalence could be achieved by standardising serving sizes within food groupings of similar composition. However, portion sizes eaten, food composition within food groupings and the number of items of each food consumed at a time have not been designed or standardized with GI-based food selection in mind.

Food exchange tables, giving quantities of foods that are theoretically equivalent in glycaemic impact, show that one CSM of any food is seldom equivalent in glycaemic potency to a whole number of CSM of other foods.[14] A 'this' for 'that' approach to management of glycaemia, based on GI and

Table 6. Effect of changing meal composition and quantity on meal GI, and on relative glycaemic impact as GGE intake

Food	Serving	CHO dose (g)	Total meal CHO (%)	GI	CHO-weighted GI	GGE
Breakfast 1						
Bread	2 slices	22	32	70	22.4	15.4
Porridge (low GI)	1 cup	27	39	42	16.4	11.3
Orange juice	1 cup	20	29	46	13	9.6
Totals		69	100		51.8	35.9
Breakfast 2						
Bread	2 slices	22	234	70	16	15.4
Porridge	2 cups	54	565	42	23	22.7
Orange juice	1 cup	20	21	46	9.7	9.2
Totals		96	100		48.7	45.8

CHO, carbohydrate; GGE, glycaemic glucose equivalents; GI, glycaemic index.

standard food portions, must therefore involve approximations that reduce the accuracy of glycaemic control. Fractions of food portions could be used to attain carbohydrate equivalence, but the benefit of working with whole food quantities that are familiar and easy for people to use would then be lost.

GGE content of individual food items

For many foods consumed as individual items, serving size, in practice, is determined by the size of the food item. An apple, a muesli bar, an ice cream, a can of drink, and so on, will usually be consumed entirely. GI is unlikely to be a useful guide to the relative glycaemic impact of such food items because the items differ in composition and weight. Such foods are often consumed in between meals as snacks and may include a number that are eaten specifically for their glycaemic effect. However, as the numbers in Table 4 showed, foods of very similar GI can be several-fold different in the GGE that they provide per serving.

The difference between the GI of a food item and its GGE content could be important to individuals who wish to manage hypoglycaemia, as well as those prone to hyperglycaemia, because GGE content, but not GI, would give an accurate indication of the glycaemic impact they could achieve with a given amount of a specified food item. The difference between GI and GGE content also highlights the danger of putting GI values on food packaging when a more direct guide to the glycaemic impact of a food is its GGE content, which is therefore less likely to be misleading.

Meal effects on GI and on GGE intake

One of the most promising attributes of the GGE is that it may allow the individual GGE contents of each food within a meal to be added, giving a total GGE content for the whole meal. A meal GGE total differs importantly from a meal GI because meal GGE is a simple summation of the GGE contributions of the foods in the meal, whereas a meal GI is an average of the foods' GI, weighted by their proportional contribution to meal carbohydrate.[14] In other words, a meal GI is like a food GI in that it is not related to the quantity of food consumed and is relatively complicated to use. As Table 6 showed, meal GI can decrease while GGE intake increases, possibly giving a false impression of the glycaemic effects of changing foods. However, when the changes are expressed in terms of relative glycaemic impact, the connection between food choice, intake and the direction and magnitude of glycaemic response becomes understandable.

Several studies have shown that including low GI foods in meals lowers glycaemia.[2] It is important to note, however, that in many such studies, carbohydrate intake has been kept constant in order to identify GI effects, so the studies are not a guide to changes in GGE intakes that might occur when food intakes and meal compositions fluctuate, as they are likely to do in reality. Furthermore, although substitution of low GI for high GI foods will have a good probability of reducing postprandial glycaemia, such studies do not measure the precise correspondence between GGE intake per se and glycaemic response.

The ability of the sum of GGE contributed by the different foods in a meal to predict glycaemic response is yet to be tested directly. However, as meal GI and carbohydrate content together predict glycaemic response to a meal,[15] there is no reason to suppose that the sum of GGE would not predict glycaemic response to meals that provide different carbohydrate doses much more accurately than would GI. Clearly, the use of GGE to predict the glycaemic impact of meals will benefit from further validation studies.

Predictive validity of GGE intake as a measure of relative glycaemic impact

The common sense notion that the glycaemic impact of a food depends on its carbohydrate content, the amount of food consumed and the glycaemic potency of the carbohydrate in it is now quite well supported. Only one study to date that has tested the validity of GGE intake per se as a predictor of postprandial glycaemic response,[16] but because GGE is a combination of GI and carbohydrate dose, all studies of joint glycaemic effects of GI and carbohydrate dose are also tests of the ability of GGE to predict glycaemic response.[15–18]

We fed several foods differing in carbohydrate content and GI, at different GGE doses, to individuals with (n = 12) and without (n = 11) type 2 diabetes. After adjusting for individual glycaemic responsiveness, the results showed GGE intake to be a robust predictor of glycaemic impact over as wide a range of carbohydrate doses as would be met in most foods and meals.[19]

Wolever and Bolognesi showed that GI and carbohydrate dose together predict glycaemic response, and found the relationship between GI and carbohydrate dose to be curvilinear, but approximately linear up to at least 50 g carbohydrate intake, reaching a plateau at about 100 g carbohydrate dose.[15] Their data for white bread and spaghetti showed that increments in the area under the blood glucose response curve, above the 25 g carbohydrate dose, were directly proportional to increasing food intake, at least up to the maximum dose of 100 g carbohydrate. Furthermore, the plateau effect observed by Wolever and Bolognesi for several foods is likely to have resulted from truncation of the blood glucose response curves rather than from a real reduction in blood glucose response per unit of carbohydrate intake at high intakes, because measurements of the area under the curve are terminated at 180 min,[20,21] well before the blood glucose response curve has returned to baseline at high carbohydrate doses. Colagiuri and Brand-Miller showed the relationship between carbohydrate dose and glycaemic response at a given GI to be linear, to over 100 g carbohydrate intake for some foods and to pass through the origin, showing direct proportionality.[18]

Studies to date therefore suggest that the assumption of a linear relationship between glycaemic response and carbohydrate dose, when calculating GGE, is justified. But even if the dose–response curve were curvilinear, the GGE calculation would overestimate glycaemic impact at high carbohydrate doses, so the discrepancy would lead to conservative glycaemia management.

