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CARBOHYDRATE SUPPLEMENTATION DURING EXERCISE: DOES IT HELP? HOW MUCH IS TOO MUCH?

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KEY POINTS

- Carbohydrate intake during exercise can delay the onset of fatigue and improve performance of prolonged exercise as well as exercise of shorter duration and greater intensity (e.g., continuous exercise lasting about 1 h and intermittent high-intensity exercise), but the mechanisms by which performance is improved are different.
- During prolonged exercise, the performance benefits of carbohydrate ingestion are likely achieved by maintaining or raising plasma glucose concentrations and sustaining high rates of carbohydrate oxidation, whereas during intense exercise, carbohydrate intake seems to positively affect the central nervous system.
- Carbohydrate from a single source, such as glucose, can only be oxidized at rates of approximately 60 g/h.
- When a combination of carbohydrates is ingested (e.g., glucose and fructose) oxidation rates of slightly more than 100 g/h can be achieved if large amounts of carbohydrate are ingested (e.g., > 140 g/h).
- Ingesting a carbohydrate solution that is very concentrated and/or has a high osmolality is likely to cause gastrointestinal discomfort.
- The amount of carbohydrate an individual athlete should ingest during exercise should be determined by trial and error, and a balance should be struck between increasing carbohydrate availability during exercise and minimizing gastrointestinal distress.

INTRODUCTION

As described in more detail later in this paper, carbohydrate ingestion during long-duration exercise lasting 2 h or more nearly always delays the onset of fatigue and improves performance. Carbohydrate may also be beneficial during more intense continuous exercise lasting about 1 h and during intermittent high-intensity exercise. In long-duration exercise, a greater contribution of exogenous carbohydrate (carbohydrate ingested in beverages or other foods) will spare liver glycogen, prevent a drop in blood glucose concentration, and help maintain the high rate of carbohydrate oxidation necessary to sustain exercise intensity. However, even when carbohydrate is ingested, there is almost always a negative energy balance during exercise, i.e., the energy expenditure exceeds the energy intake. For example, it has been reported that in major cycling stage races (including the Tour de France) the riders ingest on average 25 g of carbohydrate per hour (Garcia-Roves et al., 1997). This is an energy intake of only 100 kcal/h, whereas the energy expenditure could be at least ten times that value. In extreme cases of exercise that lasts 5-6 h, this could conceivably amount to a negative energy balance of 4000-5000 kcal.

The negative energy balance developed during extremely prolonged races was traditionally compensated by an exceptionally large pre-race dinner (Jeukendrup et al., 2000a); even so, it can be difficult for some athletes to maintain energy balance (Saris et al., 1989). Of course, energy intake during the race need not be restricted to carbohydrate only; fat and protein could be ingested as well in an attempt to minimize the negative energy balance. Unfortunately, fat and protein can be potent inhibitors of gastric emptying, delaying not only the delivery of energy, but also of fluids (Brouns & Beckers, 1993). For these reasons, it makes sense to increase carbohydrate intake during exercise and thereby increase carbohydrate oxidation by exercising muscles.

However, ingesting too much carbohydrate can have detrimental effects; highly concentrated carbohydrate solutions and drinks with high osmolality have been linked to the development of gastrointestinal discomfort (Rehrer et al., 1992a). Therefore, athletes must find the appropriate balance between ingesting enough carbohydrate to provide extra energy, but not so much as to increase the risk of gastrointestinal discomfort. There are other complicating factors: the development of gastrointestinal discomfort seems to be highly individualized and is dependent on the intensity and duration of exercise, hydration status, environmental conditions, and other factors.

As discussed below, the mechanism underlying the beneficial effects of carbohydrate ingestion for exercise that lasts about 1 h and perhaps for intermittent exercise (sometimes lasting longer than 1 h) appears to be different than that for more prolonged continuous exercise and is associated with effects on the central nervous system. For exercise of shorter duration, lesser amounts of ingested carbohydrate are required compared to more prolonged exercise. As with prolonged exercise, there is a potential for gastrointestinal distress if an athlete ingests too much carbohydrate during high-intensity exercise.

The major purpose of this article is to provide a brief review of the scientific literature related to the effects of carbohydrate intake on performance and the optimal dose and type of carbohydrate ingested during exercise. Attention is also given to the metabolism of ingested carbohydrate, gastrointestinal disturbances during prolonged exercise, the relationship between carbohydrate intake and fluid delivery, and the possibility that carbohydrate ingestion during exercise might adversely affect genetic adaptations to physical training.

RESEARCH REVIEW

Effects of Carbohydrate Intake on Performance

The beneficial effects of carbohydrate feeding on exercise performance have been well described. In older studies, the ergogenic effects of carbohydrate feeding were typically seen during exercise lasting at least 2 h (Bjorkman et al., 1984; Coyle et al., 1983; Hargreaves et al., 1984; Ivy et al., 1983; Murray et al., 1989; Neufer et al., 1987). More recent studies have found positive effects of carbohydrate feeding during exercise of relatively high intensity (>75% VO_2max) lasting approximately 1 h (Anantaraman et al., 1995; Below et al., 1995; Carter et al., 2003; el-Sayed et al., 1997). As an example, Jeukendrup et al. (1997) investigated the effects of carbohydrate ingestion during the equivalent of a 40-km time trial (~ 1 h) in well-trained cyclists and found that performance was improved by 2.3%. However, it should also be noted that some investigators were unable to detect an ergogenic effect of carbohydrate feedings for high-intensity exercise (Clark et al., 2000; McConell et al., 2000; Powers et al., 1990). Carter and colleagues (2004b) concluded that any beneficial effect was unrelated to substrate availability because glucose infusion at high rates did not affect performance; rather, this group suggested that the effects might operate via the central nervous system (Jeukendrup et al., 1997).

