Special Publication

The Glycemic Index:

Research Meets Reality

By

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Introduction

Almost all carbohydrates, regardless of the form in which they are consumed (e.g., starch, lactose, sucrose) are metabolized to the monosaccharide glucose, which then enters general circulation causing a temporary rise in blood glucose levels (figure 1). This "glycemic response" is the basis for the increasingly popular measure known as the glycemic index (GI) (Jenkins et al. 1981).

Although the glycemic effects of different carbohydrate foods were first documented in the early 1970s, the precise terminology and methodology for measuring the GI was not introduced until almost ten years later when Jenkins (1981) published his landmark study documenting the GI as a tool for managing type I diabetes (and later dyslipidemia) (Jenkins et al. 1985, Pi-Sunyer 2002).

In the 20 years since its inception, the GI has been the subject of more than 100 scientific studies and the basis for several popular diet plans (Brand-Miller and Foster 2005). The first edition of the *International Tables of Glycemic Index* was published in 1995 (Foster-Powell and Miller 1995) and included 565 entries. The revised *International Table of Glycemic Index and Glycemic Load Values* (Foster-Powell et al. 2002) containing 750 different types of foods was published in 2002. In 1997 a committee brought together by the Food and Agriculture Organization (FAO) of the United Nations and World Health Organization (WHO) endorsed the use of the GI for classifying CHO-rich foods and recommended that the GI values of foods be used in conjunction with information about food composition to guide food choices (Foster-Powell et al. 2002).

Despite the increasing popularity of the GI, its validity and practicality remains controversial, particularly in the United States. Currently, the American Diabetes Association (ADA), the American Heart Association (AHA), and the American Dietetic Association (ADA) do not recognize the GI as a useful dietary planning tool for weight management or disease prevention (Cummings et al. 2002, Krauss et al. 2000, Sheard et al. 2004). Similarly, the 2005 Dietary Guidelines for Americans committee indicated that current evidence does not support the use of GI or glycemic load (GL) for providing dietary guidance for Americans (DG committee report 2005).

The following review will provide an overview of the concepts of GI and GL, describe their limitations and discuss their applications for dietary planning and disease prevention.

GI Defined

A number of definitions for GI can be found in the popular press, many of which oversimplify the measure and, thus, paint an inaccurate portrait of what it truly represents.

* Common/popular definitions of GI:
  - *the rate of digestion and absorption of a carbohydrate-rich food*
  - *blood glucose raising capacity of a carbohydrate-rich food*

The operational definition of GI demonstrates the physiological complexity of the measure and illustrates why it is so infrequently used, particularly in the popular press.

* Operational (accurate) definition of GI
  - *the incremental area under the blood glucose curve (AUC) after the ingestion of 50 grams of a test food, expressed as a percentage of the AUC of an equal amount of a reference food (generally glucose or white bread)* (Jenkins et al. 1981).

$$\text{GI} = \frac{\text{Blood glucose response to 50 g test food (e.g., beans)}}{\text{Blood glucose response to 50 g reference food (e.g. glucose)}} \times 100$$

As the definition indicates, the GI of a given food (i.e., the "test" food) is calculated by comparing the glycemic response to a 50 gram portion of the food with that of an equal portion of a reference food and multiplying that ratio by

100. The calculated GI values are then categorized as low, medium and high; the numerical value that is representative of these categories depends on the reference food used (i.e., white bread or glucose) (Table 1).

Table 1 Glycemic Index Categories

Category	Glucose Reference*	White Bread Reference*
Low	< 55	< 60
Medium	55-70	60-85
High	> 70	> 85

** The reference food is arbitrarily assigned a GI of 100. Both glucose and white bread have been used as reference foods. Glucose has a glycemic response that is 40% greater than that of white bread; conversely, white bread has a GI that is 71% of glucose.*

A question that often arises is how the categorical designations for GI (i.e., low, medium and high) were determined. Why is a GI of < 55 considered low and a GI of > 70 deemed high? Unfortunately the answer to this question is not readily available as it has never been published. In fact, the cut-offs were rather arbitrarily determined by Dr. Jeanette Brand-Miller and her colleagues. According to Dr. Brand-Miller, a value of < 55 was chosen for low GI foods because foods such as legumes had GI values < 50. But because some breakfast cereals had GIs > 50, (and since they helped ensure variety in the low GI diet), a cut-off of 55 was selected. A GI > 70 was chosen for the classification of "high" GI because, foods such as white bread, rice and potatoes had GI values of 70 and above (Personal Correspondence). Instead, they were based upon the notion of a single researcher and a small group of practitioners. This certainly calls into question the validity of the results derived from epidemiological studies employing GI (an issue that will be discussed in greater detail later in this review).

It is decidedly disconcerting that the categorical values representing low, moderate, and high GI which have been used in diet books, clinical trials, and numerous epidemiological studies documenting associations with chronic diseases were not based on physiological, metabolic, or even statistical rationale.

Methodological Considerations

Accurately measuring GI involves following a standardized protocol. In their initial study documenting the measurement of GI, Jenkins et al. (1981) compared 50-gram portions (calculated from food tables) of 62 commonly consumed carbohydrate-rich foods to 50 grams of glucose. Venous blood samples were taken at baseline (i.e., fasting) and at 30-minute intervals for two hours after carbohydrate consumption. The area under the blood glucose curve was determined and expressed as a percentage of the area under the curve obtained after the ingestion of 50 grams of glucose by the same subject. Unfortunately, such a protocol does not readily translate into real life eating occasions. Moreover, numerous methodological factors may influence the value and/or variability of the results obtained as will be described below.

Area under the curve

As previously described, for the purposes of calculating GI, blood glucose response is expressed as the area under the curve (AUC). There are two commonly calculated AUC values: (1) total AUC and (2) incremental AUC.

