Carbohydrate during exercise: what is new?

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KEY POINTS

- Carbohydrate intake during exercise can delay the onset of fatigue, improve endurance capacity and exercise performance during prolonged (>2h) exercise.
- Carbohydrate feeding may also improve exercise performance during exercise of shorter duration and higher intensity (approximately 1 h) although the mechanisms are different.
- During prolonged exercise the effect of carbohydrate may be exerted by maintaining plasma glucose concentrations and high rates of carbohydrate oxidation whereas during intense exercise it may have central effects.
- Small amounts of carbohydrate already have an effect on performance. It is not clear if there is a dose response relationship but emerging evidence suggests that being able to oxidize more exogenous carbohydrate may result in better performance.
- A single carbohydrate can only be oxidized at rates up to 60 g/h..
- When a combination of carbohydrates is used (i.e. glucose and fructose) oxidation rates can amount up to 105 g/h if large amounts of carbohydrate are ingested.
- The ingestion of energy dense carbohydrate solutions and drinks with a high osmolality has been linked with the prevalence of gastro-intestinal discomfort.
- The amount of carbohydrate that needs to be ingested is individually determined and a balance should be struck between increasing carbohydrate availability during exercise and minimizing gastro-intestinal distress.

ABSTRACT

Although carbohydrate has been shown to improve exercise performance, it is not so clear whether there is a dose response relationship. A greater contribution of exogenous carbohydrate (carbohydrate from a drink or food) will spare liver glycogen and is generally believed to be beneficial. However, ingesting more carbohydrate can also have detrimental effects. Highly concentrated carbohydrate solutions and drinks with high osmolality have been linked with the development of gastro-intestinal problems. It therefore appears that there is a fine balance between ingesting optimal amounts of carbohydrate to enhance exogenous carbohydrate oxidation but avoiding gastrointestinal distress at the same time. A single carbohydrate can be oxidized up to 60 g/h. The use of multiple transportable carbohydrates can increase the contribution of exogenous carbohydrate oxidation up to 1.75 g/h and have been demonstrated to reduce fatigue and improve exercise performance. It is also suggested that it reduces gastro-intestinal distress, possibly because the oxidation efficiency is increased and less carbohydrate remains in the intestinal tract.

INTRODUCTION

It is long known that carbohydrate ingestion during exercise can delay the onset of fatigue and improve exercise performance especially during more prolonged exercise (>2h). The ingested carbohydrate can prevent a drop in blood glucose concentration and can help to maintain high rates of carbohydrate oxidation which is necessary to maintain a relatively high exercise intensity. A greater contribution of exogenous carbohydrate (carbohydrate from a drink or food) will spare liver glycogen and is generally believed to be beneficial. However, even in the presence of carbohydrate ingestion there is almost always a negative energy balance during exercise: i.e. the energy expenditure exceeds the energy intake. It has been reported that in major cycling stage races (including the Tour de France) the riders ingest on average 25 g/h of carbohydrate (17). This is an energy intake of only 100 kcal/h, whilst the energy expenditure could be at least 10 times that. In extreme situations like stages in the Tour de France which last 5-6 h, this could amount up to a 4000-5000 kcal negative energy balance.

In stage races like the Tour de France the negative energy balance developed during the race was traditionally compensated by an exceptionally large dinner (33). However, it was often difficult to maintain energy balance (55). Of course energy intake during the race does not have to be restricted to carbohydrate only and fat and protein could be ingested as well in an attempt to minimize the negative energy balance. Unfortunately, however, fat and protein have been described as potent inhibitors of gastric emptying, delaying not only the delivery of energy but also of fluids (4). So, in these extreme situations, attempts should be made to increase the carbohydrate intake during exercise.

Ingesting more carbohydrate can also have detrimental effects as highly concentrated carbohydrate solutions and drinks with high osmolality have been linked with the development of gastro-intestinal problems (52). It therefore appears that there is a fine balance between ingesting optimal amounts of carbohydrate to enhance exogenous carbohydrate oxidation but avoiding gastrointestinal distress at the same time. There are various complicating factors as the development of gastro-intestinal distress seems to be highly individually determined and is dependent on many factors like the intensity of exercise, the duration, hydration status and environmental conditions.