Correspondence between relative glycaemic impact (GGE dose) and glycaemic load

Relative glycaemic impact is similar, but not identical, to the concept of glycaemic loading.[9] The two were derived independently for different purposes and differ in emphasis. Glycaemic load is a score for the 'global dietary glycaemic load as an indicator of glucose response or insulin demand induced by total carbohydrate intake'[9] and uses 'carbohydrate content per serving for each food times the average number of food servings of that food per day, times its glycaemic index'.[9] Glycaemic load is therefore a measure of cumulative or ongoing exposure to glycaemia and is used in an epidemiological context.

Glycaemic glucose equivalent intake, on the other hand, refers to the acute relative glycaemic impact of a single food intake event, such as a meal, and is intended for use in the management of glycaemia. Glycaemic load is, in effect, an extension of relative glycaemic impact to a sequence of intake events over a relatively long period. The words 'impact' and 'load' reflect the different emphases of the terms.

Attributes of GGE and contrasts with GI

Freedom from the constraint of carbohydrate equivalence, and responsiveness to food intake gives GGE content important advantages over GI or carbohydrate content in management of glycemia (Table 7). By being a function of food intake, GGE intake as a measure of glycaemic impact should confer accuracy in predicting postprandial glycaemic response to foods, and so may improve precision in insulin adjustment or medication. Similarly, GGE content should allow individual meal targets to be precisely and realistically specified according to glycaemic effect, once an individual's tolerance to GGE intake has been established by measuring their glycaemic response to known GGE intakes – their glucose equivalent tolerance.

Table 7. Some properties and applications of relative glycaemic impact (GGE content or intake) compared with GI

Property or application	RGI	GI
Is a property of foods	+	–
Is a property of carbohydrates in foods	–	+
Is a quantitative function of food intake/serving size	+	–
Can be used to accurately rank and classify foods of different composition by glycaemic impact	+	–
May allow accurate matching of insulin or drug dose to postprandial glycaemic impact	+	–
Represents relative glycaemic effect of individual food items eaten completely, such as snacks, irrespective of size and composition	+	–
Is consistent with consumer experience that effects of a food component depend on content of component in food and on food intake	+	–
Is easily explained as the amount of glucose equivalent to a given amount of food in its glycaemic impact	+	–
Useful in behaviour change as it makes clear the contingency between eating behaviour (choice and intake) and glycaemic impact	+	–
Can be treated as a nutrient in nutrition management systems	+	–

GGE, glycaemic glucose equivalents; GI, glycaemic index; RGI, relative glycaemic impact.

Use of GGE in the self-management of glycaemia would be user friendly and practical because GGE content directly represents the relative glycaemic impact of a food, without the need for users to calculate the combined effect of carbohydrate content, GI and food intake. Total GGE intake in a meal requires simple addition, whereas a meal GI is a weighted average and, like a food GI, is not related to food intake. GGE is therefore a common sense concept because it is consistent with the everyday experience that food effects depend on composition, quality and quantity consumed. Furthermore, GGE is easily explained as the amount of glucose that has the same effect on blood glucose as a given amount of a food.

A ranking of foods by GGE content is a ranking of the foods according to their effect on blood glucose. It will therefore allow classification of foods for glycaemic control without anomalies caused by variations in food composition. Unlike GI, GGE do not require carbohydrate equivalence before they can be validly applied. In contrast to GGE content, which ranks foods, GI provides a ranking of carbohydrates in foods, which translates to a ranking of foods only under equicarbohydrate conditions.

Freedom from the need for carbohydrate equivalence should allow GGE to be used practically for accurate glycaemia management in whole food terms. Simple nutritional messages strictly in food terms can be based on GGE content. In food labelling for glycaemic functionality, for instance, GGE content could usefully tell consumers directly the relative degree of glycaemic effect that a food item will have.

The ability to treat GGE as a food component allows them to be used in conjunction with other nutrient information, in any food management system. In computerised nutrition management systems, for instance, concurrent analysis of nutrient intake and glycaemic impact may be achieved with GGE.[8]

Conclusion

Despite its apparent simplicity and the apparent ease with which it is used, GI is in fact complicated to apply generally to foods as a guide to their glycaemic impact because allowance has to be made for food composition and intake before relative glycaemic impact can be determined. In practice, GI works only where similar-sized portions of similar composition are exchanged. By taking into account differences in carbohydrate content and intake, GGE is not limited to such equicarbohydrate comparisons and should reduce the inaccuracies that occur when food classifications for glycaemic control are based on GI. Because relative glycaemic impact relates to entire foods rather than to their carbohydrate alone, and is expressed as a GGE content in foods, it could have many more applications than GI, particularly in conditions where there is a need for accurate control of glycaemia.

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