Consistent with this idea, our laboratory showed that rinsing the mouth with a carbohydrate solution improved cycling performance during a 1-h time trial by 2-3% even when the subjects did not actually swallow the carbohydrate (Carter et al., 2004a). This performance improvement was of the same magnitude as that seen with carbohydrate ingestion during a similar exercise task (Jeukendrup et al., 1997). These results suggest the existence of receptors in the mouth that communicate with the brain to affect exercise performance. Although direct evidence for such receptors is lacking, it is clear that the brain can sense changes in the composition of the contents of the mouth and stomach. Oropharyngeal receptors, including those situated in the oral cavity, are known to have important roles in perceptual responses during rehydration and exercise in the heat (Maresh et al., 2001; Riebe et al., 1997). In these studies, ratings of perceived exertion (RPE) and thirst sensations were lower when fluid intake was by mouth compared to infusing fluids intravenously. These findings are supported by reports of temporary reductions in thirst due to the gargling of tap water (Seckl et al., 1986). Although speculative, it is possible that triggering of stimuli within the oral cavity by the carbohydrate solution could initiate a chain of neural messages in the central nervous system, resulting in the stimulation of the reward and/or pleasure centers in the brain.

It must be noted that maximal continuous exercise lasting less than 45 min may not benefit from carbohydrate feeding (Palmer et al., 1998). At such high exercise intensities, other factors may override a possible beneficial central effect of carbohydrate. Relatively few studies have been conducted using exercise durations less than 1 h, so additional work in this area is needed. However, some laboratories have observed positive effects of carbohydrate drinks on high-intensity intermittent exercise using a shuttle run as a model for team sports such as basketball and soccer (Davis et al., 1999; Nicholas et al., 1995; Welsh et al., 2002).

Although central mechanisms might play a role in enhancing performance during exercise lasting approximately 1 h, the long-established mechanism during more prolonged exercise remains the maintenance of blood glucose concentrations and relatively high rates of carbohydrate oxidation. Once the effect of carbohydrate on endurance performance had been established in the 1980s, the next obvious objective was to determine the optimal dose.

The Optimal Dose

There are only a few published reports of the effects of different doses of carbohydrate on exercise performance. Mitchell and co-workers (1989) compared ingestion of 37 g, 74 g, or 111 g of carbohydrate per hour (6%, 12%, and 18% carbohydrate solutions, respectively) or flavored water. Compared to water, only the trial using 74 g of carbohydrate per hour significantly enhanced the performance of a 12-min isokinetic cycling time-trial following 105 min of continuous exercise. However, all of the performance results for the three carbohydrate trials were statistically similar. In an earlier investigation using a similar isokinetic performance ride, but following 105 min of intermittent exercise, the same authors found improved performance compared to a water trial for 5%, 6% and 7.5% carbohydrate solutions (33, 40, and 50 g/h, respectively), with no significant differences among the carbohydrate trials (Mitchell et al., 1988). However, in this study both the amount and type of carbohydrate ingested were varied.

A study by Fielding and colleagues (1985) is often used to claim that a minimum of 22 g of carbohydrate per hour is required to achieve a performance benefit. In that study, subjects performed a cycling sprint after having exercised for 4 h. Performance improvements were observed when 22 g of carbohydrate were ingested every hour, whereas no effects were observed when half this dose was consumed (11 g/h). But in an experiment reported by Maughan's group (1996), the intake of 16 g of glucose per hour improved endurance capacity by 14% compared with water. (However, no placebo was given in this study). To add to the uncertainty, Flynn and colleagues (1987) did not find any differences in performance with the ingestion of placebo, 5%, or 10% carbohydrate solutions that provided 0, 15, and 30 g of carbohydrate per hour, respectively, during 2 h of cycling.

The majority of studies provided 40-75 g of carbohydrate per hour and observed performance benefits. Ingesting carbohydrate from a single source, e.g., glucose or maltodextrins, at a rate greater than 60-70 g/h does not appear to be any more effective at improving performance than ingesting carbohydrate at 60-70 g/h, perhaps, as discussed later, because of limitations in the rate of absorption of a single type of carbohydrate from the intestine. It is also possible that the current performance measurements are not sensitive enough to pick up the small differences in performance that may exist when comparing different carbohydrate solutions.

One might conclude that performance benefits can sometimes be observed with the ingestion of relatively small amounts of carbohydrate, e.g., 16 g/h, but more reliably with greater amounts. If carbohydrate ingestion is to improve endurance performance, it is likely that the beneficial effect is primarily dependent on the oxidation of that carbohydrate.

Oxidation of Ingested Carbohydrate

Several factors can influence the oxidation of exogenous carbohydrate supplied in liquid and solid foods, including feeding schedule, type and amount of carbohydrate ingested, and the exercise intensity. These factors independently affect the rate of carbohydrate oxidation.

Type of single-source carbohydrate. Some types of carbohydrate from a single source are oxidized more readily than others (Jeukendrup et al., 2000b). They can be divided into two arbitrary categories: carbohydrates that can be oxidized at rates up to approximately 30 g/h and up to 60 g/h (Table 1).

