SPORTS SCIENCE EXCHANGE

GLYCEMIC INDEX AND EXERCISE METABOLISM

Janet Walberg Rankin, Ph.D.
Dept. of Human Nutrition, Foods, and Exercise
Virginia Tech
Blacksburg, VA
Member, Sports Medicine Review Board, Gatorade Sports Science Institute

KEY POINTS
1. The glycemic index (GI) of a food represents the magnitude of the increase in blood glucose that occurs after ingestion of the food.
2. GI tends to be lower for foods that have a high fructose content, exhibit high amylose/amylopectin ratios, are present in relatively large particles, are minimally processed, and are ingested along with fat and protein.
3. Consumption of lower GI foods 30-60 min prior to an endurance exercise bout tends to promote the following effects during exercise:
   • Minimizes the hypoglycemia that occurs at the start of exercise.
   • Increases the concentration of fatty acids in the blood.
   • Increases fat oxidation and reduces reliance on carbohydrate fuel.
4. The GI of a food consumed during exercise is probably less important than at other times because the insulin response to carbohydrate ingestion is suppressed during exercise.
5. Consumption of high GI foods soon after exercise will probably optimally promote the restoration of muscle glycogen.
6. Although manipulation of the GI of ingested foods may alter exercise metabolism, the effect of the GI on exercise performance is controversial and requires additional research.

FUEL UTILIZATION DURING EXERCISE

The relative utilization of carbohydrates and fats as fuels during exercise depends primarily on the intensity and duration of the activity. In general, carbohydrate use increases with increasing intensity and falls with increasing duration of an activity. However, the absolute amount of carbohydrate and fat used by muscles can be shifted, depending on fuel availability; greater availability of fatty acids increases fat use, and when more carbohydrate is present more carbohydrate is metabolized for energy. This reciprocal interplay between fat and carbohydrate use should be carefully considered when deciding on food consumption for athletic competition.

The goals of dietary intervention for the athlete are to fill carbohydrate (glycogen) stores in the muscles and liver and to make both carbohydrate and fat readily available in the blood for use by the muscles. Carbohydrate fuel can support higher intensity exercise than can fat and is stored in more limited amounts in the body. The metabolic challenge is to maintain carbohydrate supply to the muscles and to somehow slow its depletion by relying optimally on fat as a fuel. Insulin plays a key role in fuel partitioning because insulin tends to increase the metabolism of carbohydrate and reduce fat use. An interesting question is whether or not certain foods can provide sufficient carbohydrate, affect insulin minimally, and also encourage fat use for energy.

Many studies have investigated the ergogenic value of consuming carbohydrate before, during, or after an exercise bout. There is overwhelming evidence that carbohydrate consumption before and/or during prolonged exercise can enhance endurance performance. Thus, a typical recommendation for the daily diet of athletes is to increase carbohydrate intake to at least 60% of the energy in the food ingested or to ingest at least 7 g of carbohydrate per kilogram of body weight. There are also recommendations about the amount and frequency of carbohydrate consumption during exercise (e.g., Walberg - Rankin, 1995), but these recommendations typically do not include any comment on the specific type of carbohydrate that should be consumed. The remainder of this review will summarize the evidence that consuming different types of carbohydrate causes different effects on exercise metabolism and, possibly, performance.

TYPES OF CARBOHYDRATE FOODS

Biochemical Forms

Biochemically, most carbohydrate foods can be classified as mono-, di-, or polysaccharides. Examples of monosaccharides are fructose, glucose, or galactose. When two of these monosaccharides are linked together with a chemical bond, a disaccharide is produced. Sucrose, for example, is made up of one glucose bonded to one fructose molecule. Lactose, found in dairy products, is produced by linking a glucose with a galactose molecule. Polysaccharides can be made up of hundreds or thousands of linked monosaccharides. For example, starches found in plant foods are polysaccharides made up of many glucose molecules. The two forms of starch are amylose, a straight chain of repeating glucose molecules, and amylopectin, a branched chain. Through digestion or with food processing, starches can be partially broken down to smaller chains, called dextrans.

Digestion

All carbohydrates are mostly broken down to their constituent monosaccharides during digestion. Although some digestion of carbohydrates begins in the mouth through the actions of enzymes in the saliva and in the stomach by the effects of acids,
most occurs in the small intestine. Enzymes released from the pancreas into the gut split the larger carbohydrates into fructose, galactose, and mostly glucose. The absorption of these monosaccharides happens in the intestinal mucosal cells where glucose and galactose are actively transported (i.e., energy is expended) with a carrier protein to help them cross the membrane. Fructose is absorbed differently by a facilitated diffusion process that involves a carrier protein but no energy expenditure. However, it is difficult for fructose to be absorbed against a concentration gradient. In other words, fructose absorption will be slowed if there has already been significant fructose absorption.