- *Total AUC*: includes the area beneath the curve down to a blood glucose of zero and is a measure of the average blood glucose concentration during the period of the test (Wolever 2003).
- *Incremental AUC*: includes the area beneath the curve only down to fasting level. If the blood glucose level falls below the baseline, the area below fasting is ignored. Thus, the incremental AUC can never be less than zero (Wolever 2003).

The original methodology for measuring GI described by Jenkins et al. (1981) utilized total AUC; however, more recent research, as well as the operational definition, recommends using incremental AUC (Wolever 2003). Nonetheless, it has been argued that only including glucose values above fasting level (i.e., incremental AUC) is inaccurate (Pi-Sunyer 2002). As Pi-Sunyer argued in a 2002 *AJCN* article, "*glucose molecules are all the same and circulate in the blood stream similarly*." Why then should a glucose molecule below the fasting level be considered any different than one above it? Shouldn't all glucose molecules be considered similarly and the AUC for all of the available glucose be calculated? As might be expected, if total AUC is used, the differences in GIs between foods are greatly attenuated. For example, a person with a fasting blood glucose of 75 mg/dL ingests two foods, one with a GI of 100 and another with a GI 72 (calculated using incremental AUC), a difference of 28 units. If the GI were calculated using the total AUC the values would be 100 and 92, respectively, a difference of only 8 units (Pi-Sunyer 2002). Clearly then, glycemic responses and subsequently the calculation of GI will vary markedly depending upon how AUC is calculated (Wolever 2003).

Shape of the Blood Glucose Response Curve

As previously indicated, the GI describes the area under the blood glucose response curve above the fasting level. Thus, while GI provides an indication of the extent of the blood glucose response, it says little about the *pattern* of the response (i.e., the shape of the blood glucose response curve). For example, the GI of pineapple juice is very similar to that of macaroni (46 and 45, respectively) despite markedly different blood glucose response curves (Wolever 2003) (Figure 2). The reason for the different patterns lies in the digested end-products of the carbohydrate. With a few exceptions (e.g., pure fructose and pure glucose), foods rich in dietary sugars are rapidly digested and absorbed but have a low GI because only half of the carbohydrate is glucose. Thus, after sucrose absorption, blood glucose (and insulin) concentrations increase rapidly but also fall rapidly, while after starch digestion blood glucose levels rise and fall more gradually. In this instance AUC does not accurately represent glucose kinetics which then begs the question of which is more clinically relevant? Most would probably agree that a rapid rise and fall in blood glucose would be less desirable than one which is more gradual; however, this has not been borne out by research.

Amount and Availability of Carbohydrate Provided

Blood glucose responses differ depending on the amount of carbohydrate consumed; thus, the amount of carbohydrate used to determine GI is critical. Research indicates that the AUC increases almost linearly as carbohydrate intake increases from 0-50 grams; however, as intake increases further from 50-100 grams, the AUC tends to level off (Wolever 2003), thus, the rationale for the 50-gram carbohydrate portion. Using less than 50 grams of carbohydrate will attenuate the glycemic response and produce falsely lowered GI.[1] Of equal importance to the absolute amount of carbohydrate in the food portion is the *availability* of that carbohydrate. Accurate GI measurement requires 50 grams of absorbable carbohydrate. Thus, the 50-gram carbohydrate portion should not include carbohydrates that cannot be digested and absorbed in the small intestine (e.g., dietary fiber, resistant starch, and other unabsorbed carbohydrates) (Wolever 2003). Although this may seem a simple concept, in practice it can be quite difficult as definitions of and methodology for measuring available carbohydrate can vary greatly from lab to lab. Moreover, the issue of carbohydrate availability greatly limits the applicability of GI to "real life" eating situations, as many foods as consumed contain fiber, resistant starch, and other carbohydrates with low bioavailability.

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[1] It is recommended, but not necessary, to use a 50-gram portion of carbohydrates so long as the test and reference foods both contain the same amount of available carbohydrates. However, at least a 50-gram dose of carbohydrate is recommended for GI testing because the variability of the measure increases as the portion of available carbohydrate becomes smaller.

Mode and Timing of Blood Sampling

Blood glucose concentrations can be measured using whole blood or serum/plasma obtained from a vein, artery, or capillary (Wolever 2003). For clinical purposes, (e.g., glucose tolerance tests) venous serum/plasma samples are used to measure blood glucose concentrations. Early GI research measured glucose in whole blood from capillary blood samples as it involved minimal processing and subjects could draw their own blood (i.e., using finger pricks) (Wolever 2003). It has been suggested, however, that capillary blood sampling may be less accurate than sampling from venous blood due to variable contamination of the blood samples with interstitial fluid resulting from subjects "milking" their finger (Wolever 2003). Nonetheless, a study conducted by Wolever and Bolognesi (1996) found that glycemic response measured in capillary blood resulted in larger absolute differences in AUC between foods and less random variation. Most, but not all, recent studies have utilized capillary blood to ascertain glucose values and calculate the AUC and, subsequently GI. Even so, given the potential differences in GI values with different blood sampling methodology, it is important to critically evaluate the methods of each study before drawing conclusions and/or making comparisons.

The timing of blood sampling can also significantly impact the GI value derived. As previously described, the sampling procedure involves measuring blood glucose concentrations every 15-30 minutes for two hours after carbohydrate consumption. The choice to mimic the glucose tolerance test makes little sense because this standard was established only as a diagnostic tool for identifying type 2 diabetes and impaired glucose tolerance, not to mark the total period of postprandial glucose evaluation (Pi-Sunyer 2002). In fact, the postprandial disposal of glucose can take much longer than two hours, especially in individuals with type 2 diabetes (Gannon & Nuttall 1987, Pi-Sunyer 2002). Gannon and Nuttall (1987) showed that differences in GIs between foods are attenuated as length of the postprandial measurement time increases.