TABLE 1. *Oxidation of different carbohydrates*

Rapidly Oxidized Carbohydrates (~60 g/h)

- Glucose (a sugar formed by the breakdown of starch)
- Sucrose (table sugar—glucose plus fructose)
- Maltose (two glucose molecules)
- Maltodextrins (from starch breakdown)
- Amylopectin (from starch breakdown)

Slowly Oxidized Carbohydrates (~30 g/h)

- Fructose (a sugar found in honey, fruits, etc.)
- Galactose (a sugar found in sugar beets)
- Isomaltulose (a sugar found in honey and sugarcane)
- Trehalose (a sugar found in microorganisms)
- Amylose (from starch breakdown)

Amount of carbohydrate. The optimal amount of ingested carbohydrate should ideally be the amount that results in the maximal rate of exogenous carbohydrate oxidation without causing gastrointestinal discomfort. Rehrer et al. (1992b) studied the oxidation of different amounts of carbohydrate ingested during 80 min of cycling exercise at 70%VO_2max. Subjects received either a 4.5% glucose solution (a total of 58 g glucose during 80 min of exercise) or a 17% glucose solution (220 g during 80 min of exercise). Total exogenous carbohydrate oxidation was only slightly higher with the larger dose of carbohydrate (42 g versus 32 g in 80 min). Even though the amount of carbohydrate ingested was increased almost four-fold, the oxidation rate was hardly affected. Jeukendrup et al. (1999) investigated even larger carbohydrate intakes (up to 180 g/h) and found that oxidation rates peaked at 56 g/h at the end of 120 min of cycling exercise. These results suggest some sort of limitation in the maximal rate of oxidation of ingested carbohydrates.

Based on the scientific literature in this area, it must be concluded that the maximal rate at which a single source of ingested carbohydrate can be oxidized is about 60-70 g/h (Figure 1). Although the vast majority of studies was performed with men, the same conclusion seems to hold true for endurance-trained women, i.e., the highest rates of exogenous glucose oxidation and the greatest endogenous carbohydrate sparing were observed when carbohydrate was ingested at moderate rates (60 g/h) during exercise (Wallis et al., 2007). This knowledge implies that athletes who ingest a single type of carbohydrate should ingest about 60-70 g/h for optimal carbohydrate delivery. Ingesting more than this will not increase carbohydrate oxidation rates any further and is likely to be associated with gastrointestinal discomfort.

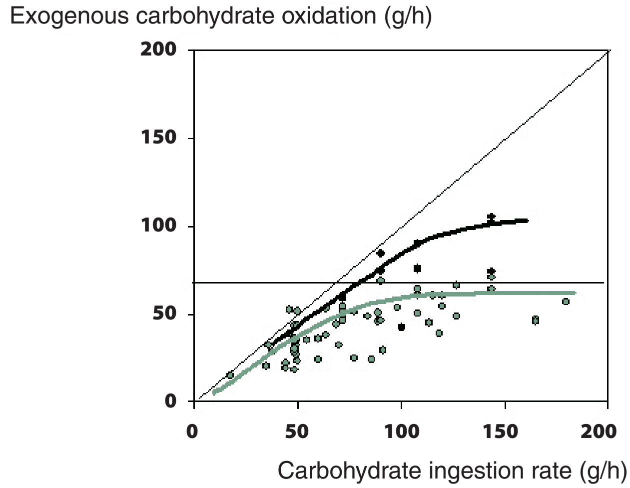

FIGURE 1. ***Oxidation of ingested carbohydrate.*** This figure is modified from Jeukendrup (2004) and is compiled from studies investigating the oxidation of exogenous (ingested) carbohydrate during exercise. The oxidation rate is plotted as a function of the ingestion rate. In green are the values from studies in which a single type of carbohydrate was studied. In black are the oxidation rates from combinations of multiple carbohydrates. The green line is an estimation of the average from all studies of single carbohydrates and the black line for multiple transportable carbohydrates. As the amount ingested increases, the oxidation rate also increases, but only up to a certain point. Ingesting more than 60-70 g/h of a single carbohydrate source does not further increase the rate of oxidation of that carbohydrate, and the excess carbohydrate is likely to accumulate in the intestine. However, if multiple carbohydrates are ingested at high rates, greater maximal rates of exogenous carbohydrate oxidation can be achieved, perhaps because multiple carbohydrates stimulate multiple transport mechanisms to transfer carbohydrate from the intestine into the blood and thereby increase carbohydrate delivery to muscles.

Multiple transportable carbohydrates. As reviewed by Jeukendrup (2004), it is likely that oxidation of a single exogenous carbohydrate is limited to approximately 60 g/h because there is a limitation in the rate of intestinal absorption of that carbohydrate. It is suggested that by feeding a single carbohydrate source (e.g., glucose or fructose or maltodextrins) at high rates, the specific transporter proteins that aid in absorbing that carbohydrate from the intestine become saturated. Once these transporters are saturated, feeding more of that carbohydrate will not result in greater intestinal absorption and increased oxidation rates.