Under most circumstances, all the carbohydrate that is ingested is eventually absorbed into the blood. The absorbed monosaccharides enter the blood in the capillaries surrounding the intestinal villi and are taken to the liver via the portal vein. The liver will typically convert all monosaccharides to glucose or to a product of glucose metabolism, such as lactate. Thus, the blood concentrations of monosaccharides other than glucose are ordinarily very low. The liver may take up some of the monosaccharides to form glycogen or fat or let them pass through to provide carbohydrate to the rest of the body.

**Simple and Complex Carbohydrates and the Glycemic Index**

Carbohydrate foods are often classified as “simple” or “complex” carbohydrates—mono- and disaccharides are grouped as “simple” and polysaccharides as “complex.” Although one might guess that simple molecules would be absorbed more rapidly than larger ones, this assumption is not always correct; digestion and absorption do not occur at the same rates for all carbohydrates within a biochemical grouping.

A newer system of carbohydrate classification is the “glycemic index” (GI). The term has been used for some time in clinical nutrition, particularly as it pertains to diabetes, but has only recently been used in the healthy, active population. This term refers to the relative degree to which the concentration of glucose in the blood rises after consumption of a food, i.e., the so-called “glycemic response.” Testing of the GI requires ingestion of 50 g of carbohydrate from a variety of foods, and measuring the blood glucose response over 2 h. After the blood glucose concentration over the two hours is graphically represented—with glucose concentration on the vertical axis and time on the horizontal axis—the area under the blood glucose curve is measured for each food and compared to consumption of 50 g of glucose as the reference. The glycemic index is given as a percentage, i.e., the percentage of the area under the blood glucose curve for the test food compared to that for glucose. Accordingly, a GI of 70 indicates that consuming 50 g of the food in question provokes an increase of blood glucose 70% as great as that for ingesting 50 g of pure glucose.

Factors that influence the glycemic index of a food include the biochemical structure of the carbohydrate, the absorption process, the size of the food particle, the degree of thermal processing, the contents and timing of the previous meal, and the co-ingestion of fat, fiber, or protein (Guezenec, 1995). For example, the ratio of amylose to amylopectin in starchy foods affects GI; the blood glucose response to amylopectin is more rapid than for amylose because the digestive enzymes more rapidly break down the branched structure of the amylopectin. In addition, there is some evidence that amylose is not fully digested; therefore, the full carbohydrate content of a high-amylose food may not be available to the body for use.

Because fructose is absorbed from the intestine more slowly than glucose and is metabolized mainly by the liver, fructose ingestion has little immediate effect on blood glucose concentration; thus, foods high in fructose content have a relatively low GI. Therefore, since some monosaccharides (e.g., fructose) have low glycemic indexes and some polysaccharides (e.g., amylopectin) have high glycemic indexes, the classification of carbohydrates as simple or complex has little value in predicting the metabolic effects of ingesting these foods.

Mechanical or thermal processing of food that breaks the food into smaller particles or makes it more susceptible to the actions of the digestive enzymes increases the glycemic index of the food. For example, making flour from wheat will increase the glycemic index relative to ingesting wheat kernels. Finally, because ingestion of fat and protein tends to slow stomach emptying, absorption of carbohydrates and elevations in blood glucose usually occur more gradually if the carbohydrates are consumed along with fats and proteins.

Tables listing the glycemic index of foods have been developed mainly for use with diabetic persons (Foster-Powell & Brand Miller, 1995), but because blood glucose appears to be so critical to athletic performance these tables may also be useful for athletes; our understanding of this issue remains rudimentary. Thus, only a few studies have investigated the effects of feeding different forms of carbohydrate on factors related to exercise metabolism (e.g., blood glucose, fatty acids, insulin, respiratory exchange ratio, muscle glycogen use) or to performance (e.g., ratings of perceived exertion and time to exhaustion). Methods of achieving different glycemic responses have included using different monosaccharides (e.g., fructose versus glucose), whole foods with different GI (e.g., lentils versus potatoes), foods that are processed differently (e.g., flour versus whole grain), and the addition of other macronutrients (e.g., protein or fat) to a carbohydrate source.