Factors Affecting the Reproducibility and Applicability of GI

The GI was originally conceived as an inherent property of a food as opposed to a metabolic response of an *individual* to a food. Based on this conception, the GI of a food should be consistent and reproducible among identical food products from person to person regardless of preparation methods and other foods with which it was ingested. The most recently published *International Table of Glycemic Index Values* (Foster-Powell 2002) clearly demonstrates that there can be a wide range of GIs for the same carbohydrate-rich food. According to the table, the variability in GI for glucose (chosen as the reference food because of its ease of measurement and supposed "superior" coefficient of variation relative to other carbohydrates) was 25 percent (GI range 85-111).

In fact, the GI of a carbohydrate-rich food can vary greatly depending on a number of factors including the variety, origin, processing, and preparation of the food, the other nutrients that are consumed with the food, and even the time of day in which the GI is measured (Pi-Sunyer 2002).

Moreover, research has shown that there is a large degree of variance (i.e., coefficient of variation) both between and within subjects.

For the GI to be useful as a dietary planning tool, it must have a predictable effect on blood glucose; it must not only be valid but reliable. For many foods, this is not the case (Foster-Powell et al. 2002). The following sections highlight the multitude of factors that can impact the GI of a given food and serve to demonstrate the impracticality of using the GI diet planning purposes.

Variability in the food

The GI of a carbohydrate-rich food can vary significantly depending on the way in which it is processed or prepared, the cooking method used, as well as the variety (i.e., white rice vs. wild rice), origin (i.e., where it was grown), maturation and/or degree of ripeness (Pi-Sunyer 2002).

Processing/Preparation: Grinding, rolling, pressing, mashing and even thoroughly chewing a starch-rich carbohydrate will disrupt the amylase and/or amylopectin molecules, making them more available for hydrolysis thereby increasing the GI (Collier & O'Dea 1982, Pi-Sunyer 2002, Wolever et al. 2001). For example, Wolever and colleagues (2001) showed that the GI of a one-inch cube of potatoes could increase by almost 25 percent simply by mashing the cube. Chemically modifying a carbohydrate-rich food can also affect its GI. Decreasing the pH of a starch (e.g., by adding acid) can lower the GI; thus, adding vinegar to potatoes (such as when making potato salad) will lower the GI of the potatoes. Similarly, acetylation or the addition of beta-cyclodestrin has been shown to decrease the GI of potato starch (Raben et al. 1997).

Cooking has also been shown to exert a differential effect on GI of a carbohydrate-rich food, particularly one that is high in starch. For example, the starch contained in an uncooked potato is resistant to hydrolysis by digestive enzymes and, thus, an uncooked potato has a relatively low GI. However, when a potato is cooked, the starch molecules gelatinize and become readily digestible, thereby increasing the GI (Pi-Sunyer 2002). If the potato is then cooled after cooking, the gelatinization reverses forming what known as "resistant starch" (i.e., resistant to digestive enzymes) and, hence, a significantly lower GI (Fernandes, 2005).

A recent study by Fernandes et al. (2005) illustrates the differential effect of cooking on GI. These researchers compared the GIs of potatoes prepared in a variety of different ways (including mashed, baked, reheated, boiled, boiled and cooled, and fried). The results indicated that the GI values of potatoes varied significantly depending on both the variety and cooking method used ($p=0.003$) ranging from intermediate (boiled red-potatoes consumed cold: 56) to moderately-high (roasted California white-potatoes: 72; baked U.S. Russet potatoes: 77) to high (instant mashed potatoes: 88; boiled red potatoes: 89). In addition, precooked Russet potatoes (i.e., potatoes baked, cooled and then reheated) elicited a lower AUC than day cooked ($p<0.05$) while pre-cooking had no effect on boiled white potatoes.

The type of cooking method used (i.e., baked, boiled, microwaved) may also affect the GI, although the significance of the effect remains controversial. In one study, baked potatoes had a lower GI than their boiled counterparts, although other studies have failed to find an effect of cooking method (Wolever et al. 1994; Soh and Brand-Miller 1999; Fernandes et al. 2005).

Variety/origin/maturation: Different varieties of a similar food can have very different GIs. For example, different varieties of rice have been shown to produce very different GIs largely due to differences in the amylose to amylopectin ratios (Pi-Sunyer 2002). Similarly, the GIs of potatoes can differ greatly depending upon both the variety and place of origin. According to the most recently published international table of GI values (Foster-Powell 2002) the GIs for potato varieties ranges from a low of 24 for a non-specified type boiled potato from Kenya to a high of 111 for a U.S. Russet. Ironically, even for presumably the same variety, the GI value can vary widely. According to Foster-Powell (2002), the GI values for U.S. Russet range from 78 to 111. While it could be hypothesized that origin and/or maturation may be responsible for some of this variation, because information regarding these variables is frequently not provided, it is difficult to determine whether this is the only source of the variation. Nonetheless, one study found no difference between the GI values of three different potato varieties (Soh and Brand-Miller 1999). It should be noted, however, that this particular study reported a GI value for Pontiac potatoes that was 32 units greater than a previously published value, thus raising the issue of the reliability of GI measures and the validity of comparing GI values obtained from a number of different laboratories.

The unreliability of the GI is highlighted by a recent study comparing the GI of four centrally distributed foods (instant potatoes, rice, spaghetti and barley) measured in seven separate laboratories (Wolever et al. 2003). The difference between the highest and lowest measures of the GI of instant potatoes was 33 units. Given that these were supposedly identical potato products, it certainly calls into question the reliability of the measure.