In 1995, Shi et al. suggested that the ingestion of carbohydrates that use different transporters might increase total carbohydrate absorption. Subsequently, we began a series of studies using different combinations of carbohydrates to determine their effects on exogenous carbohydrate oxidation. In the first study, subjects ingested a drink containing glucose and fructose (Jentjens et al., 2004a). Glucose was ingested at a rate of 72 g/h and fructose at a rate of 36 g/h. In the control trials, the subjects ingested glucose at a rate of 72 g/h and 108 g/h (matching glucose intake or energy intake). We found that the ingestion of glucose at a rate of 72 g/h resulted in oxidation rates of about 48 g/h. Ingesting glucose at 108 g/h did not increase the oxidation rate. However, after ingesting glucose plus fructose, the rate of total exogenous carbohydrate oxidation increased to 76 g/h, an increase in oxidation of 45% compared with a similar amount of glucose. In the following years, we tried different combinations and amounts of carbohydrates in an attempt to determine the maximal rate of oxidation of mixtures of exogenous carbohydrates (Jentjens et al., 2004abc, 2005ab, 2006; Wallis et al., 2007). We observed very high oxidation rates with combinations of glucose plus fructose, with maltodextrins plus fructose, and with glucose plus sucrose plus fructose. The highest rates were observed with a mixture of glucose and fructose ingested at a rate of 144 g/h. With this feeding regimen, exogenous carbohydrate oxidation peaked at 105 g/h. This is 75% greater than what was previously thought to be the absolute maximum.

The increased oxidation resulting from the ingestion of multiple types of carbohydrate is theoretically beneficial, although considerably more research needs to be accomplished in this area. From a study in which subjects cycled for 5 h at 50% of their maximal work rates (~58% VO_2max) with water, glucose, or glucose plus fructose, we saw some indication that ingesting multiple carbohydrates may result in greater improvements in performance (Jeukendrup et al., 2006). In this study, carbohydrate was ingested at a rate of 90 g/h. The first indication of improved performance was that the subjects' ratings of perceived exertion (RPE) tended to be lower with the mixture of glucose and fructose compared with glucose alone; the water placebo treatment produced the greatest RPE values. In fact, not all participants were able to complete the 5-h ride when they drank the water placebo. In addition, the self-selected cadence dropped significantly with water, which is generally acknowledged as an indication of developing fatigue. With glucose, cycling cadence was somewhat greater than with water, but with glucose plus fructose, cadence was highest and remained almost unchanged from the beginning of exercise. We have since confirmed the beneficial effects on prolonged exercise performance of drinking solutions of glucose plus fructose compared with glucose only (K. Currell et al., unpublished findings).

We introduced the term *oxidation efficiency* to describe the percentage of the ingested carbohydrate that is oxidized (Jeukendrup et al., 2000b). High oxidation efficiency means that smaller amounts of carbohydrate remain in the gastrointestinal tract, reducing the risk of causing gastrointestinal discomfort that is frequently reported during prolonged exercise (Brouns & Beckers, 1993; Rehrer et al., 1992a). Importantly, in our studies, the oxidation efficiency of drinks containing carbohydrates that use different transporters for intestinal absorption was higher than for drinks with a single carbohydrate source. Therefore, compared to a single source of carbohydrate, ingesting multiple carbohydrate sources results in a smaller amount of carbohydrate remaining in the intestine, and osmotic shifts and malabsorption may be reduced. This probably means that drinks with multiple transportable carbohydrates are less likely to cause gastrointestinal discomfort. Interestingly, this is a consistent finding in studies that have attempted to evaluate gastrointestinal discomfort during exercise (Jentjens et al., 2004abc, 2005b, 2006; Wallis et al., 2007). Subjects tended to feel less bloated with the glucose plus fructose drinks compared to drinking glucose solutions. A larger-scale study of the effects of drinks with different types of carbohydrates on gastrointestinal discomfort has not yet been published.

Exercise intensity. With increasing exercise intensity, the active muscle mass becomes progressively more dependent on carbohydrate as a source of energy. However, the oxidation of exogenous carbohydrate seems to remain constant at intensities of 50-60% VO_2max or greater (Pirnay et al., 1982).

Gastrointestinal Discomfort During Exercise

Gastrointestinal discomfort is very common during exercise, especially in endurance and ultra-endurance sports. Peters et al. (1999) mailed a questionnaire to 606 athletes (runners, cyclists and triathletes) to assess the prevalence of gastrointestinal problems as well as their training background and nutrition habits. Symptoms presumably originating in the upper gastrointestinal tract (nausea, vomiting, belching, heartburn, chest pain) and in the lower gastrointestinal tract (bloating, abdominal cramps, side ache, urge to defecate, and diarrhea) were evaluated in all participants. For all subjects, 45-79% reported symptoms of lower gastrointestinal distress, and 36-67% had upper gastrointestinal symptoms. Symptoms generally seem to be more severe during running than cycling, are more prevalent in women than in men, and seem to be more frequent in prolonged exercise. For example, in an extreme long-distance triathlon event, 93% of the participants reported some type of gastrointestinal disturbance, and 45% of these problems were classified as serious (Jeukendrup et al., 2000c).

The occurrence of gastrointestinal disturbances has been related to carbohydrate intake during exercise (Brouns & Beckers, 1993). A relatively high intake of carbohydrate during exercise may increase the incidence of gastrointestinal symptoms such as diarrhea and abdominal cramps, either by the osmotic attraction of fluid from the blood into the intestine (Brouns & Beckers, 1993) or by malabsorption. The fact that mesenteric blood flow to the intestines is reduced during high-intensity exercise and even more with dehydration (Brouns & Beckers, 1993) might explain the fact that symptoms seem to be more prevalent if exercise is more prolonged and performed in hot conditions. Although the occurrence of gastrointestinal distress has been related to carbohydrate intake during exercise, this may be more related to the hyperosmolality of solutions than the actual carbohydrate content (Rehrer et al., 1992). In fact, in a laboratory study, 7% hypotonic carbohydrate drinks did not result in significantly greater discomfort during 2.5 h of running and cycling compared with water (Peters et al., 2000). Although direct evidence is lacking, it is likely that carbohydrate ingested at very high rates (>60 g/h), which almost certainly results in hyperosmolality of the stomach contents, will cause an increased incidence of gastrointestinal problems. It is also likely, however, that the gastrointestinal discomfort associated with a particular source or sources of carbohydrate is mainly dictated by the oxidation efficiency of the carbohydrate. It is therefore tempting to speculate that multiple transportable carbohydrates ingested at high rates will be associated with reduced gastrointestinal discomfort while providing carbohydrate at high rates. The tolerance of athletes for large doses of various carbohydrate drinks and the likelihood that an athlete will develop gastrointestinal discomfort seem highly individualized. Therefore, strategies for carbohydrate intake should always be developed on an individual basis, largely by trial and error.

