Carbohydrates and Increases in Obesity: Does the Type of Carbohydrate Make a Difference?

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Abstract

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With the prevalence of obesity increasing in the U.S. and elsewhere, the place of carbohydrates in the diet has recently been under closer examination. This has led to the development of methods for analyzing the effects of dietary carbohydrate. Primary among these methods is the glycemic index, a measure of a food's effect on blood glucose levels, which was initially designed as a method for determining suitable carbohydrates for people with diabetes. However, the glycemic index does not address other metabolic issues related to excess sugar consumption. Prominent among these issues is the use of low glycemic index sweeteners, particularly fructose, which is increasingly present in processed food. Fructose is associated with increased adiposity, which may result from its effects on hormones associated with satiety. Other methods of determining "good" carbohydrates have also been developed. The common theme among them is increased nonstarchy vegetables and higher-fiber legumes.

Key words: glycemic index, fructose, carbohydrate, appetite

Introduction

Over the past 30 years, the incidence of obesity has risen, first in developed countries and, more recently, in developing countries. At the same time, the food industry has increasingly replaced sucrose with fructose in an ever-increasing number of processed foods, because of the de-velopment of inexpensive corn-derived high-fructose sweeteners (1). Meanwhile, Crapo et al. (2) discovered that foods with similar amounts of carbohydrate had differential effects on blood glucose, and Jenkins et al. (3) created the glycemic index (GI)[1] to assist people with diabetes in choosing carbohydrate-containing foods that did not rapidly raise blood sugar. Because fructose does not cause a rapid rise in blood glucose or trigger an insulin response (1), fructose-containing foods have been considered "low glycemic." However, the picture has recently become much more complicated and interesting. Recent hormonal studies comparing the effects of glucose vs. fructose metabolism have shown that the two sugars elicit very different patterns that may explain how obesity and fructose intake may be linked. Furthermore, while simple in theory, the GI has sparked heated controversy and may be easier to explain than to apply.

The purpose of this article is to briefly review some of the research on fructose consumption and obesity and link it to both recent research on the GI and research on satiety and energy density.

Fructose and Obesity

Fructose consumption has increased dramatically in recent years. High-fructose corn syrup is used extensively in soft drinks, baked goods, condiments, prepared desserts, and other processed foods (1). While the per capita average consumption of refined cane and beet sugars has decreased from 1970–1974 to 2000 by 35%, the consumption of corn sweeteners has increased by 277%, with high-fructose corn syrup increasing by 4080% (4). High-fructose corn syrup (generally ~55% fructose, although it can be as high as 90%) (1) intake has increased from <0.5 grams daily per capita in 1970 to 53.9 grams daily per capita in 2003 (5). Soft drink consumption, for example, has increased 500% in the past 50 years, and soft drinks are now the leading source of added sugar in children's diets (6). A more recent epidemiological study has reinforced the importance of sweet-

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[1] Nonstandard abbreviations: GI, glycemic index.

ened beverages, most with high-fructose corn syrup, in the development of obesity in 9 to 17 year olds (7). In 2000, the intake of added sugars for the average American was 2.5 times that of the dietary guidelines, and almost one-half of the total came from high-fructose corn syrup (4).

This increase in fructose consumption has paralleled an increased prevalence of obesity in the U.S. Recently, Slyper (8) has reviewed various trends relating to pediatric obesity and found that the evidence for the "obvious" causes of obesity—increased caloric intake, decreased physical activity, and increased fat intake—was not conclusive. On the other hand, changes in carbohydrate consumption, particularly in the type of carbohydrate, have correlated with trends in pediatric obesity over the last three decades. Because obesity is associated with increased insulin levels, foods that had a lower glycemic response were encouraged. In this context, the lower glycemic response seen with prepared foods using fructose (compared with sucrose) (9) has been seen as beneficial.

GI

While it had been known for some time that different carbohydrates had differential effects on blood glucose levels (2), and thus, serum insulin levels, it was not until Jenkins et al. (3) developed the GI that a standardized method for measuring this was available. The GI for a food was defined relative to a standard food (glucose or white bread). Over a 2-hour period, the area under the glucose response curve after consuming 50 grams of carbohydrate from the test food was compared with the area under the glucose response curve after consuming 50 grams of carbohydrate from the reference food. Both levels were given as the difference from fasting blood glucose levels (3). The tests have been done in both healthy people and people with diabetes (10).