**The Influence of Glycemic Index on Exercise Metabolism**

**FEEDINGS PRIOR TO EXERCISE**

Food consumed prior to exercise should supply carbohydrate that can elevate or maintain blood glucose without dramatically increasing insulin secretion. This would theoretically optimize the availabilities of both glucose and fatty acids for use by the muscles. One concern about feeding carbohydrate prior to exercise is that a rapid increase in blood glucose and thus insulin might cause hypoglycemia at the start of the activity. A second effect of hyperinsulinemia prior to exercise is a reduction in lipolysis. Both of these conditions may increase reliance on muscle glycogen during the exercise. For example, Foster et al. (1979) observed that consumption of glucose 30 min before a cycling bout caused a quick increase in blood glucose but a hypoglycemic effect at the start of the exercise bout. Relative to a control trial, blood glucose and fatty acid concentrations stayed depressed for the glucose trial throughout exercise. Time to exhaustion was reduced 19% by the glucose feeding compared to the water trial. The authors concluded that glucose should not be consumed shortly before an event because this practice can cause reactive hypoglycemia and suppression of fatty acid concentration in the blood.

However, as reviewed by Sherman (1991), although the metabolic effects of pre-exercise carbohydrate ingestion shown in the report of Foster et al. are quite commonly observed during the initial phase of endurance exercise, findings of an adverse effect on performance are atypical; in fact, several more recent reports showed improvements in performance. Nevertheless, to the extent that even a few athletes may be negatively affected by a drop in blood glucose at the onset of exercise, several investigators have thought it important to compare glucose feedings with ingestion of fructose, which has a lower glycemic index, in hopes of minimizing the changes in blood glucose and insulin and maximizing the potential positive effects of the carbohydrate feeding on performance.

**Biochemical Form of Carbohydrate**

Craig (1993) reviewed many of the exercise studies using fructose feedings and noted that fructose consumption prior to exercise does not cause an increase in either blood glucose or insulin. Although one study demonstrated a reduction in muscle glycogen use when fructose had been ingested prior to a 30 min exercise bout compared to a water supplement (Levine et al 1983), the glycogen-sparing effect of fructose ingestion was not confirmed in later studies using longer exercise bouts when glycogen could become more limiting (Hargreaves, 1987; Koivisto, 1985). This absence of effect on muscle glycogen occurred in spite of different glycemic and insulinemic patterns for the glucose versus fructose trials in the various studies. In addition, no performance benefit, as measured by time to exhaustion, was noted in most experiments showing fructose compared to glucose. However, there may be some benefit to fructose ingestion prior to exercise when it is used in combination with other carbohydrate sources. For example, muscle glycogen sparing and per-
formance enhancement were observed in athletes consuming a mixture of maltodextrin and fructose when compared to maltodextrin alone (Brouns et al. 1989).

To summarize the studies that have used fructose feedings prior to exercise, blood glucose was maintained at higher levels during the initial period of exercise relative to high-GI carbohydrates like glucose, but there were few reports of an ergonomic effect or a change in rate of muscle glycogen use. Because virtually all authors who fed fructose commented on the high incidence of gastrointestinal distress (due to slow fructose digestion), fructose alone is probably not practical in the concentrations required to provide sufficient energy; it may be useful as part of a mixture with other carbohydrates.

Guezennec et al. (1993) studied the difference in carbohydrate oxidation during exercise when amylose and amylopectin were consumed prior to exercise. Amylopectin was oxidized more quickly during exercise than was the amylose. Goodpaster et al. (1996) tested whether high amylase or high amylopectin foods fed prior to endurance exercise had different effects on metabolism or performance when compared to placebo or glucose feedings. A lower glycemic response was seen for both starches compared to glucose during the 30 min prior to exercise. However, in contrast to the results of Guezennec et al. (1993), the starches did not differ from one another in their glycemic responses in this pre-exercise period. Furthermore, all carbohydrate treatments increased the reliance on carbohydrate as a fuel during exercise. When compared to the placebo, the high-amylopectin starch was as effective as the glucose feeding in enhancing endurance performance but, in spite of similar glycemic effects of the two starches, the increased amount of work done during the 90 min performance test when the high-amylopectin starch was consumed was not statistically significant from the placebo. The authors felt that the lower digestibility of the high-amylopectin starch contributed to its reduced benefit on exercise performance. This study did not support a benefit of a lower glycemic food, i.e., starch, over a higher glycemic food (glucose) fed prior to exercise.

Adding Fat or Protein.

The previously mentioned study by Foster et al. (1979) compared milk, which contains a mix of macronutrients, to glucose or water fed prior to exercise. The glycemic response to milk ingestion was less than that of glucose prior to exercise. Although the blood glucose concentration dropped at the start of exercise after milk ingestion, it later rose above that observed during the glucose trial. Serum fatty acid concentration during exercise was higher for milk (the lower glycemic index food) than for glucose. Performance after milk ingestion was improved relative to the glucose trial but was not superior to the control trial.