Carbohydrate and Fluid Delivery

Another reason to avoid the intake of highly concentrated carbohydrate solutions is that such solutions have been shown to delay gastric emptying and fluid absorption. But impairment of fluid delivery is minimized when combinations of multiple transportable carbohydrates are ingested. We found that fluid delivery with a solution of glucose plus fructose is greater than with a glucose solution (Jentjens et al., 2006). Both of these carbohydrate solutions contained about 15 g of carbohydrate per 100 ml (i.e., a 15% carbohydrate solution), and such highly concentrated carbohydrate solutions would normally result in severely impaired fluid delivery. Interestingly, the rate of fluid delivery to the blood with the glucose-plus-fructose drink was closer to that of plain water than it was to glucose. Nevertheless, in hot, humid environments, especially at relatively low exercise intensities, fluid delivery is more important than carbohydrate delivery, and athletes should consume less-concentrated carbohydrate solutions.

Carbohydrate needs in endurance athletes are fairly constant in different environmental conditions, although carbohydrate oxidation rates are somewhat increased in the heat. This increased carbohydrate oxidation is mainly from muscle glycogenolysis, and the contribution from exogenous carbohydrate may actually be decreased (Jentjens et al., 2002). The most logical explanation for this decrease is a redistribution of blood flow to the skin and muscle, with a reduction in blood flow to the intestines. This redistribution of blood would presumably adversely affect carbohydrate absorption. However, combinations of multiple carbohydrates can at least partly overcome this problem, and high rates of exogenous carbohydrate oxidation can be achieved even in these hot conditions (Jentjens et al., 2002).

Does Carbohydrate Ingestion Impair Metabolic Adaptations to Training?

Civitarese et al. (2005) suggested that carbohydrate ingestion during exercise may suppress the gene expression of oxidative enzymes involved in fat metabolism and might therefore interfere with the process of training adaptations that involve a greater reliance on fat metabolism for energy. They showed that the transcription of several genes related to fat metabolism is transiently induced after exercise when no feeding is provided during exercise and that glucose feeding interfered with these adaptations. Moreover, Cluberton et al. (2005) demonstrated that glucose ingestion attenuated the exercise-induced increase in other enzymes involved in energy metabolism and of certain types of messenger RNA. However, there may be a flaw in extrapolating these results to practical implications for the athlete; carbohydrate ingestion may allow the athlete to train harder, which would then most likely result in enhanced transcription of metabolic genes. So it may be too early to provide practical advice based on the small number of laboratory studies currently published (Hawley et al., 2006).

SUMMARY

Although carbohydrate ingestion can improve exercise performance, consuming large amounts of carbohydrate is not necessarily a good strategy. Carbohydrate from a drink or food will spare liver glycogen, increase carbohydrate oxidation by muscle, and positively impact certain central nervous system responses, but ingesting too much carbohydrate can have detrimental effects. Highly concentrated carbohydrate solutions and drinks with high osmolality have been linked to the development of gastrointestinal discomfort. It therefore appears that there is a fine balance between ingesting optimal amounts of carbohydrate that can be oxidized for energy while at the same time avoiding gastrointestinal discomfort that can lead to poor performance.

REFERENCES

Anantaraman, R., A. A. Carmines, G. A. Gaesser, and A. Weltman (1995). Effects of carbohydrate supplementation on performance during 1 h of high intensity exercise. *Int. J. Sports Med.* 16(7):461-465.

Below, P. R., R. Mora-Rodriguez, J. Gonzales Alonso, and E. F. Coyle (1995). Fluid and carbohydrate ingestion independently improve performance during 1 h of intense exercise. *Med. Sci. Sports Exerc.* 27(2):200-210.

Bjorkman, O., K. Sahlin, L. Hagenfeldt, and J. Wahren (1984). Influence of glucose and fructose ingestion on the capacity for long term exercise in well trained men. *Clin. Physiol.* 4:483-494.

Brouns, F., and E. Beckers (1993). Is the gut an athletic organ? Digestion, absorption and exercise. *Sports Med.* 15(4): 242-257.

Carter, J., A. E. Jeukendrup, T. Mundel, and D. A. Jones (2003). Carbohydrate supplementation improves moderate and high-intensity exercise in the heat. *Pflugers Arch.* 446(2):211-219.

Carter, J. M., A. E. Jeukendrup, and D. A. Jones (2004a). The effect of carbohydrate mouth rinse on 1-h cycle time trial performance. *Med. Sci. Sports Exerc.* 36(12):2107-2111.

Carter, J. M., A. E. Jeukendrup, C. H. Mann, and D. A. Jones (2004b). The effect of glucose infusion on glucose kinetics during a 1-h time trial. *Med. Sci. Sports Exerc.* 36(9):1543-1550.

