Abstract  The focus of this paper is on the glycemic index (GI) that provides effective information on planning nutritional strategies for carbohydrate (CHO) supplementation in exercise. Related research has suggested that the GI can be used as a reference guide for the selection of an ideal CHO supplement in sports nutrition. Recently, the manipulation of GI of CHO supplementation in optimizing athletic performance has provided an exciting new research area in sports nutrition. There is a growing evidence to support the use of the GI in planning the nutritional strategies for CHO supplementation in sports. The optimum CHO availability for exercise has been demonstrated by manipulating the GI of CHO. Research has shown that a low GI CHO-rich meal is a suitable CHO source before prolonged exercise in order to promote the availability of the sustained CHO. In contrast, a high GI CHO-rich meal appears to be beneficial for glycogen storage after the exercise by promoting greater glucose and insulin responses. The prescribed feeding patterns of CHO intake during recovery and prior to exercise on glycogen re-synthesis and exercise metabolism have been studied in the literature. However, the studies on the subject are still limited, leaving some open questions waiting for further empirical evidences. The most significant question is whether CHO supplementation before and after exercise is beneficial when consumed as large feedings or as a series of snacks. Further research is needed on the effect of feeding patterns on exercise performance. J Physiol Anthropol Appl Human Sci 23 (1): 1–6, 2004 http://www.jstage.jst.go.jp/en/

Keywords: glycemic index, feeding patterns, exercise performance

Introduction

The glycemic index (GI) provides effective information in planning the appropriate nutritional strategies on carbohydrate (CHO) supplementation in exercise (Burke et al., 1998; Coyle, 1991; Hargreaves, 1991; Walton & Rhodes, 1997). It has been suggested that the GI can be used as a reference guide for the selection of an ideal CHO supplement in sports nutrition (Walton & Rhodes, 1997). The concept of the GI is to classify foods based on their actual postprandial blood glucose response compared to a reference food, which is either glucose or white bread. The rate of digestion and absorption are based on the GI ranking of a particular food. The availability of CHO for exercise can be optimized by manipulating the GI of the CHO supplementation (BrandMiller et al., 1996; Burke et al., 1998; Coyle, 1991; Walton & Rhodes, 1997). A low GI CHO-rich meal has been recommended as the CHO supplement before prolonged exercise while a high GI CHO-rich meal appears to be beneficial during the post-exercise recovery period.

In addition, the beneficial effect of the manipulation of feeding patterns on exercise performance has also been investigated. When compared to a single bolus feeding, several small feedings have produced a more modest, sustained elevation of blood glucose and insulin rather than the characteristic fluctuations in levels of these blood constituents (Short et al., 1997). Regarding the homeostatic balance, there were fewer disturbances of hormonal homeostasis with the feeding pattern of frequent small CHO snacks (Jenkins et al., 1989). In other words, a significant economy of insulin secretion would be obtained when the frequency of CHO feeding is increased (Jenkins, 1997). Therefore, the adjustment of the feeding patterns of CHO appears to be one of the possible strategies to optimize athletic performance. The purpose of the present article is to review the effects of GI and feeding patterns on exercise performance.

Definition of Glycemic Index

According to the contemporary classification system in nutrition, CHO foods can be categorized into several different groups. Traditionally, a classification based on the structure of CHO foods has been used, and CHO foods have been...
categorized into simple and complex CHO groups. Burke et al. (1998) argued that this classification presents an inaccurate view of CHO nutrition with regards to the effect of CHO foods on the actual blood glucose and insulin responses. Considering that a mixture of CHO types and different nutrients are involved in the composition of “real” foods, classification of simple/complex CHO would be over-simplified and inaccurate. In order to avoid confusion with interpretation of the resultant metabolic and physiological responses, the use of GI is recommended in order to describe more accurately the blood glucose responses to CHO foods (Frail & Burke, 1994).