Horowitz and Coyle (1993) tested six meals, each with carbohydrate at a dose of 0.7 g/kg body weight, fed 30 min prior to 60 min of exercise at 50-70% VO_{2}\text{max}. The carbohydrate sources were either potato, rice, or sucrose. Each carbohydrate source was consumed alone in one trial and in another trial with added fat. The addition of fat reduced the glycemic responses of the carbohydrate sources. Of the six treatments, the three with the highest glycemic effects were potato, sucrose, and sucrose plus fat. The other three feedings caused less of an increase in blood glucose and insulin at rest. The lower insulin concentration coincided with a nonsignificant trend toward a higher free fatty-acid concentration during exercise for the lower GI foods. Maximal performance was not evaluated; all individuals did identical cycling bouts. The fact that RPE did not differ by treatment suggests that the onset of fatigue was not different. However, the average RPEs ranged from 10.2-12.9, indicating that the exercise bout was not very demanding for these physically fit males. The authors concluded that although there were differences in metabolic responses prior to exercise, these metabolic factors converged among groups by about 20 min of exercise and were unlikely to affect ability to do endurance exercise. However, it should be noted that these individuals were clearly not metabolically or physiologically highly stressed by this exercise bout. Differences may not appear unless individuals are pushed to fatigue.

Whole Foods.

Thomas et al. (1991) tested whether foods with varying GIs affected the ability to continue exercise. They compared four meals, each containing 1 g carbohydrate per kg body weight, fed 60 min prior to cycling to exhaustion at 65-70% VO_{2}\text{max}. The meals were boiled lentils (GI = 29), baked potato (GI = 98), glucose solution (GI = 100), and water. The blood glucose concentrations reached their peak 30 to 45 min after eating, with higher values for potato and glucose compared to lentils. Blood glucose began to decline toward baseline just before the exercise bout and dropped below baseline within 15 min of exercise for all food trials. The greatest declines in blood glucose with the onset of exercise were seen with the high-GI foods, i.e., potato and glucose. In the lentil trial, insulin levels were lower prior to exercise and the plasma free fatty acid concentration was higher during exercise. Calculation of the respiratory exchange ratio showed that carbohydrate oxidation tended to be highest for the high-GI foods. Finally, the subjects cycled longer before exhaustion after they had consumed lentils, as compared to any of the other treatments. In summary, this study found an ergonomic benefit of a lower-GI food for endurance exercise. This appeared to be mediated through maintenance of blood glucose and enhancement of fatty acid oxidation. The authors suggested that this metabolic environment might reduce the use of muscle glycogen during exercise.

A subsequent study from the same laboratory failed to confirm the earlier findings of an ergonomic benefit of low-GI foods. Thomas et al. (1994) had six trained cyclists consume four different meals prior to exercise bouts. Two of the meals, flaked potato and rice cereal, had a high GI, and two had a low GI (flaked lentils, bran cereal). The experimenters added tomato to the potato and lentil flakes and low-fat milk to the cereals to improve palatability. Although the meals were identical in carbohydrate content (1 g/kg), there was a range from 1271 to 2024 kJ (308-490 kcal) per meal. Using the potato feeding as a reference, GI varied as follows: 100 (potato flakes), 73 (rice cereal), 36 (lentil flakes), 38 (lentil cereal), 67 (bran cereal). Each meal was consumed 60 min prior to an exercise bout to exhaustion at 65-70% VO_{2}\text{max}. Blood glucose changes during the 60 min after food ingestion were consistent with the GI values of the foods. Insulin pattern reflected the glycemic response during the period before exercise but fell to similar levels for all trials during exercise. The area under the curve for free fatty-acid concentration versus time during exercise was inversely correlated with GI. In other words, blood free fatty acid concentration was lowest for potato and highest for lentils during exercise. There was a positive correlation between the respiratory exchange ratio and GI, i.e., subjects used the most fat as fuel during the bran cereal trial and the most carbohydrate during the potato trial. Although these metabolic differences between trials would suggest an advantage of the lower GI foods, there was no significant difference in time to exhaustion between trials (mean ± SEM = 95 ± 12 min).

Guezennec et al. (1993) fed subjects five high-carbohydrate foods—potato, rice, white spaghetti, white bread, or glucose—containing 200-250 kcal. Exercise on a cycle ergometer at roughly 56% VO_{2}\text{max} began 60 min later and continued for 2 h. Glycemic responses after the feedings were as expected with glycogen and potato having higher responses than rice or spaghetti; bread was intermediate. As shown in other studies, the drop in blood glucose upon initiation of exercise was related to GI; blood glucose dropped lower after the glucose and potato meals compared to the other meals. This difference persisted at the end of exercise when blood glucose was significantly higher for the spaghetti and bread meals, and lipid utilization was greater during the exercise bout for the lower GI meals—rice and spaghetti—compared to the other foods. More of the carbohydrate was oxidized during the exercise period from the glucose beverage than from the spaghetti. Thus, the lower GI food was apparently more slowly oxidized than the higher GI food, implying that more lipid was oxidized with the spaghetti meal.