The maturation stage or ripeness of a food may also be an important determinant of GI. As a fruit ripens, the GI tends to decrease as the starch gradually turns to sugars. Thus, a green or unripe banana would have a higher GI than a ripe banana (Englyst & Cummings 1986). Similarly, research suggests that new potatoes have a relatively low GI (Soh and Brand-Miller 1999).

<u>Variability in the measurement</u>

As previously indicated, the GI has generally been regarded as an inherent property of a food and not as a metabolic response of an individual to a food. As such, any given food should have a consistent and reproducible response from day to day and from person to person regardless of other foods with which it is ingested. In fact, as will be demonstrated in the following paragraphs, **research indicates that the GI for a given food can vary significantly between individuals and for the same individual depending on such factors as the time of day the food was consumed as well as what else was consumed along with it.**

Between Subject Variability: Research clearly shows that individuals can vary significantly in their glycemic responses to the same food (Wolever 2003). Nonetheless, in laboratory studies, this source of variation is reduced to the point where it is no longer statistically significant by expressing an individual's glycemic response to the food of interest relative to that of a reference food (i.e., white bread or glucose). For example, Wolever and colleagues (1990) examined glycemic responses (AUC) and GI (i.e., the AUC of the test food expressed relative to white bread) to three different foods (white bread, rice, and spaghetti) in 12 subjects with diabetes. The average coefficient of variation (a representation of the variability in responses between subjects) for the AUC (for the same food) was 45 percent, whereas that for GI was only 10 percent. While mathematically correcting for differences in glycemic responses makes for a nice, consistent GI, it is artificial and masks a very important and practical consideration — individuals differ significantly in their blood glucose responses to the same food. Thus, knowing the GI of a food cannot really tell an individual anything about how his or her blood glucose might respond to that particular food.

Within Subject Variation: Not only do blood glucose responses to similar foods differ between individuals, they can vary significantly in the same person on different occasions. In fact, the within subject variation can sometimes be greater than the between subject variation! Wolever et al. (1985) showed that for repeated tests of 50 grams of carbohydrate from glucose or bread, the coefficient of variation of AUC was approximately 15 percent in subjects with type 2 diabetes, 23-25 percent in non-diabetic subjects, and 30 percent in subjects with type 1 diabetes. It bears noting that these tests were done in a laboratory, under controlled conditions (i.e., using 50 grams of a single food at the same time of day, etc.). The variation would likely be much greater under less controlled or more "real life" conditions.

Time of Day: The time of day during which glycemic response is measured may impact not only the absolute glycemic response (i.e., the AUC) but, also, the relative glycemic response (i.e., the GI) (Gannon et a. 1998, Jenkins et al. 1987, Wolever 1996). For example, Wolever and Bolognesi (1996) compared the glycemic responses to two different breakfast cereals under two conditions: (1) after a 12-hour fast and (2) at midday four hours after consuming a standard breakfast. The AUCs at midday were significantly less than those after the 12-hour fast, despite the fact that the subjects consumed the exact same foods. More specifically, the mean AUC to the high-fiber cereal was 50 percent lower than that of the low fiber after the 12-hour fast, while this difference shrunk to just

10 percent at midday. Similarly, a study by Brand-Miller (1994) showed no differences between glucose responses to the second meal of the day regardless of whether it was technically a high GI or low-GI meal. Based on this data then, GI is only valid for the morning meal, after an overnight fast. Moreover, if GI values for foods had been determined at midday (or later) the differences would have been considerably attenuated and, based on the Brand (Pi-Sunyer 2002).

Addition of Other Macronutrients

Perhaps one of the biggest criticisms leveled against the GI is that it is differentially impacted by the addition of macronutrients (other than carbohydrate) and, thus, it is not valid with meals made up of "mixed" macronutrients (i.e., meals and snacks containing carbohydrate along with protein and/or fat). Although proponents of the GI deny this (Wolever and Jenkins 1986), several studies have shown that GI cannot be reliably predicted from mixed meals (Coulston et al. 1984, Hollenbeck and Coulston 1991, Flint et al. 2004). For example, a series of studies documented in a review by Hollenbeck and Coulston (1991) it was shown that predicted GI values for mixed meals (i.e., predicted from table values) were not significantly correlated with measured values. Similarly, a recent study by Flint and colleagues (2004) examined the predictability of measured GI in composite breakfast meals when calculated from table values. Thirteen breakfast meals and a reference meal were tested. All meals contained 50 grams available CHO but differed in energy and macronutrient composition. The results indicated that the GI of mixed meals calculated by table values did not predict the measured GI (particularly when there is sufficient fat and protein in the meal). In fact, the author's prediction models showed that the GI of mixed meals was more strongly correlated with fat, protein, and/or energy content than with carbohydrate alone.

These studies have been criticized for invalid methodology and/or inappropriate interpretation of the data (Wolever 1997). For example, studies by Coulston and her colleagues have been deemed "invalid" for using total AUC vs. incremental AUC (Wolever and Jenkins 1986). Nevertheless, there is currently debate regarding which is a more valid representation of actual blood glucose changes. Similarly, the Flint et al. study (2004) has been criticized for using meals containing different energy levels. To be sure, carefully controlling the amounts of different macronutrients in a meal to ensure a equal number of grams and/or calories of each will likely reduce the variance and allow for a more predictive GI; however, one must question the practicality of this. Is it realistic to expect the average individual to go to such lengths? The fact is that people rarely eat single foods consisting of a single macronutrient; rather they eat meals and snacks containing a mixture of macronutrients. Moreover few will take the time or make the effort to precisely weigh and measure out the amounts of carbohydrates, proteins, and fats at each meal needed to ensure that the predicted GI correlates closely with the actual GI of the mixed meal.