Since then, much research into the GI has been done, both in determining values for different foods (10) and in investigating its value for research and clinical applications. The Food and Agriculture Organization of the United Nations and the World Health Organization have issued an extensive report on various aspects of carbohydrate in the diet that endorsed using the GI as an appropriate guide for preventing obesity (11), and other organizations have followed suit, particularly in Europe (12), Canada, and Australia (10). Jenkins et al. (13) have proposed that all carbohydrates are not equivalent and that the rate of absorption of carbohydrate foods into the bloodstream is a critical factor in hyperinsulinemia. Slowly absorbed foods would be beneficial because they trigger less of a rise and fall in blood glucose and, thus, less of a rise and fall in insulin levels. Writing in support of statements from the European Association for the Study of Diabetes, Ha and Lean (12) have endorsed the use of the GI as one method of assuring that carbohydrate foods with slower absorption times be encour-

aged to assist in glycemic control. In the U.S., Bell and Sears (14) have similarly encouraged the use of the GI to create a diet that features low-GI carbohydrates as a way of reducing the rising levels of both obesity and type 2 diabetes in the U.S.

The glycemic load of a food was developed as a way of comparing the glucose-raising effect of foods with widely differing amounts of carbohydrate. The glycemic load is defined as the GI multiplied by the grams of carbohydrate in a specific portion of a carbohydrate-containing food. Carrots illustrate the leveling effect of using glycemic load. A carrot has a high glycemic index, but because it contains relatively little carbohydrate, it ends up with a modest glycemic load (15).

Because it slows absorption and lessens hyperinsulinemia, a low–glycemic-load diet would promote appropriate weight loss, improve cardiovascular health, and reduce diabetes (16). Along these lines, Ludwig (17) has developed an alternative food pyramid based on the GI. The base (low-GI foods) is vegetables and fruits; the second tier is reduced-fat dairy, lean protein, nuts, and legumes; the third tier is unrefined grains and pasta; and the top level, which should be the most restricted in diet planning, is refined grains, potatoes, and sweets.

A review in 2002 by Brand-Miller et al. (18) has looked at the effects of low-GI foods on fat storage and weight gain. In single-meal studies, voluntary energy intake was increased after a high-GI meal, and fat oxidation lessened. The converse was true of low-GI meals. In longer-term human studies using isoenergetic diets, similar effects have been seen, as well as an increase in weight with a high-GI diet. In a retrospective pediatric study, greater weight loss has been seen with a low-GI diet compared with a conventional low-fat diet, although these do not seem to have been isoenergetic diets. Weight gain was also lessened with an ad libitum low-GI diet in a small study ($n = 12$) of pregnant women. Long-term animal studies (32 weeks) using isoenergetic diets have shown distinctive and significant differences in total fat mass, particularly visceral fat. Fat oxidation rates were lower, and hepatic lipogenesis was raised significantly in rats fed a high-GI diet. A more recent review by Brand-Miller et al. (19) has reviewed 14 studies of glycemic control in people with diabetes using high- vs. low-GI diets. Although most of the studies were on small numbers of people, and the usual dietary compliance problems in free-living individuals can be assumed, a slight, but significant, benefit in glycemic control with low-GI diets was detected.

Criticisms of the GI

Numerous difficulties with using the GI as a basis for clinical advice have arisen. As is immediately apparent from examination of the GI table (10), values for the GI of foods can be rather broad. Published GI for boiled white rice, for

instance, varied from 45 to 112 (glucose = 100). Bananas ranged from 30 to 70, partially depending on their degree of ripeness. White durum-wheat semolina spaghetti varied from 46 to 65, depending on length of cooking time. The GI for different types of spaghetti (different brands, different types of wheat) varied even more widely. Prepared foods, which might be assumed to have manufacturing control of content, fared no better. Kellogg's All-Bran Cereal ranged from 30 in Australia to 51 in Canada, and Doritos corn chips varied from 72 in 1985 to 42 in 1998 (10). Pi-Sunyer (20) has pointed out that the variability of GI for some of the individual foods was larger than the mixed-meal GI deduced in two different analyses of the Nurses' Health Study. He has noted that simple preparation (mashing a potato) can change the GI by 25%. Other types of processing and cooking also can vary the GI value, as can adding fiber, sugar, or acids such as vinegar (20).