Food Processing.

Guezennec et al. (1993) fed crude and gelatinized forms of both amylease and amylopectin to subjects prior to exercise. Gelatinization involved the bonding of water molecules to the starch structure, increasing its viscosity and bioavailability. The gelatinized forms of each starch were more quickly oxidized than the crude form.
bolic effects of different processing forms of the same food. They had six women consume water or 75 g of carbohydrate as either whole-grain oats or oat flour 45 min before exercise at 60% VO_{2} max. The greater amount of fiber and larger particles of the whole grain oats suggest that they would have a lower GI than the flour. However, there were no significant differences in blood glucose, free fatty-acids, insulin, glyc- erol, or muscle glycogen reduction during exercise for these two treatments.

Interestingly, the subjects cycled longer after consuming the whole grain oats than they did after the water trial. There was a non-significant increase in cycling duration for the whole grain-oats trial compared to the oat-flour trial.

Summary

The evidence suggests that consuming higher-GI foods 30-60 min before exercise causes more of a decrease in blood glucose upon the initiation of exercise and increases reliance on carbohydrate as a fuel during the exercise. These facts tend to identify lower-GI foods as promoting a preferable metabolic response prior to exercise. However, there is conflicting evidence on whether or not these metabolic differences have any effect on endurance performance.

DURING EXERCISE

Much research has focused on provision of food, particularly carbohydrate-rich items, during exercise to slow the depletion of body carbohydrate and thus delay the onset of fatigue. The concerns about carbohydrate feedings increasing insulin and thus depressing fatty acid availability are obviated when the carbohydrate is fed during exercise because the exercise-induced elevation in epinephrine depresses the release of insulin from the pancreas.

Biochemical Forms of Carbohydrate

Using feedings of C_{6} labeled glucose and fructose every 20 minutes during exercise, Massicotte et al. (1986) found that fat utilization was higher for the fructose trial during a 180-min exercise bout at 50% VO_{2} max. Also, Flynn et al. (1987) tested blood metabolites and performance of subjects during a 2-h cycling bout when the subjects were fed fructose, maltodextrin, or glucose in varying concentrations at regular intervals during exercise. The treatments that included fructose in the beverage mix maintained blood glucose at higher levels during exercise than did water or drinks with higher-GI carbohydrates. However, neither total amount of work done nor muscle glycogen utilization was different among the different carbohydrate trials.

Murray et al. (1989) compared the effects of ingesting 6% fructose, sucrose, or glucose solutions during 115 min of intermittent cycling and found that the plasma glucose and insulin responses before exercise were lower for fructose than for either sucrose or glucose, but the ratings of perceived exertion as well as stomach upset during exercise were significantly higher for the fructose trial. They concluded that the lower-GI carbohydrate source, fructose, was not useful for endurance performance in the concentrations tested.

In conclusion, although fructose tends to maintain blood glucose and increase reliance on fatty acids as a fuel when fed during exercise, fructose does not seem to improve endurance performance; in fact, its effect on producing gastrointestinal distress when fed in even moderate amounts raises serious concerns about its utility as a carbohydrate supplement.

AFTER EXERCISE

A goal of feeding after exercise is to elevate glucose as soon as possible to provide substrate for glycogen synthesis; as reviewed by Robergs (1991), glycogen synthesis can occur more rapidly if carbohydrate is consumed quickly and in adequate amounts after exercise.

Biochemical Forms of Carbohydrate

The low GI of fructose in addition to its preferential uptake by liver makes fructose a poor post-exercise carbohydrate source (Robergs, 1991), but other biochemical forms of carbohydrates may be more useful. For example, Jozsi et al. (1996) tested two different forms of starch compared to glucose for glycogen replacement. They fed subjects one of four diets—glucose, maltodextrin, high-amylopectin starch, or high-amyllose starch—for 12 h following a glycogen-depleting bout of cycling. At 24 h after the ride, muscle glycogen replenishment was lower with the high-amyllose starch trial than with the other diets. It was not possible to assess whether the impair-ment of glycogen replacement was due to a lower GI or to poor digestibility of the high-amyllose starch. Unfortunately, the researchers did not confirm whether the diets caused differences in glucose or insulin concentrations in the blood. In another study the same group fed these starches prior to exercise and found no significant difference in GI (Goodpaster et al. 1996).