Aside from the impact that the addition of protein and/or fat have on the GI of a given carbohydrate-rich food, one must also consider the effect on insulin responses as well as energy density. It bears reiterating that the GI was originally conceived as a dietary tool in the management of diabetes. The belief was that knowing the GI of a food would not only help predict the glycemic response, but, more importantly, the insulinemic response. However, GI and insulin response are not closely correlated, particularly when macronutrients other than carbohydrate are involved in the equation (Pi-Sunyer 2002). For example, the addition of protein to a carbohydrate-rich food and/or meal is known to increase the insulin response while reducing the glycemic response (Nuttall et al. 1984, Pi-Sunyer 2002). Similarly, adding fat to a carbohydrate-rich food/meal also enhances insulin secretion while reducing the glycemic response. Moreover, the addition of protein, and especially fat, increases the caloric value of the food. For example, a baked potato with salsa will produce a moderately high glycemic index while that same baked potato smothered with butter and sour cream will have a significantly lower glycemic index; however it will have more than double the calories. In our obesity-plagued society it is probably not prudent to increase the calorie value of a food or meal in the name of reducing its glycemic index.

It is commonly believed that fiber lowers the GI of a carbohydrate-rich food. In fact, the impact of fiber on the GI of foods remains controversial.

In their initial report on GI, Jenkins et al (1981) concluded that insoluble fiber has little if any impact on glycemic response, while soluble fiber tends to lower GI. In contrast, 10 years later, Wolever (1990) (a co-author on Jenkins's original paper) demonstrated just the opposite. This particular study examined the relationship between the dietary fiber content and composition and GI of 25 different foods. The results indicated that total dietary fiber was only weakly related to GI (r-.461, $p<0.05$). An examination of the type of fiber indicated that insoluble but not soluble fiber was significantly correlated with GI ($r=.584$; $p<0.05$). This relationship was attributed to the uronic acids found in insoluble fiber. Nonetheless, even the uronic acid could only explain 50 percent of the variance.

A review of the *International table of glycemic index values* (Foster-Powell 2002) indicates that, for many foods, the presence of naturally occurring fiber has very little impact on GI. Comparisons between brown and white rice, regular and whole-wheat spaghetti, and regular and whole wheat breads show very small differences in GI despite the differences in fiber (Table 2). Nonetheless, the health benefits of fiber are well-documented and, thus, fiber-rich foods should be chosen regardless of their GI.

Table 2 GIs of select "regular" and fiber-rich versions of food

Food	Fiber (g)*	GI**
Bread		
white	1.0	70
whole wheat	8.0	71
Spaghetti		
regular	3.0	42
whole wheat	8.5	37
Rice		
white	1.0	64
brown	4.0	55

** based on a 50 g carbohydrate portion*
*** from Foster-Powell et al. (2002)*

Additional Limitations of the GI

As previously described, the GI represents the glycemic response to 50 grams of a test food relative to equal amounts of glucose or white bread. This 50-gram value is used to "standardize" the amount of carbohydrate, as the glycemic response to a carbohydrate-rich food generally increases linearly with increasing amounts of carbohydrate up to about 50 grams, at which time it begins to level off somewhat (Pi-Sunyer 2002, Wolever 2003). Unfortunately, this standardization presents its own source of bias by overestimating the GI of foods that are generally not eaten in such large quantities. For example, watermelon is classified as having a high GI; however, to obtain 50 grams of carbohydrate (and achieve the GI listed in common tables) one would have to consume almost 5 cups of watermelon! In an attempt to correct for this bias, the Glycemic Load (GL) was developed as a way to categorize the glycemic responses of "*normal*" servings of CHO rich foods (Foster-Powell 2002). The GL is mathematically determined by taking the product of the GI of a CHO-rich food multiplied by the amount (grams) of carbohydrate in a serving of that food divided by 100. Thus, the GL of watermelon would be:

$$[72 \times 5.5] \div 100 = 4$$

The introduction of serving size into the equation significantly alters the ranking of several carbohydrate-rich foods (Table 3).

Indeed, using the method, some foods that rank high on the GI are actually low on the GL and vice versa. Of course some foods, such as bagels and bananas, do not change much.

Table 3: A comparison of the GI and GLs of various foods

Food	GI	GL
Bagel	72	25
Cornflakes	81	21
Shredded wheat	75	15
Popcorn	79	4
Watermelon	72	4
Sucrose	68	7
Bananas	59	12
Kidney beans	28	8
Spaghetti	42	23
Fettuccini	40	18

From: Foster-Powell (2002)
*** GI: low=1-55 mid=56-69 High=70-100*
GL: low=1-10 mid=11-19 High=20 or more

Although considered by some nutrition professionals to be a more accurate measure than GI (because it takes into account the actual *amount* of CHO consumed), many question its validity (Wolver 2004). In fact, two recently conducted studies found that GL was not an accurate predictor of glycemic response (Brand-Miller et al. 2003 Liu et al. 2003). In the first, Brand-Miller et al (2003) fed 10 different test meals with the same estimated GL to a group of subjects and found that there were statistically significant differences in glycemic responses to as many as two of the meals. If the concept of GL were valid all of the meals should have produced the same glycemic response. Similarly, Liu et al. (2003) tested whether the *glycemic glucose equivalent* (GGE) (a value equivalent to GL) was a valid predictor of glycemic response. Although the authors stated that GGE was a valid predictor of GI, the data do not support this conclusion. For example, five foods were fed to both normal and diabetic subjects at two levels of GL, and in 3 of 4 cases there were significant differences in glycemic responses at the same GL level. Again, if the concept of GL were valid, the glycemic responses should have all been the same. It bears emphasizing that the GL is not a measured value but a mathematical derivation based on an already questionable and controversial measure.