In addition, the insulin response to a given food is not linear. The insulin response to a 100-gram portion of a particular food is not double that of the GI standard of 50 grams (20). A study by Wolever et al. (21) has shown that, although GI was relatively constant across different populations (lean, obese, impaired glucose tolerance, diabetic), the insulin responses varied widely. Thus, GI may not be a good marker to predict the insulin response.

Raben (22) has reviewed 31 short-term studies of low- vs. high-GI meals. About one-half the studies have reported decreased hunger (or increased satiety) and decreased food intake with low-GI diets. Of the 28 studies where the energy, macronutrient, and fiber compositions of the diets were similar, it was an even split. Of three longer-term studies of low- vs. high-GI isoenergetic weight maintenance diets, two studies have shown a decrease in body weight and one an increase with a low-GI diet (22). Overall, the other studies he has reviewed also have shown no clear pattern of difference between low- and high-GI diets in terms of decreased food intake or weight loss (22).

On the other hand, Pawlak et al. (23) noted that several single-meal studies have shown that GI is directly related to postprandial hunger and food intake. They also pointed out that low-GI diets may have other benefits: several studies have shown that a low-GI diet might lower triglycerides and raise high-density lipoprotein cholesterol. In contradiction to the complaint that a low-GI diet is too complex for clinical use, they mentioned several studies of low-GI diets involving self-selection of food by patients who found the diets "simple and practical" (23). The addition of dietary fiber, which lowers GI and slows adsorption of carbohydrate, has also been shown to decrease hunger and promote a negative energy balance (23). It has been suggested that the classic studies showing the effectiveness of high-carbohydrate diets for glycemic control in people with diabetes were high in fiber, and therefore, "probably de facto low-GI diets" (19).

Fructose Metabolism and Effects on Weight Gain

One difficulty with the GI is that it measures only the glucose response. Much of the carbohydrate consumed today is in the form of high-fructose corn syrup and added sugar (sucrose, which is 50% fructose). The metabolism of fructose follows a completely different pathway from that of glucose, avoiding key rate-limiting steps in the liver (1).

Overall, the hormonal pattern seen with ingestion of fructose is the opposite of that seen with glucose. Insulin is not increased, leptin is reduced, and ghrelin is not suppressed with fructose ingestion (24). Leptin generally decreases with fasting, rises with food intake, and is thought to decrease appetite (25). Ghrelin has been reported to generally rise with fasting and may increase hunger and stimulate appetite (24,26). The rise in ghrelin is suppressed with the administration of glucose (24) or unspecified carbohydrate-rich meals (27) and remains low after a meal (28). The short-term satiating effect of carbohydrates is well known, and ghrelin reductions may play a role in this effect (28). Fructose intake, however, suppresses ghrelin to a much lesser degree (1,24). Additionally, ghrelin has been shown to rise with vegetable (tomato, carrot, cucumber) meals and rise substantially after an initial drop with fruit (apple, kiwi, banana) meals (27), and this rise might correlate to an increase in hunger. As leptin, ghrelin, and insulin are all thought to play key roles in the regulation of food intake, these processes have implications when the ingested food is fructose rather than glucose.

The increase in fructose consumption and the pattern of hormonal response to fructose intake has led Bray et al. (29) to suggest that fructose, especially as high-fructose corn syrup in beverages, is an important factor in the epidemic of obesity in the U.S. Compared with eucaloric glucose ingestion, fructose ingestion favors de novo lipogenesis (24), which could increase adiposity. Fructose intake could increase overall food intake because of decreased satiety, resulting from its effects on ghrelin, leptin, and insulin and the fact that fructose cannot enter brain cells, unlike glucose (29). Ludwig et al. (6) have shown that "the odds ratio of becoming obese among children increased 1.6 times for each additional can or glass or sugar-sweetened drink that they consumed every day" and noted that children who drank soft drinks had a total energy intake substantially higher than those who did not. While Ludwig et al. have proposed that the increase in obesity has some connection to the liquid nature of the food, which has some support in the literature (29), it seems equally plausible that the differential metabolism of fructose is the culprit.