Whole Foods

Costill et al. (1981) investigated the effect of a diet containing primarily "simple" or "complex" carbohydrates on muscle glycogen resynthesis after exercise. They reported that the glycogen replacement after the exercise-carbohydrate diet was similar to that with a simple-carbohydrate diet after 24 h but caused a higher glycogen level after 48 h. This study is difficult to interpret because neither the diet nor the glycemic and insulimemic responses were provided. The authors defined simple carbohydrates as sucrose, glucose, and fructose, and because fructose has a very low GI, this study was not a reasonable test of glycemic index on metabolism after exercise.

Kiens et al. (1990) tested the effect of diets of 70% carbohydrate with either low or high GI for 44 h following glycogen-deplet-ing cycle ergometry. The insulin response to the high GI diet was 98% higher, even though blood glucose levels were similar for the two diets. The rate of muscle glycogen resynthesis was twice as fast during the first 6 h after exercise with the high GI diet, but there was no difference in glycogen replacement by 2 h after exercise. This study was published only as an abstract, and the actual foods used in the two diets were not reported.

Thomas et al. (1994) found that pre-exercise low GI meals, (e.g., lentils or bran cereal with milk) produced higher levels of blood glucose and insulin during 30 min of recovery from exercise than did a high GI meal, potato. Muscle glycogen was not assessed, but the comparative glucose and insulin results after exercise seem to favor faster glycogen replacement for the low GI meal before exercise. The limitation of this interpretation is that this may be true only if no food is ingested during recovery. Nevertheless, it seems reasonable to hypothesize that athletes who do not have food accessible or who do not have the desire to eat during the first 30 min after exercise may benefit from consuming a low GI meal prior to exercise.

Burke et al. (1993) fed five elite cyclists diets containing primarily low or high GI foods for 24 h after a glycogen-depleting ride. Both diets were similar in total carbohyd-rate (10 g/kg) which was divided equally among four meals. Blood glucose and insulin were assessed for 90 min following each meal. Interestingly, the glycemic and insulimemic responses tended to be higher for the low GI diet than for the high GI diet after the first meal, whereas the opposite pattern was observed for each subsequent meal. Because the first and fourth meals were identical in content but promoted different glycemic responses, there may have been an interaction between magnitude of muscle glycogen depletion and glycemic response, i.e., a high GI meal caused less of a rise in blood glucose when glycogen stores are depleted than when they are at least partly replenished. Thus, the predicted GI of a food or meal may not be valid shortly after exercise. Nevertheless, muscle glycogen increased almost twice as much after 24 h on the high GI diet compared to the low GI diet.

Adding Fat or Protein

Zawadzki et al. (1992) tested a combination of carbohydrate with protein in a post-exercise feeding and found that the mix of carbohydrate with protein caused a greater increment in blood glucose and insulin than either carbohydrate or protein alone. This contributed to a higher rate of glycogen synthesis for the mixture than for either macronutrient ingested separately. These data are provocative, but the results need to be confirmed because the treatments did not have the same energy value; the carbohydrate plus protein treatment provided more than three times the energy as the protein trial and about a third more than the carbohydrate trial. Thus, the higher glucose and insulin levels could have been functions of the higher energy value of the combination meal, rather than the macronutrients themselves.

Burke et al. (1995) were interested in whether the addition of GI-lowering fat and protein to a high-carbohydrate diet would...
affect the rate of replacement of glycogen after a prolonged exercise bout. They compared two diets containing 7 g of carbohydrate per kg body weight; the fat-protein (FP) diet had extra fat and protein and only 51% of the energy from carbohydrate, whereas the control diet had 77% carbohydrate energy. The authors included an energy-matched group that increased the carbohydrate content of their diets to 11.8 g/kg to equal the energy content of the FP diet. The addition of fat and protein did reduce the glycemic response and increased the plasma fatty acid concentration versus the carbohydrate control diet, but it did not affect the increment in plasma insulin. Because the change in muscle glycogen over 24 h was similar for all diets, the authors concluded that the insulin response—not the GI—may be critical in predicting glycogen synthesis rate. An alternate interpretation is that 24 h may have been sufficient time to obscure any earlier differences between treatments. It is possible that there may have been a benefit to the higher GI diet during the first hours after exercise. Furthermore, all diets were relatively high in carbohydrate and may have been above a plateau of optimal carbohydrate for glycogen synthesis. Even the FP diet had more than 50% of its energy and 7 g/kg as carbohydrate. This is above what many individuals typically consume (Walberg-Rankin, 1995). [Thus, a higher fat/protein diet may not be ideal for glycogen synthesis in the typical diet because it would tend to displace carbohydrate.] In light of the results of Zawadski et al. (1992) that protein added to carbohydrate is superior to carbohydrate alone, it may be interesting to compare diets of similar carbohydrate and fat content, but varying protein. This combination may provoke a higher insulin response to the diet and thus promote greater glycogen synthesis.