A final limitation of the GI is that it does not consistently reflect the nutrient density of a given food. Nutrient density is defined as the nutrient content of a food relative to its calorie value (i.e., nutrient density = nutrients per calorie). Thus, foods that are high in nutrient density, such as fruits and vegetables, provide substantial amounts of vitamins and minerals for relatively few calories. Many foods that are "high" on the GI and thus considered "off limits" are very high in nutrient density such as potatoes, whole wheat breads and other grains, watermelon, dates, and carrots. On the other hand, many high calorie, non-nutrient dense foods are low on the GI such as chocolate, croissants, ice cream, cookies, and most candy bars.

GI, Obesity and Weight Loss

Despite the limitations noted above, the GI has enjoyed increasing popularity as a dietary planning tool for weight loss and obesity prevention. There are two theories about how high GI foods contribute to the development of obesity. The first and most popular holds that high GI foods are lower in satiety and, thus, individuals eat more of them leading to positive energy balance and subsequent weight gain. The second maintains that high GI foods result in hyperinsulinemia which may promote fatty acid synthesis and inhibit fat oxidation. There are no published studies examining the effects of GI on fat metabolism, thus, there is currently no support for this hypothesis. On the other hand, several studies have examined the relationship between postprandial glucose concentration and satiety. In studies unrelated to GI, results have generally indicated that higher postprandial blood glucose is associated with *greater* satiety (Holt et al. 1992, Chapman et al. 1998, Lavin et al. 1998).

Studies which have directly measured the relationship between GI and satiety have provided mixed results, with some indicating that low GI foods are associated with increased satiety (Holt et al. 1992; van Amelsvoort and Weststrate 1992), delayed onset of hunger (Benini et al. 1995) or decreased ad libitum energy intake (Guss et al. 1994, Rigaud et al. 1998; Ludwig et al. 1999). Yet others showed just the opposite (Chapman et al. Am J Physiol 1998, Lavin et al. AJCN 1998, Holt et al. 1995). It should be noted that of those studies that found that a higher GI meal was associated with an increased food intake, two compared only glucose to fructose, which is an unfair comparison as there are other metabolic differences between these two sugars unrelated to their GI (Pi-Sunyer 2002).

A frequently cited study by Holt and colleagues (1995) examined the satiating effects of 38 commonly eaten foods grouped into 6 different categories (fruits, bakery products, cereals, snack foods, protein-rich foods and carbohydrate-rich foods). Subjects consumed 240 kcal (1000 kj) portions of each food item and their feelings of hunger/satiety were assessed every 15 minutes for a total of 120 minutes using an equilateral 7-point rating scale that ranged from “extremely hungry” to “extremely full.” The subjects were then allowed to eat ad libitum from a standard range of foods and drinks. A Satiety Index (SI) score was calculated for each food by dividing the area under the satiety response curve (AUC) for the given food by the group mean satiety AUC for white bread and multiplying by 100. The results indicated that there were significant differences in satiety scores both within and between food groups.

Boiled potatoes were the most satiating food with a satiety index seven times that of croissants (the lowest scored food), three times that of the control food (i.e., white bread), and significantly higher than any of the other carbohydrate-rich foods.

In addition, the authors found no significant relationships between satiety, plasma glucose or insulin responses among the 38 test foods. However, a negative correlation was found between insulin responses and ad libitum food intake at 120 minutes, which suggests that test foods producing a *higher insulin response* were associated with less food intake and thus, indirectly, greater satiety.

Of course, from an obesity perspective, it is important to determine if differences in short-term satiety as a result of different GIs actually have an impact on body weight regulation. Unfortunately, few well-controlled studies have examined the impact of GI on body weight. Table 4 provides a summary of the research to date. Each of the four categories of research are described briefly below.

<u>Isoenergetic diets</u>: Thirteen isoenergetic diets were identified with study periods ranging from approximately one week to six months. Interestingly, although body weight maintenance was the goal of the studies (hence the isoenergetic diets), body weight losses were often observed both on high and low-GI diets. Of these studies, two reported a greater weight loss on low GI diets, one reported a greater weight loss on the high GI diet and 11 reported no significant differences. It should be noted that of the two studies reporting a greater weight loss on the low GI diet, one compared a low-GI to a low-fat diet which may or may not have been high-GI (the authors did not specify). Moreover, of the 13 studies, only seven utilized *equal macronutrient composition distributions* and all of those found no significant difference in weight loss between the diets.

<u>Energy restricted diets</u>: To date only seven published studies have examined differences between low-GI and “other” energy restricted diets. The study periods ranged from six weeks to six months. Of these, two studies showed a significantly greater weight loss on the low-GI diets and five showed no significant differences between the diets. It should be noted that one of the studies that indicated a significantly greater weight loss on the low-GI diet utilized a low-fat diet as the comparison (not a high-GI diet) (Spieth et al. 2000). Moreover, this particular study did not randomize subjects to diets (and there were significant socioeconomic and ethnic differences between the groups), used children

as subjects, and did not monitor dietary adherence/compliance.

Ad libitum diets: To date, only three ad libitum feeding/diet studies have been published, the longest spanning just 10 weeks. In only one was there a significant difference in body weight between the diet groups and it actually found that body weight and fat mass decreased significantly more on the high GI diet compared to a low GI diet.

Epidemiological studies: Four epidemiological studies have examined the association between a high- or low-GI diet and body weight and/or body mass index (BMI) (Jacobs et al. 1998, Liu et al. 2000, Van Dam et al. 2000). Jacobs et al. (1998) found that BMI and waist-to-hip ratio (WHR) in postmenopausal women decreased slightly as the intake of whole grains (low GI) increased; however, a number of other dietary and other factors varied with whole grain intake (that were not adequately controlled for) making interpretation of the results difficult. Liu et al. 2000 found no relationship between GI or GL and body weight or BMI. Van Dam et al. (2000) found that the lowest tertile of GI in the diet was associated with the highest BMI compared with the highest tertile.