Clark, V. R., W. G. Hopkins, J. A. Hawley, and L. M. Burke (2000). Placebo effect of carbohydrate feedings during a 40-km cycling time trial. *Med. Sci. Sports Exerc.* 32(9):1642-1647.

Cluberton, L. J., S. L. McGee, R. M. Murphy, and M. Hargreaves (2005). Effect of carbohydrate ingestion on exercise-induced alterations in metabolic gene expression. *J. Appl. Physiol.* 99:1359-1363.

Coyle, E. F., J. M. Hagberg, B. F. Hurley, W. H. Martin, A. A. Ehsani, and J. O. Holloszy (1983). Carbohydrate feeding during prolonged strenuous exercise. *J. Appl. Physiol.* 55(1):230-235.

Davis, J.M., R.S. Welsh, K.L. De Volve, and N.A. Alderson (1999). Effects of branched-chain amino acids and carbohydrate on fatigue during intermittent, high-intensity running. *Int. J. Sports Med.* 20(5):309-314.

el-Sayed, M. S., J. Balmer, and A. J. Rattu (1997). Carbohydrate ingestion improves endurance performance during a 1 h simulated time trial. *J. Sports Sci.* 15(2):223-230.

Fielding, R. A., D. L. Costill, W. J. Fink, D. S. King, M. Hargreaves, and J. E. Kovaleski (1985). Effect of carbohydrate feeding frequencies and dosage on muscle glycogen use during exercise. *Med. Sci. Sports Exerc.* 17(4):472-476.

Flynn, M. G., D. L. Costill, J. A. Hawley, W. J. Fink, P. D. Neufer, R. A. Fielding, and M. D. Sleeper (1987). Influence of selected carbohydrate drinks on cycling performance and glycogen use. *Med. Sci. Sports Exerc.* 19(1):37-40.

Garcia-Roves, P., N. Terrados, S. Fernandez, and A. Patterson (1997). Macronutrients intake of top level cyclists during continuous competition-change in the feeding pattern. *Int. J. Sports Med.* 19:61-67.

Hargreaves, M., D. L. Costill, A. Coggan, W. J. Fink, and I. Nishibata (1984). Effect of carbohydrate feedings on muscle glycogen utilisation and exercise performance. *Med. Sci. Sports Exerc.* 16(3):219-222.

Hawley, J. A., K. D. Tipton, and M. L. Millard-Stafford (2006). Promoting training adaptations through nutritional interventions. *J. Sports Sci.* 24(7):709-721.

Ivy, J. L., W. Miller, V. Dover, L. G. Goodyear, W. M. Sherman, S. Farrell, and H. Williams (1983). Endurance improved by ingestion of a glucose polymer supplement. Med. Sci. Sports Exerc. 15(6):466-471.

Jentjens, R. L., A. J. Wagenmakers, and A. E. Jeukendrup (2002). Heat stress increases muscle glycogen use but reduces the oxidation of ingested carbohydrates during exercise. *J. Appl. Physiol.* 92(4):1562-1572.

Jentjens, R. L., L. Moseley, R. H. Waring, L. K. Harding, and A. E. Jeukendrup (2004a). Oxidation of combined ingestion of glucose and fructose during exercise. *J. Appl. Physiol.* 96(4):1277-1284.

Jentjens, R. L., M. C. Venables, and A. E. Jeukendrup (2004b). Oxidation of exogenous glucose, sucrose, and maltose during prolonged cycling exercise. *J. Appl. Physiol.* 96(4):1285-1291.

Jentjens, R. L., and A. E. Jeukendrup (2005a). High rates of exogenous carbohydrate oxidation from a mixture of glucose and fructose ingested during prolonged cycling exercise. *Br. J. Nutr.* 93(4):485-492.

Jentjens, R. L., C. Shaw, T. Birtles, R. H. Waring, L. K. Harding, and A. E. Jeukendrup (2005b). Oxidation of combined ingestion of glucose and sucrose during exercise. *Metabolism* 54(5):610-618.

Jentjens, R. L., K. Underwood, J. Achten, K. Currell, C. H. Mann, and A. E. Jeukendrup (2006). Exogenous carbohydrate oxidation rates are elevated after combined ingestion of glucose and fructose during exercise in the heat. *J. Appl. Physiol.* 100(3):807-816.

Jentjens, R. L. P. G., J. Achten, and A. E. Jeukendrup (2004c). High oxidation rates from combined carbohydrates ingested during exercise. *Med. Sci. Sports Exerc.* 36(9):1551-1558.

Jeukendrup, A., F. Brouns, A. J. Wagenmakers, and W. H. Saris (1997). Carbohydrate-electrolyte feedings improve 1 h time trial cycling performance. *Int. J. Sports Med.* 18(2):125-129.

Jeukendrup, A. E., A. J. Wagenmakers, J. H. Stegen, A. P. Gijsen, F. Brouns, and W. H. Saris (1999). Carbohydrate ingestion can completely suppress endogenous glucose production during exercise. *Am. J. Physiol.* 276(4 Pt 1): E672-E683.

Jeukendrup, A. E., N. P. Craig, and J. A. Hawley (2000a). The bioenergetics of World Class Cycling. *J. Sci. Med. Sport* 3(4):414-433.

Jeukendrup, A. E., and R. Jentjens (2000b). Oxidation of carbohydrate feedings during prolonged exercise: current thoughts, guidelines and directions for future research. *Sports Med.* 29(6):407-24.