Fructose is also associated with other negative metabolic states. Animal studies have shown a relationship between fructose intake and insulin resistance, possibly through decreases in adiponectin (1). Adiponectin, a protein released by adipocytes, is suppressed in obesity and has positively

correlated to insulin sensitivity (25). Declines in adiponectin has coincided with the development of type 2 diabetes in obese rhesus monkeys, an animal model that parallels the progression of insulin resistance seen in humans (25). The results in humans have been less consistent, however (30).

De novo lipogenesis in the liver is markedly increased (3- to 15-fold) with fructose, whereas there is little lipogenesis from glucose (1). Teff et al. (24) have shown that ingestion of high-fructose beverages with meals resulted in elevated triglyceride levels and speculated that this is likely due to the effects of fructose on leptin levels, because leptin increases fat use, and the differential pathway through which fructose is processed in the liver. Fructose feeding induces hyperlipidemia, particularly in hyperinsulinemic persons (1). The elevated levels of triacylglycerol seen with sucrose intake has also been suggested to be caused by the fructose content of sucrose, and this has been supported in human studies (1). Although it has not been shown in humans (30), high-fructose diets are well known to cause hypertension in dogs and rodents (31). Additionally, when fructose has been added to a high-fiber, high-carbohydrate, low-fat diet used by people with type 2 diabetes, glucose levels improved, but they gained weight (12).

Although older studies found that, similarly to fructose, sugar alcohols (i.e., sorbitol, xylitol, maltitol, mannitol) induced low glycemic responses (32), more recent studies have found that some sugar alcohols, notably maltitol, induce no less of a glucose surge than glucose itself when used in certain products, such as chocolate (34). Maltitol is used frequently in "sugar-free" chocolate and other candies (33,34), so this effect is clinically meaningful. Other sugar alcohols, such as sorbitol, lacitol, and xylitol appear to raise blood glucose and insulin levels substantially less than glucose and for this reason are being used with increasing frequency as sweeteners in the creation of "sugar-free" products. They are incompletely absorbed in the digestive tract, and as a result, have a lower calorie content than sugar (range, 1.5 to 3 kcal/g) (35). Diet products, especially those aimed at low-carbohydrate dieters, seek to position themselves as lower calorie and lower carbohydrate, and thus, better for weight loss. Because sugar alcohols and fiber are not completely metabolized, there is a trend toward subtracting them from the carbohydrate count reported on the nutrient facts panel. This results in the "net" carbohydrate count, which is substantially lower than the actual carbohydrate content. This is primarily a food marketing scheme to promote products as "dietetic" or "healthy" and "low carb." Additionally, the perception that these products are healthy may lead people to eat more, and excess calorie intake is the prime cause of obesity (33).

Alternatives to GI

Extending the time for absorption of a given food reduces the precipitous rise and fall of insulin levels, improves glycemic control in people with diabetes, and increases satiation. This latter effect in particular has recently been shown in preschool children (36). In theory, these are precisely the properties of low-GI foods, and a diet based on low GI should have these effects (10,13,14). Jenkins et al., the originators of the glycemic index, have noted, however, that there are other factors that affect absorption rates, such as type of starch, degree of hydration, particle size of the food, and amount of fiber, among other factors (11,13). Two of these factors have been particularly important in another method of ranking foods: by energy density, which has also been shown to be associated with satiety (37).

Because water and fiber add weight to foods without increasing the caloric content, low-energy-dense foods tend to have more water or fiber content. Studies by Rolls and Bell (38) have shown that people often select food quantity by weight, so that when low-energy-dense foods are selected, calorie content is often decreased. More recent work by Rolls et al. (37) has shown that modifying meals to increase the amounts of fruits and vegetables, which are generally not particularly energy dense, increases satiety and leads people to select meals with a lower total calorie content. They further have shown that awareness of the satiating effects of low-energy-dense foods did not change the effect. Additionally, when only a portion of the total diet was replaced with lower-energy-dense foods, the calorie loss was still substantial. However, they have also found that instructing subjects to increase the fruits and vegetables in their diet was not sufficient for weight loss to occur, unless the added fruits and vegetables also displaced high-energy-dense foods (37). Low energy density and low GI tend to cluster, because both categories favor increased fiber, lowered added sugars, and increased whole grains.