It bears reiterating that epidemiological studies can only demonstrate an association between two variables. They cannot indicate the direction of the association nor can they delineate cause and effect. Moreover, it should be noted that the methodology used for determining GI (and subsequently GL) in these studies is highly suspect (Pi-Sunyer 2002). In most cases an *average dietary GI* was calculated using the following equation:

Average Dietary GI=
[(carbohydrate content of each food item) x (number of servings/d)
x (GI)/ total daily carbohydrate content]

An examination of how these values were derived highlights the limitations of this data. First, a food frequency questionnaire was used to estimate all three values used in the above calculation. Because FFQs are retrospective, they rely heavily on memory for accuracy. Subjects were not only required to remember how frequently they consumed a food but estimate their "average" serving/portion sizes as well in order to calculate carbohydrate content of each item as well as total daily carbohydrate content. In most cases the number of food items contained within the FFQs were limited, totaling only 116-131 items (Pi-Sunyer 2002). The GIs for the food items were derived from published tables vs. actual measurements, which, given the multitude of factors that can impact the GI not accounted for in these tables, severely limits the accuracy of this value. Finally, the FFQs were generally completed only once, at entry into the study and were used to assess intake over the previous year with the assumption that the individual's diet did not change significantly during the entire course of the follow-up period (generally 10 years or more) (Pi-Sunyer 2002). If GL was used (as opposed to GI), the data becomes even more precarious as GL requires additional mathematical computations. Given these methodological complications, it is no wonder that the results of these studies are inconsistent. Clearly, well-controlled, clinical trials are needed before a definitive role of GI in obesity and weight loss can be determined.

Table 4 Efficacy of Low-GI diets compared to high-GI diets or Low-fat diet on weight loss.

Reference	Duration	Diets	Weight Loss Differences
Isoenergetic			
Jenkins et al. 1985	4 weeks	L-GI vs. Low-fat diet	Low GI > High GI
Jenkins et al. 1987	2 weeks	L-GI vs. H-GI	NS
Jenkins et al. 1987	4 weeks	L-GI vs. H-GI	Low FI > High GI
Santacroce et al. 1990	2 weeks	L-GI vs. H-GI	High GI > Low GI
Brand-Miller et al. 1991	12 weeks	L-GI vs. H-GI	NS
Fontvielle et al. 1992	5 weeks	L-GI vs. H-GI foods	NS
Frost et al. 1994	12 weeks	L-GI vs. H-GI foods	NS
Frost et al. 1998	3 weeks	L-GI vs. H-GI foods	NS
Luscombe et al. 1999	4 weeks	L-GI vs. H-GI foods	NS
Jarvi et al. 1999	24 days	L-GI vs. H-GI diets	NS
Tshillas et al. 2000	6 months	L-GI vs. H-GI breakfasts	NS
Giacco et al. 2000	24 weeks	L-GI vs. H-GI foods	NS
Alfenas & Mattes 2004	8 days	L-GI vs. H-GI diets	NS
Energy Restricted			
Wolever et al. 1992	6 weeks	L-GI vs. H-GI foods	NS
Slabber et al. 1994	12 weeks	L-GI vs. H-GI diets	NS
Spieth et al. 2000	4 months	L-GI vs. Low-fat diets	L-GI > Low-fat
Agus et al. 2000	6 days	L-GI vs. H-GI diets	NS
Ebbling et al. 2003	6 months	L-GI vs. Low-fat diets	NS
Frost et al. 2004	12 week	L-GI vs. Low-fat diets	NS
Ad libitum			
Raben et al. 1997	2 weeks	L-GI (sucrose) H-GI (starch)	H-GI > L-GI
Boche et al. 2000	5 weeks	L-GI vs. H-GI diets	NS
Sloth et al. 2004	10 weeks	L-GI vs. H-GI diets	NS

L-GI = Low GI; H-GI = High GI; NS = No significant difference between diets

Table 5: Epidemiological studies examining GI/GL and Obesity

Author	Sample	Diet	Weight or BMI Difference
Jacobs et al. (1998)	34,492 women	Low GI (whole grains) High GI (refined grains)	Low GI < High GI
Liu et al. (2000)	75,512 women	Low GI (low GL "score") High GI (high GL "score")	NS
Van Dam et al. (2000)	646 men	Low GI (lowest tertile) High GI (highest tertile)	High GI < Low GI

Summary/Conclusions

Like the low-carbohydrate craze that preceded it, the GI has enjoyed increasing popularity despite the lack of research to support its efficacy as a dietary tool for weight loss, disease prevention, and/or health promotion. However, unlike the low-carbohydrate diets whose popularity could be attributed in a large part to their simplicity (i.e., just eliminate carbohydrates from the diet), there is nothing simple about the GI. It is a complex measure that is made even more complex by the multitude of factors that can impact it (e.g., processing, preparation, maturation, the addition of other macronutrients, time of day, etc.). Until large-scale studies are done using the GI in a variety of circumstances and disease conditions, Americans should strive to follow the recommendations set forth in the *US Dietary Guidelines*, and new Food Guidance System (MyPyramid), which encourages balancing energy intake with energy expenditure and consuming a diet that contains plenty of fruits, vegetables, and whole grains, small amounts of healthy fats and moderate amounts of low-fat or nonfat dairy and other protein-rich foods.