Jeukendrup, A. E., K. Vet-Joop, A. Sturk, J. H. Stegen, J. Senden, W. H. Saris, and A. J. Wagenmakers (2000c). Relationship between gastro-intestinal complaints and endotoxaemia, cytokine release and the acute-phase reaction during and after a long- distance triathlon in highly trained men. *Clin. Sci. (Colch)* 98(1):47-55.

Jeukendrup, A. E. (2004). Carbohydrate intake during exercise and performance. *Nutrition* 20(7-8):669-677.

Jeukendrup, A. E., L. Moseley, G. I. Mainwaring, S. Samuels, S. Perry, and C. H. Mann (2006). Exogenous carbohydrate oxidation during ultraendurance exercise. *J. Appl. Physiol.* 100(4):1134-1141.

Maresh, C. M., J. A. Herrera-Soto, L. E. Armstrong, D. J. Casa, S. A. Kavouras, F. T. Hacker, Jr., T. A. Elliott, J. Stoppani, and T. P. Scheett (2001). Perceptual responses in the heat after brief intravenous versus oral rehydration. *Med. Sci. Sports Exerc.* 33(6):1039-1045.

Maughan, R. J., L. R. Bethell, and J. B. Leiper (1996). Effects of ingested fluids on exercise capacity and on cardiovascular and metabolic responses to prolonged exercise in man. *Exp. Physiol.* 81(5):847-859.

McConell, G. K., B. J. Canny, M. C. Daddo, M. J. Nance, and R. J. Snow (2000). Effect of carbohydrate ingestion on glucose kinetics and muscle metabolism during intense endurance exercise. *J. Appl. Physiol.* 89(5):1690-1698.

Mitchell, J. B., D. L. Costill, J. A. Houmard, W. J. Fink, D. D. Pascoe, and D. R. Pearson (1989). Influence of carbohydrate dosage on exercise performance and glycogen use. *J. Appl. Physiol.* 67(5):1843-1849.

Murray, R., J. G. Seifert, D. E. Eddy, G. L. Paul, and G. A. Halaby (1989). Carbohydrate feeding and exercise: effect of beverage carbohydrate content. *Eur J. Appl. Physiol.* 59:152-158.

Neufer, P. D., D. L. Costill, M. G. Flynn, J. P. Kirwan, J. B. Mitchell, and J. Houmard (1987). Improvements in exercise performance: effects of carbohydrate feedings and diet. *J. Appl. Physiol.* 62(3): 983-988.

Nicholas, C.W., C. Williams, H.K. Lakomy, G. Phillips, and A. Nowitz (1995). Influence of ingesting a carbohydrate-electrolyte solution on endurance capacity during intermittent, high-intensity shuttle running. *J. Sports Sci.* 13(4):283-290.

Palmer, G. S., M. C. Clancy, J. A. Hawley, I. M. Rodger, L. M. Burke, and T. D. Noakes (1998). Carbohydrate ingestion immediately before exercise does not improve 20km time trial performance in well trained cyclists. *Int. J. Sports Med.* 19:415-418.

Peters, H. P., M. Bos, L. Seebregts, L. M. Akkermans, G. P. van Berge Henegouwen, E. Bol, W. L. Mosterd, and W. R. de Vries (1999). Gastrointestinal symptoms in long-distance runners, cyclists, and triathletes: prevalence, medication, and etiology. *Am J. Gastroenterol.* 94(6):1570-1581.

Peters, H. P., J. W. Wiersma, J. Koerselman, L. M. Akkermans, E. Bol, W. L. Mosterd, and W. R. de Vries (2000). The effect of a sports drink on gastroesophageal reflux during a run-bike-run test. *Int. J. Sports Med.* 21(1):65-70.

Pirnay, F., J. M. Crielaard, N. Pallikarakis, M. Lacroix, F. Mosora, G. Krzentowski, A. S. Luyckx, and P. J. Lefebvre (1982). Fate of exogenous glucose during exercise of different intensities in humans. *J. Appl. Physiol.* 53:1620-1624.

Powers, S. K., J. Lawler, S. Dodd, R. Tulley, G. Landry, and K. Wheeler (1990). Fluid replacement drinks during high intensity exercise: effects on minimizing exercise-induced disturbances in homeostasis. *Eur. J. Appl. Physiol.* 60:54-60.

Rehrer, N. J., M. van Kemenade, W. Meester, F. Brouns, and W. H. M. Saris (1992a). Gastrointestinal complaints in relation to dietary intake in triathletes. *Int. J. Sport Nutr.* 2:48-59.

Rehrer, N. J., A. J. M. Wagenmakers, E. J. Beckers, D. Halliday, J. B. Leiper, F. Brouns, R. J. Maughan, K. Westerterp, and W. H. M. Saris (1992b). Gastric emptying, absorption and carbohydrate oxidation during prolonged exercise. *J. Appl. Physiol.* 72(2):468-475.

Riebe, D., C. M. Maresh, L. E. Armstrong, R. W. Kenefick, J. W. Castellani, M. E. Echegaray, B. A. Clark, and D. N. Camaione (1997). Effects of oral and intravenous rehydration on ratings of perceived exertion and thirst. *Med. Sci. Sports Exerc.* 29(1):117-24.

Saris, W. H. M., M. A. van Erp-Baart, F. Brouns, K. R. Westerterp, and F. ten Hoor (1989). Study on food intake and energy expenditure during extreme sustained exercise: the Tour de France. *Int. J. Sports Med.* 10(suppl.1):S26-S31.