Summary

If no food is consumed after exercise, a low GI meal ingested prior to exercise may be warranted because it is likely to cause higher blood glucose and insulin concentrations after exercise than a high GI meal. However, glycogen synthesis will be faster if high GI meals are consumed as soon as tolerated after exercise. The increased blood glucose—and especially insulin—after exercise appear to be critical for resynthesizing muscle glycogen.

Chronic Diet

All of the above studies have used acute feedings of foods with different GI. A longer term feeding study was recently conducted by Kiens and Richter (1996). They fed seven healthy lean men high GI and low GI diets, each for 30 d, in a cross-over design. No exercise was involved, but the authors examined blood metabolites, insulin sensitivity, and muscle fuel stores before and at the end of each feeding period. Although there was a difference in glycemic effect of the diets at the beginning of the feeding period, with the lower GI diet causing a smaller increase in postprandial blood glucose, this difference disappeared over the 30 d. Higher insulin sensitivity was noted in subjects on the high GI diet and was associated with higher glycogen and triglyceride storage in muscle. Thus, this study suggests that a high GI diet pushes the body towards carbohydrate oxidation (i.e., enhanced insulin sensitivity?) and increases muscle storage of both fat and carbohydrate fuels. A limitation to interpreting this study for athletes is that both diets contained only 46% of the energy as carbohydrate and contained a high fat content (41% of total energy). Because it is recommended that athletes consume a higher carbohydrate and lower fat diet, the findings may not be directly generalizable.

OTHER HEALTH ISSUES RELATED TO GLYCEMIC INDEX

There are several general health implications for high versus low GI diets. Much of the early research regarding the effects of GI used diabetic subjects because most of the complications of diabetes are related to excessive blood glucose levels; a lower GI diet moderates blood glucose in these individuals. The few studies outlined in this review used healthy, non-diabetic subjects. A low GI diet typically improves glucose tolerance and indicators of high blood glucose, such as serum fructosamine, in diabetic subjects (Brand Miller, 1994). Similarly, Jenkins et al. (1987) found that 2 wk of a lower GI diet in non-diabetic males also reduced serum fructosamine and overall daily insulin concentrations. However, those ingesting a low GI diet demonstrated poorer glucose tolerance to an oral carbohydrate challenge than when they consumed the higher glycemic diet. Keins and Richter (1996) also found a better glucose tolerance in normal subjects when they consumed a higher GI diet.

Because blood glucose has been implicated in appetite control, it has been suggested that a lower GI diet may increase satiety and make it easier to control food intake and body weight. Holt et al. (1992) tested the effects of six test meals on serum glucose and insulin, and hunger. They found a direct relationship between GI and hunger during the 3 h after the meal, i.e., the high GI meals caused a greater feeling of hunger than did the low GI meals.

Finally, total and low-density-lipoprotein cholesterol may decrease on a lower GI diet. Synthesis of cholesterol in the liver is sensitive to insulin concentrations, which tend to be higher with a high GI diet (Jenkins 1987; Kiens and Richter 1996). For example, Jenkins et al. (1987) reported a 15% drop in cholesterol of normal subjects after 2 wk on a low GI diet.

PRACTICAL APPLICATIONS

It is valuable to consume carbohydrate before, during, and after prolonged endurance exercise to provide fuel during exercise and substrate for glycogen synthesis following exercise. It is possible that carbohydrate foods with different GI may alter exercise metabolism and further affect performance. The research concerning GI and performance in athletes is limited, and recommendations concerning carbohydrate choices are still tentative. In addition, it is important to note that only a limited number of foods have been tested for their GI.

Consuming low versus high GI foods in the hour before exercise may moderate the decline in blood glucose that occurs at the beginning of exercise, reduce reliance on carbohydrate as a fuel, and increase lipid use during exercise. However, there is insufficient evidence to claim that these metabolic changes translate to reduced muscle glycogen depletion and improved endurance performance. Although fructose has a relatively low GI, it should be used in small amounts and in combination with other CHO sources because it often causes gastrointestinal distress. Other foods with a low GI that may be consumed before exercise include most fruits, pasta, rice, and possibly legumes if they are tolerated. The glycemic indices of commercial sports drinks have not been published, but drinks high in glucose would presumably be the highest GI, whereas those with more fructose or sucrose would tend to have a lower GI. It is important to note that the glycemic index of a food is not easily predictable. Multiple foods are generally consumed together; each food can impact the glycemic response of the other. In addition, the metabolic state of the person will influence glycemic index of a food. For example, a person with low glycogen stores will likely have less of an increase in blood glucose following food consumption than when initial glycogen stores are high.