The introduction of the GI concept was more than twenty years ago by Jenkins and his colleagues (Jenkins et al., 1981). It is a system for ranking foods which is based on their actual post-prandial blood glucose response compared to a reference food, either glucose or white bread. The index is calculated by measuring the incremental area under the blood glucose curve following ingestion of a test food providing 50 g of CHO. This is compared with the area under the blood glucose curve following an equal CHO intake from the reference food. All the tests are conducted after an overnight fast. Generally, the GI reflects the overall rate of digestion and absorption of a CHO food. A CHO food carrying a high GI indicates that this food would be digested and absorbed at a faster rate than those with low GI. With regards to the GI of mixed meals, this can be predicted the glycemic indices of individual CHO foods, by taking the weighed mean of the individual GI values based on the percentage of the total meal CHO provided by each food (Foster-Powell & BrandMiller, 1995; Wolever et al., 1991). The accuracy of GI greatly reduces the variability among individuals when comparing the effect of different GI foods on exercise (Walton & Rhodes, 1997). Consequently, as the research shows, the use of GI may play an important role in planning CHO supplementation on exercise performance (Burke et al., 1998; Coyle, 1991; Hargreaves, 1991; Walton & Rhodes, 1997).

**GI of Pre-exercise Carbohydrate Feeding and Exercise Performance**

Carbohydrate availability for exercise can be optimized by manipulating the GI of CHO supplementation (Burke et al., 1998; Coyle, 1991; BrandMiller et al., 1996; Walton & Rhodes, 1997). A low GI CHO-rich meal is proposed as a suitable CHO source before prolonged exercise in order to promote the availability of the sustained CHO (Burke et al., 1998; Walton & Rhodes, 1997). In contrast, a high GI CHO-rich meal appears to be beneficial for glycogen storage after exercise by promoting greater glucose and insulin responses (Burke et al., 1998; Walton & Rhodes, 1997).

Several studies have examined the effect of GI foods on metabolism and exercise performance consumed at different times prior to the prolonged exercise. Improvements in exercise performance have been found when the low GI foods were consumed before exercise (DeMarco et al., 1999; Thomas et al., 1991). Thomas et al. (1991) raised interest in the role of the GI in sport nutrition by manipulating the glycemic response to pre-exercise CHO-rich meals. In this study, eight trained cyclists consumed one of the four test-foods 1-hr prior to cycling to exhaustion at 65–70% VO_{max}. The four test-foods were potatoes (high GI), lentils (low GI), glucose and water. Each meal provided 1.0 g · kg^{-1} body mass, except for water. It was found that the endurance time was significantly prolonged by 20-min after consumption of the low GI foods when compared with consumption of the high GI foods. Less post-prandial hyperglycemia and hyper-insulinemia have been observed after the consumption of the low GI foods when compared with high GI foods. Such metabolic and hormonal responses promoted more stable blood glucose levels and maintained free fatty acids (FFA) at higher levels during exercise. The investigators also speculated that glycogen sparing prompted by the low GI trial resulted in the improved endurance performance.

In 1999, DeMarco’s group demonstrated that a low GI meal taken 30-min before exercise can exhibit a beneficial effect on maximal performance following the sustained exercise. In this particular study, ten cyclists performed an exercise task of 2-hr cycling at 70% maximal oxygen uptake (VO_{max}) followed by cycling to exhaustion at 100% VO_{max} as a means to measure their subsequent maximal effort. Either a moderately-high GI meal or a low GI meal was consumed 30-min prior to the exercise task. The amount of CHO provided in both meals was equal to 1.5 g · kg^{-1} body mass. The exhaustion time was significantly prolonged by 59% in the low GI trial compared with the high GI trial. It was also found that the plasma insulin levels were significantly lower after the low GI meal than after the high GI meal through 20-min exercises. After the low GI meal, plasma glucose levels were higher, ratings of the perceived exertion were lower and the respiratory exchange ratio (RER) values were lower until 2-hr of exercise when compared with the high GI trial. The higher fat oxidation and possibly an increase in the availability of FFA as an energy source for exercise were supported by the lower RER values. The investigators concluded that a pre-exercise low GI meal may positively affect the maximal performance following the sustained exercise. The improvement in the subsequent maximal effort is supported by the maintenance of the higher plasma glucose levels at the end of 2-hr strenuous exercise following the consumption of the low GI meal, when results were compared with that of the high GI meal.