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Figure 1: Carbohydrate Metabolism - Glucose as the Final End Product

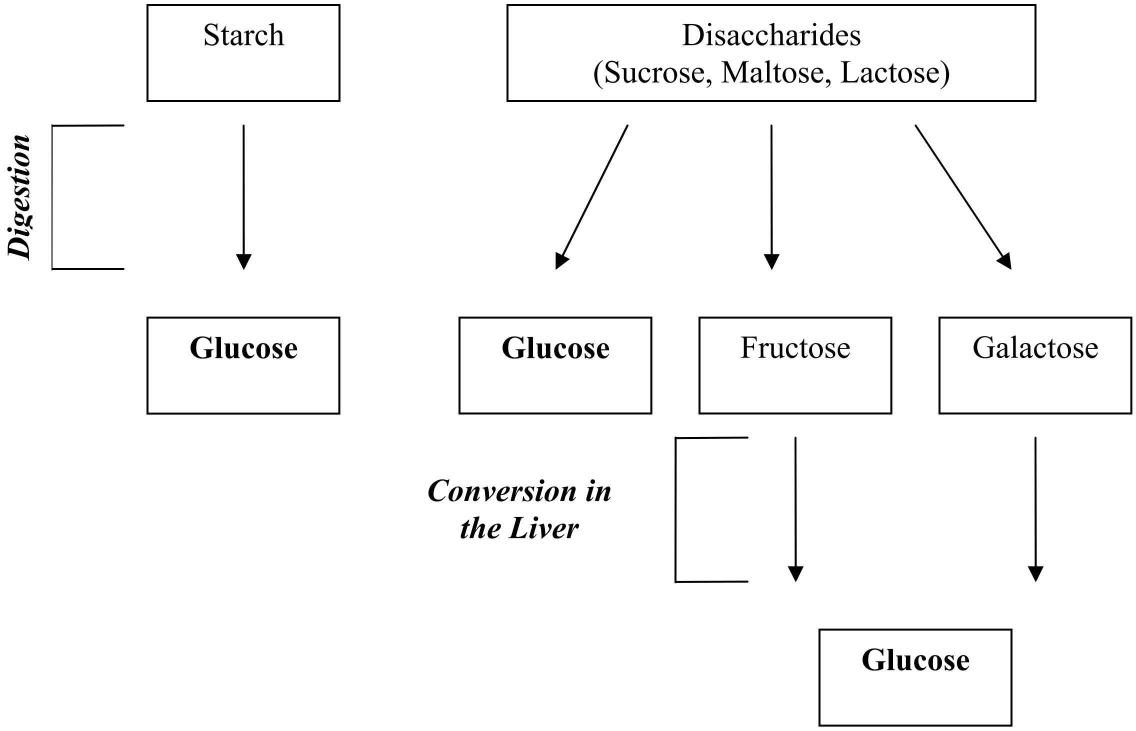
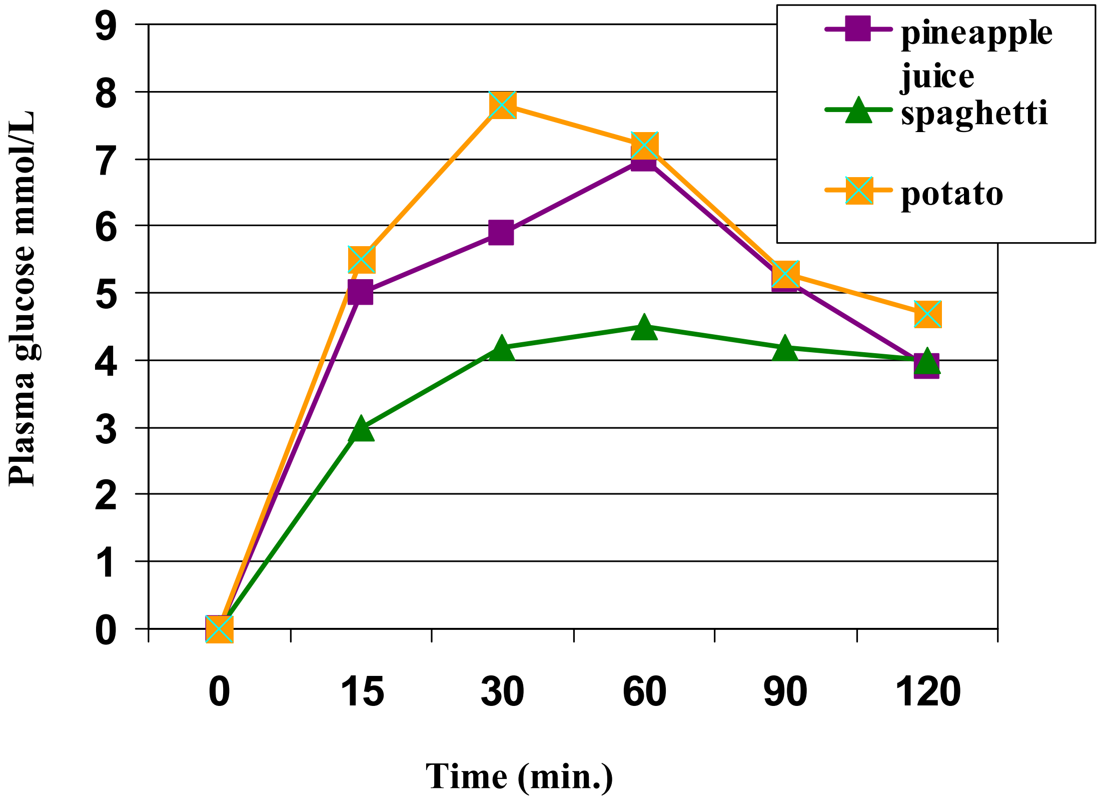


Figure 2 Glucose Response Curves for Pineapple Juice, Spaghetti, and Potatoes



* Adapted from Wolever 2003 and Fernandes et al. 2005