How can these concepts be translated into solid clinical advice? The advice of Jenkins et al. that diets should be absorbed slowly (13) seems to be a good plan, because slower absorption has lead to increased satiety (13,36). Unfortunately, the GI provides only the scantiest guide to what these foods are, because the measured values are widely variant. There also seems to be substantial crossover between slowly absorbed low-GI foods and low-energy-dense foods. The Food and Agriculture Organization of the United Nations has recommended, in general terms, that cereals, vegetables, legumes, and fruits be encouraged because of their low GI (11). It might be noted, however, that those items also tend to be both lower in fat and lower in energy density (38). Both energy-density concerns and GI ranking would encourage more fruits and vegetables, especially those with substantial fiber, to be included in the diet.

Because French-fried potatoes, an energy-dense food, have constituted a substantial portion of the vegetables consumed in the U.S. (39), significant public health efforts to increase the consumption of other vegetables is required. Based on food disappearance data, adjusted for waste and
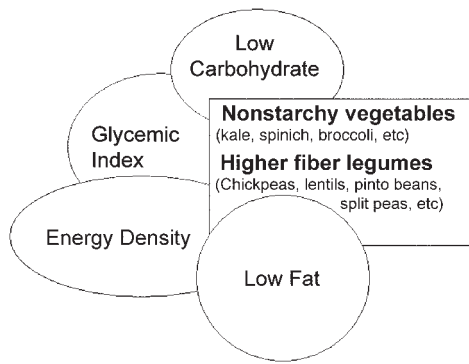
Figure 1: A graphic depiction of the overlap of several different schemes for better carbohydrate selection. The overlap shows that all of the different diet schemes promote the consumption of nonstarchy vegetables and higher-fiber legumes.

spoilage, it has been estimated that Americans ate substantially more added sugar (258.3%) and substantially less fruit (46.7%) and vegetables (95%) than the food pyramid recommendations (4). Closer analysis has shown that Americans ate an average of 1.36 servings of fruit daily (compared with the food pyramid recommendations of 3 servings) in 2000. While this represents a 17% increase over 1970 to 1974, there is still a long way to go. Vegetables, at an average intake of 3.83 servings (compared with the recommendation of 4), have seemed to do better, but a sizable portion of that is potatoes (1.23 servings, or 32% of daily vegetable intake), iceberg lettuce (0.57 servings), and canned tomatoes (0.25 servings) (4). Clearly there is much work to be done.

Camelon et al. (40) have described a methodology for clinicians to communicate proper food choices to clients that provides a clear visual picture of which foods are to be emphasized and simultaneously communicates appropriate portion sizes. The method of Camelon et al. has involved dividing a plate, representing a meal, into segments showing appropriate quantities of different foods. Several foreign countries, including Great Britain, Australia, Germany, and Mexico, have graphically packaged their public health message in a similar fashion, by using a divided plate, rather than the U.S. food pyramid (41).

The American Diabetes Association, in conjunction with the North American Association for the Study of Obesity and the American Society for Clinical Nutrition, has noted that a number of diet strategies exist for weight loss and that different individuals may find different strategies useful. Although they do not specifically endorse either the GI or energy density as methods for choosing foods, they have noted that both have some support in the literature and that further research into them is warranted (42). The American Diabetes Association has more recently indicated that both the amount and type of carbohydrate in a food influence blood glucose level and recommends that considering the

glycemic index in addition to total carbohydrate may be helpful in controlling postprandial blood glucose levels (43). "Choose carbohydrates wisely" is the advice to be given to Americans in the upcoming 2005 Dietary Guidelines for Americans (44), but as shown in this paper, that is not simple advice. However, the different approaches to carbohydrates do have certain factors in common (Figure 1). Nonstarchy vegetables and higher-fiber legumes are consistently advised, as is a reduction in added sugar. Further research into the rate of absorption of foods, as well as a consistent reproducible way to measure that effect, is needed, as is further research into satiety and appetite control. As these factors become better understood, the development of clearer guidelines will become possible.

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