Although the improvements in exercise performance have been found when the low GI foods were consumed before exercise (DeMarco et al., 1999; Thomas et al., 1991), some studies demonstrated that there was no significant difference in subsequent exercise performance when comparing the consumption of the high and low GI foods (Fleblario & Stewart, 1996; Sparks et al., 1998; Stannard et al., 2000; Thomas et al., 1994; Wee et al., 1999). Thomas et al. (1994) conducted a study that repeated the protocol of their original research in 1991. Six trained cyclists consumed one of the four
respectively. Each meal provided 1.0 g CHO · kg$^{-1}$ body mass. There was no significant difference in time to exhaustion between trials. However, a correlation was observed between the GI of the meal and the depression of blood glucose and FFA concentration during exercise. The low GI meals were found to be associated with the higher glucose and FFA concentration than the high GI meals after 90-min exercises. The results suggested that the slow digestion of CHO contained in the meal prior to exercises favors the higher concentration of energy in the blood toward the end of exercises. It should be noted that the energy, fat, and protein contents of the tested four meals were not equal and therefore the confusion on the interpretation of the results may exist.

Febbraio and Stewart in 1996 conducted another study to examine the effect of GI of pre-exercise CHO ingestion on muscle metabolism and performance during the prolonged exercise. Six cyclists consumed either a high GI meal (potatoes), low GI meal (lentils), or placebo meal (low-energy jelly) 45-min prior to an exercise trial. The amount of CHO ingested in low and high GI meal was equal to 1.0 g CHO·kg$^{-1}$ body mass. During the exercise trial, individuals cycled at a workload corresponding to 70% $\text{VO}_2\text{max}$ for 120-min, followed by a 15-min performance cycle where the total work (kJ) was measured. Although differences in the pre-exercise glucose and insulin responses were found, there were no apparent differences in the blood metabolites during the steady-state exercise ride. Similar rates of muscle glycogen utilization during the submaximal cycle and total work outputs during the performance cycle were found in all trials. From the data, it was concluded that the pre-exercise CHO ingestion, while increasing CHO oxidation irrespective of the GI, does not influence the rate of muscle glycogen utilization or exercise performance.

Sparks and co-workers (1998) investigated the effect of GI of CHO ingestion 45-min prior to exercise on exercise metabolism and performance. Eight trained triathletes ingested a high GI meal (potatoes), low GI meal (lentils), or a placebo meal (low-energy soft drink) 45-min prior to an exercise task. The amount of CHO ingested was equal to 1.0 g·kg$^{-1}$ body mass. The exercise task consisted of a 50-min cycling at 67% $\text{VO}_2\text{max}$ and then a subsequent 15-min self-paced performance trial in which the total work (kJ) was measured. A greater pre-exercise blood glucose response and a decline in blood glucose concentration at the onset of exercise were observed in the high GI trial. The decline in blood glucose was not evident after a 30-min steady-state ride. However, no differences in work output during the performance trial were found even though metabolism was altered.

Recently, Wee and co-workers conducted a study in 1999 to examine the influence of high and low GI meals on endurance running capacity. They found that the GI of the meal consumed 3-hr prior to exercise does not influence the subsequent endurance capacity. Eight runners consumed either a high GI meal or a low GI meal 3-hr before a run to the exhaustion at 70% $\text{VO}_2\text{max}$. Both GI meals were isocaloric with similar macronutrients and provided 2.0 g CHO·kg$^{-1}$ body mass. There was no difference in the exhaustion run times between trials. During the first a 80-min exercise in the low GI trial, CHO oxidation was 12% lower and fat oxidation was 118% higher than those in the high GI trial. It was found that concentrations of plasma glycerol and serum FFA during exercise were higher after the consumption of the low GI meal than after the consumption of the high GI meal. The investigators found that consumption of a low GI meal 3-hr before exercise induces a relative shift in substrate utilization from CHO to fat when compared with a high GI meal, but no enhancement of endurance capacity was observed.

Moreover, Stannard and his colleagues (2000) investigated the effect of GI meals consumed 65-min before the incremental high intensity exercises on exercise performance. Ten cyclists performed an incremental cycling ride to exhaustion (load was increased by 50 watt every 3-min with an initial loading of 50 watt) 65-min after the consumption of a high GI meal (glucose), low GI meal (pasta), or a non-carbohydrate placebo. No significant difference was found in the time to exhaustion between trials. In the high GI trial, plasma glucose concentration was lower from 200-watt until exhaustion when compared with those levels in the low GI trial. Plasma lactate concentration after the consumption of the high GI meal was higher than consumption of placebo from 30-min of rest post-prandial through the end of the 200-watt workload. The results suggested that the consumption of a high GI meal 65-min prior to the exercise decreases plasma glucose and increases plasma lactate levels during exercise when compared to a low GI meal. However, these metabolic responses are not sufficient to produce a detrimental effect on the incremental exercise performance.