The GI of foods consumed during exercise is probably not critical because the insulin response is muted during exercise. Thus, there will be less influence of GI on metabolic responses to exercise.

The best evidence for ingesting high GI foods is for post-exercise recovery of muscle glycogen. Several studies have shown an improved glycogen synthesis over at least the first hours of recovery when GI is high. High-GI foods include most breads, potatoes, and high-glucose sports drinks. If the recovery time is 20 h or longer, the GI of the carbohydrates ingested is probably less important than the quantity of CHO consumed.

The possibility that a chronic diet of high-GI foods promotes higher insulin sensitivity and greater storage of muscle glycogen and triglycerides is intriguing for athletes, but this possibility need to be confirmed by studies using subjects who consume high-carbohydrate diets. Much more research needs to be done on the relationship between GI and general health, but because a low-GI diet seems likely to cause lower blood cholesterol and improved appetite control, a low-GI diet on an everyday basis is probably a good choice for athletes and non-athletes alike.
# Glycemic Indexes of Common Foods

## Breads and Grains
- waffle: 76
- doughnut: 76
- bagel: 72
- wheat bread, white: 70
- bread, whole wheat: 69
- cornmeal: 68
- bran muffin: 60
- rice, white: 56
- rice, instant: 91
- rice, brown: 55
- bulgur: 48
- spaghetti, white: 41
- whole wheat: 37
- wheat kernels: 41
- barley: 25

## Cereals
- Rice Krispies: 82
- Grape Nuts Flakes: 80
- corn Flakes: 77
- Cheerios: 74
- shredded wheat: 69
- Grape Nuts: 67
- Life: 66
- oatmeal: 61
- All Bran: 42

## Fruits
- watermelon: 72
- pineapple: 66
- raisins: 64
- banana: 53
- grapes: 52
- orange: 43
- pear: 36
- apple: 36
- Starchy Vegetables
  - potatoes, baked: 83
  - potatoes, instant: 83
  - potatoes, mashed: 73
  - carrots: 71
  - sweet potatoes: 54
  - green peas: 48
- Legumes
  - baked beans: 48
  - chick peas: 33
  - butter beans: 31
  - lentils: 29
  - kidney beans: 27
  - soy beans: 18
- Dairy
  - ice cream: 61
  - yogurt, sweetened: 33

## Snacks
- rice cakes: 82
- jelly beans: 80
- graham crackers: 74
- corn chips: 73
- life savers: 70
- angel food cake: 67
- wheat crackers: 67
- popcorn: 55
- oatmeal cookies: 55
- potato chips: 54
- chocolate: 49
- banana cake: 47
- peanuts: 14

## Sugars
- honey: 73
- sucrose: 65
- lactose: 46
- fructose: 23

## Beverages
- soft drinks: 68
- orange juice: 57
- apple juice: 41

## Dairy
- milk, full fat: 27
- milk, skim: 32

## Example of Daily Diets with High or Low Glycemic Index

### Higher Glycemic Index

#### Breakfast
- 2 c. corn flakes: 77
- 1 c. 1% milk: 33
- 2 waffles: 76
- 2 T. syrup: ?
- 1 c. pineapple chunks: 66

#### Lunch
- 2 slices white bread: 70
- 3 oz. turkey: —
- 1 c. watermelon: 72
- 3 oz. corn chips: 73
- 1/2 c. carrots: 71
- 8 oz. cola drink: 71

#### Dinner
- baked potato: 83
- topping: 2 oz. cheese and 1 oz. ham: —
- 2 slices cheese pizza: 60
- 1 green salad: —

#### Snacks
- 1 c. ice cream: 61
- 1 slice angel food cake: 67
- 4 graham crackers: 74

### Lower Glycemic Index

#### Breakfast
- 2 c. All Bran: 42
- 1 c. 1% milk: 33
- 1 apple muffin: 44
- 1 c. orange juice: 57

#### Lunch
- 1 c. chili with beans: 27

#### Dinner
- 2 c. w. w. spaghetti: 37
- 3/4 c. tomato sauce: ?
- 1 oatmeal cookie: 55
- 1 green salad: —

#### Snacks
- 1 c. fruit yogurt: 33
- 1 sl. banana cake: 47
- 1/4 c. peanuts: 14

Each of these diets contains about 2600-2700 kcal, and 61-63% of this energy is derived from carbohydrate. Those foods listed that have very little carbohydrate do not have a glycemic index (GI) listed. Those foods with a significant carbohydrate content but without published GI are listed with a "?". Source for GI of foods listed is Foster-Powell and Brand Miller (1995).
References