Seckl, J. R., T. D. Williams, and S. L. Lightman (1986). Oral hypertonic saline causes transient fall of vasopressin in humans. *Am J. Physiol.* 251(2 Pt 2):R214-R217.

Wallis, G. A., S. E. Yeo, A. K. Blannin, and A. E. Jeukendrup (2007). Dose-response effects of ingested carbohydrate on exercise metabolism in women. *Med. Sci. Sports Exerc.* 39(1):131-138.

Welsh, R. S., J. M. Davis, J. R. Burke, and H. G. Williams (2002). Carbohydrates and physical/mental performance during intermittent exercise to fatigue. *Med. Sci. Sports Exerc.* 34(4):723-731.

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SUPPLEMENT

OPTIMIZING CARBOHYDRATES DURING EXERCISE

THE BENEFITS of consuming carbohydrates during endurance exercise are well known, but what is the optimal type and amount of carbohydrate intake? Too much or the wrong type of carbohydrate can cause bloating, nausea, and other symptoms of digestive disturbances; too little will have no real benefit to your performance. Table 1 provides recommendations for the optimal types and amounts of carbohydrate to be consumed for various types of exercise. Note that extreme endurance events like the Tour de France require fairly large amounts of carbohydrate to maintain energy balance. If the athlete is not careful, consuming these large amounts of carbohydrate could cause digestive problems. Combinations of carbohydrates (glucose and fructose for example) ingested at high rates seem to minimize the negative side effects and optimize carbohydrate delivery in these situations.

EVENT	Energy Cost	Recommended Intake of Carbohydrate for Optimal Performance	Carbohydrate Type
Maximal Exercise Lasting Less Than 45 min (Cycling sprints; Most swimming events; Most running events – including 10-km run)	>18 kcal/min	None required	
Maximal Exercise Lasting About 45-60 min (Cycling: 1-km time trial; Intense basketball game; Soccer: one period)	14-18 kcal/min	Less than 30 g/h	Glucose, sucrose, maltose, maltodextrins, amylopectin, fructose, galactose, isomaltulose, trehalose, amylose
Team Sports Lasting ~90 min (Soccer match)	5-10 kcal/min	Up to 50 g/h	Glucose, sucrose, maltose, maltodextrins, amylopectin, fructose, galactose, isomaltulose, trehalose, amylase
Submaximal Exercise Lasting More Than 2 h (Recreational tennis match; Recreational cycling; Hiking and orienteering)	5-7 kcal/min	Up to 60 g/h	Glucose, sucrose, maltose, maltodextrins, amylopectin, fructose, galactose, isomaltulose, trehalose, amylose
Near-Maximal & Maximal Exercise Lasting More Than 2 h (Marathon run; Cycling: Individual pursuit; Competitive tennis match; 50-km ski race)	7-10 kcal/min	50- 70 g/h	Glucose, sucrose, maltose, maltodextrins, amylopectin
Ironman Triathlon, Tour de France Stage Races	10-14 kcal/min	60-90 g/h	May only be achieved by intake of multiple types of carbohydrate: glucose, fructose, sucrose, maltodextrins, amylopectin, etc.

Strategies for Ingesting Carbohydrate

When? Carbohydrate ingestion often can enhance performance during exercise of 45 min or longer. So to maintain or improve the quality of a training session or to enhance your performance in competition, consuming some form of carbohydrate will probably help. If it is logistically possible in your event, you should consume a carbohydrate-containing sports drink every 15-20 minutes. Otherwise, you should drink during recovery periods or breaks in the training session or competition.

What Type of Carbohydrate? Some types of carbohydrates deliver energy at higher rates than others. The greatest rates of energy delivery occur when you ingest a combination of two or more types of carbohydrates. Examples of suitable combinations include maltodextrins and fructose, glucose and fructose, or glucose, sucrose and fructose.

How Much Carbohydrate? How much you ingest depends on a number of factors, including:

- The intensity and duration of exercise (See Table 1)
- The type of carbohydrate (or combination of carbohydrates)
- Your individual tolerance for various volumes and concentrations of carbohydrate solutions. Only trial and error with different drinking schedules during training sessions and in competitions will enable you to discover the best carbohydrate/fluid feeding schedule for you.

How? Although carbohydrates in solid foods can deliver carbohydrate, they cannot deliver fluid, which is especially critical in hot environments. Highly concentrated carbohydrate solutions can slow fluid delivery, so you should use a well-formulated sports drink containing not more than 7% carbohydrate (7 g/100 ml or 16.3 g/8 oz). Drink 240-600 ml (8-20 oz) of water or a sports drink about 10-15 minutes before exercise to stimulate fluid delivery from the stomach and then keep the stomach volume high by drinking smaller amounts of a sports drink every 15-20 minutes during exercise. Drink enough to minimize the body weight you typically lose during a similar type of training session or competition, but do not drink so much that you gain weight. (Drinking too little or too much can be dangerous to your health.)

SUGGESTED ADDITIONAL RESOURCES

Jeukendrup, A.E. (2004). Carbohydrate intake and exercise performance. *Nutrition* 20:669-677.

Jeukendrup, A.E., and R. Jentjens (2000). Oxidation of carbohydrate feedings during prolonged exercise: current thoughts, guidelines and directions for future research. *Sports Med.*. 29:407-424.

Jeukendrup, A.E., R.L. Jentjens, and L. Moseley (2005). Nutritional considerations in triathlon. *Sports Med.*. 35:163-181.