To summarize the studies that have been conducted to examine the influence of the consumption of GI meal before exercise, beneficial enhancement in exercise performance seemed to be apparent when the low GI foods were consumed before exercise (DeMarco et al., 1999; Thomas et al., 1991). Despite the fact that no improvement in subsequent exercise performance was found after the low GI meal compared with the high GI meal in some of the studies, a better outcome of metabolic and physiological consequence was observed from the data on blood metabolites and expired gases analyses (Febbraio & Stewart, 1996; Sparks et al., 1998; Stannard et al., 2000; Thomas et al., 1994; Wee et al., 1999). These findings indicate that the low GI foods may have a potential benefit over the high GI foods when considering the intake of CHO prior to exercises because of the promotion of the sustained CHO availability during exercises (Burke et al., 1998; Walton & Rhodes, 1997). However, the significance of using pre-exercise GI foods for feedings in determining CHO availability during exercises remains to be examined in further research.
GI of Carbohydrate Feeding during Post-exercise Recovery and Exercise Performance

Restoration of muscle glycogen content during the post-exercise recovery period is a major challenge for athletes who have busy competition and training schedules. Muscle glycogen re-synthesis following moderate-intensity exercises primarily depends on CHO intake following exercise (Robergs, 1991). Numerous studies have examined the influence of GI of CHO supplements on the restoration of muscle glycogen during the post-exercise recovery period.

In 1990, Kiens and colleagues compared the levels of muscle glycogen restoration during a 44-hr post-exercise recovery period. Individuals consumed either a CHO-rich diet based on foods with a high GI or a CHO-rich diet consisting of low GI foods after exercises. It was found that a greater storage of muscle glycogen was achieved in the high GI trial than in the low GI trial during 6-hr recovery. However, there were no differences in muscle glycogen contents between diets at 20, 32, and 44-hr recoveries. Plasma insulin levels during the first 6-hr recovery were found to be higher in the high GI trial. At all other time points, both the glucose and insulin concentrations were described interchangeably as high-GI/simple and complex/low-GI. It led to confusion with interpretation of the results. Later, Burke and colleagues (1993) examined the effect of GI of post-exercise CHO intake on the muscle glycogen storage during a 24-hr recovery period. In this study, five cyclists performed a 2-hr ride at 75% VO2max followed by four 30-s sprints on two occasions in order to deplete their muscle glycogen. For 24-hr after each trial, the cyclists rested and consumed diets of high CHO meals including either foods with a high GI or foods with a low GI. The total amount of CHO intake over the 24 hr was 10 g · kg⁻¹ body mass. Muscle biopsy data showed that the increase in muscle glycogen content after 24-hr recovery was greater with the high GI foods than with the low GI foods. Excluding the effects of the immediate post-exercise meal, the total incremental glucose and insulin areas after each meal were greater for the high GI trial than for the low GI trial.

Furthermore, Jozsi and co-workers in 1996 investigated the effect of ingesting the CHO supplements with the different GI on re-synthesis of the muscle glycogen during a 24-hr recovery period after glycogen depletion exercises. Eight endurance-trained male cyclists performed a glycogen depletion exercise and rested for 24 hr, followed by a 30-min cycling time trial. During the 24-hr recovery period, cyclists consumed glucose, maltodextrin (glucose polymer), waxy starch (100% amylopectin), or resistant starch (100% amylose). Glucose, maltodextrin and waxy starch were included in the high GI CHO-supplement whereas the resistant starch was related to a low GI value. It was found that the storage of muscle glycogen after the 24-hr recovery period was greater after the high GI CHO-supplement than after the low GI CHO-supplement. There were no differences in total work output during the subsequent time trial between treatments. The investigators suggested that the lower muscle glycogen storage after the low GI CHO-supplement may be due to the poor digestibility of the high-amylose starch mixture. The indigestible CHO forms provide a poor substrate for muscle glycogen re-synthesis, and the available CHO consumed by the subject therefore is overestimated.

Kiens and Richter (1996) examined the effect of chronic exposure to a high GI or low GI diet on the insulin action and muscle substrates. Recreationally active subjects consumed either a high GI or low GI CHO-rich diet for a period of 30-day. It was found that the muscle glycogen levels declined over the 30-day period with the low GI diet than with the high GI diet. Such observations support that the muscle glycogen storage is reduced with the low GI CHO-rich foods during the post-exercise recovery period.

According to these studies, high GI foods seem to be the desirable CHO-supplementation during the post-exercise recovery period. The consumption of the high GI foods elicits an increased rate of muscle glycogen re-synthesis compared with consumption of the low GI foods. A possible explanation for this difference is that the high GI foods excite greater substrate availability for glycogen re-synthesis. However, further studies are needed in order to expand the knowledge of the influence of GI foods on the post-exercise recovery.

Feeding Patterns of Carbohydrate and Exercise Performance

The feeding patterns of CHO intake during recovery (Burke et al., 1996; Costill et al., 1981) and prior to exercise (Short et al., 1997) on glycogen re-synthesis and subsequent exercise metabolism, respectively, have been studied. However, the question remains unanswered as to whether CHO-supplementation before and after exercise is best consumed as large feedings or as a series of snacks.

In 1981, Costill and his colleagues conducted a study to investigate the influence of the frequency of feedings of CHO consumed during the 24-hr after exercises. Four trained runners underwent an exercise task consisting of a 16.1-km run at 80% VO2max followed by five 1-min sprint runs (3-min rest intervals) at 130% VO2max. Then, after they rested for 24-hr followed with a 300-m sprint time trial in order to examine the effect of the glycogen levels after the dietary treatments on 300-m sprint performance. One hour after the 300-m sprint, runners performed a 30-min run at 70% VO2max. During the 24-hr recovery period, runners consumed high-CHO diet providing 525 g CHO in either two meals or seven feedings. Muscle biopsy data indicated that there was no difference in the muscle glycogen concentration after a 24-hr recovery period between the trials. Similar performance times and metabolic results were observed in the subsequent 300-m sprint and 30-min run in both trials. These results suggested that the frequent feedings of a high-CHO diet do not enhance the muscle glycogen storage when compared to the equal amounts of CHO diet in two meals during 24-hr recovery.
Also, no apparent dose effect is found when CHO intake is produce transient hypoglycemia near the onset of exercises. exercise, even when taken in several small feedings, can it was found that CHO consumed within an hour prior to the placebo. Drinks were divided into four portions and ingested at eight cyclists ingested 22.5, 45, 75 g CHO (maltodextrin and hypoglycemia near the onset of exercise if CHO was ingested and exercise. The main concern was put on the occurrence of acute alterations to glucose, insulin, and blood fat profiles does not adequately explain the reduced rate of glycogen storage. Further studies are needed to investigate an alternative explanation to glycogen storage. In 1997, a study was conducted by Short and colleagues to determine the influence of frequency of CHO-feedings before exercise on blood glucose and insulin responses during the rest and exercise. The main concern was put on the occurrence of hypoglycemia near the onset of exercise if CHO was ingested within an hour before exercise in small repeated feedings. Eight cyclists ingested 22.5, 45, 75 g CHO (maltodextrin and dextrose dissolved in 473 ml of water), or an equal volume of placebo. Drinks were divided into four portions and ingested at 15-min intervals in the hour before a 2-hr ride at 66% VO₂max. It was found that CHO consumed within an hour prior to the exercise, even when taken in several small feedings, can produce transient hypoglycemia near the onset of exercises. Also, no apparent dose effect is found when CHO intake is between 22.5 and 75 g during the pre-exercise period.

**Conclusion**

The manipulation of GI of CHO supplementation in optimizing athletic performance presents an exciting research area in sports nutrition. There is a body of growing evidence that supports the use of GI in planning the nutritional strategies of CHO supplementation in sports. According to the literature, a low GI CHO-rich meal appears to be a suitable CHO source before prolonged exercise in order to promote the availability of the sustained CHO during exercises (Burke et al., 1998; Walton & Rhodes, 1997). In contrast, a high GI CHO-rich meal appears to be beneficial for the glycogen storage after exercises by promoting greater glucose and insulin responses (Burke et al., 1998; Walton & Rhodes, 1997). The feeding pattern of CHO intake during a recovery and prior to exercises on glycogen resynthesis and subsequent exercise metabolism have been studied in the literature. However, studies on the subject are still limited, leaving some unanswered questions waiting for experimental evidences. The most significant question is whether CHO supplementation before and after exercise is beneficial when consumed as large feedings or as a series of snacks. Further research is needed before a conclusion can be made on the effect of feeding patterns on exercise performances.

**References**

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