RESEARCH REVIEW

Effects of carbohydrate intake on performance

The beneficial effects of carbohydrate feeding on endurance capacity and performance have been well described (3, 12, 13, 15, 18, 20, 21, 42-44, 56). These effects were typically seen during exercise of at least 2 h duration. More recently studies have also found positive effects of carbohydrate feeding during exercise of relatively high intensity (>75%VO_2max) lasting approximately 1 h. Jeukendrup et al (31) investigated the effects of CHO ingestion during the equivalent of a 40 km time trial in well trained cyclists and found that performance was improved by 2.3%. Several studies have reported similar results (1, 2, 7, 14) although other studies were not able to find an ergogenic effect (9, 40, 50). This effect did not seem to be related to substrate availability as glucose infusion at high rates did not affect performance (6). It was suggested that the effects might be central (31). Consistent with this idea, a carbohydrate solution mouth rinse resulted in improved performance without actually swallowing the carbohydrate (5). This performance improvement was of the same magnitude as the performance improvement seen with carbohydrate ingestion (31). These results suggest that receptors in the oral cavity exist that communicate with the brain. Although direct evidence for such an effect is lacking, it is clear that the brain can sense changes in the composition of the mouth and stomach contents. 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 (38, 54). In these studies, oral hydration resulted in reduced values for RPE and thirst sensation compared to intravenous hydration. These findings are supported by reports of temporary reductions in thirst due to the gargling of tap water (57). Although somewhat speculative, it cannot be excluded that triggering of stimuli within the oral cavity by the CHO solution could have initiated a chain of neural messages in the central nervous system, resulting in the stimulation of the reward and/or pleasure centres in the brain. It must be noted that exercise shorter than 45 min may not benefit from carbohydrate feeding (46). Other factors may override a possible beneficial central effect of carbohydrate at such high exercise intensity. Although central mechanisms might play a role during exercise lasting approximately 1 h, the long established mechanism during prolonged exercise, remain the maintenance of blood glucose and relatively high carbohydrate oxidation rates. Once the effect of carbohydrate on endurance performance had been established in the 1980s the next obvious question was what is the optimal dose?

The optimal dose

Only a few studies investigated the effects of different doses of carbohydrate on exercise performance. Mitchell et al (41) observed that 12 min of isokinetic time trial performance was enhanced at the end of 2 h of intermittent exercise. The improvements were similar with ingestion of 34, 39 or 50 g/h of carbohydrate compared with a water trial. A study by Fielding et al (15) is often used to claim that a minimum of 22 g/h of carbohydrate is required to observe a performance benefit. In that study subjects exercised for 4 hours and performed a sprint at the end. Performance improvements were observed when 22 grams of carbohydrate was ingested every hour whereas no effects were observed when half this dose was consumed (11 g/h). In a study by Maughan et al (39) the intake of 16 g/h of glucose resulted in an improved endurance capacity by 14% compared with water (However, no placebo was given in this study). Most other studies that have found positive results have indeed used ingestion rates that were higher than this. However, Mitchell et al (41) found no effect of carbohydrate ingestion on 12 min of all out isokinetic cycling when 6% was ingested but performance was enhanced when a 12% carbohydrate solution was ingested. Interestingly ingestion of an 18% carbohydrate solution did not result in a performance improvement. In an earlier study the same authors found no effect of a 6% and a 7.5% carbohydrate solution but performance was improved with a 5% carbohydrate solution. In this study however, not only the amount of carbohydrate ingested was varied but also the type of carbohydrate. Flynn et al (16) did not find any differences in performance with the ingestion of 5% or 10% carbohydrate solutions. In that study however, these drinks resulted also in similar performance to placebo. The majority of studies provided 40-75 g carbohydrate/h and observed performance benefits. Ingesting carbohydrate at a rate > 75g/h does not appear to be any more effective at improving performance than ingesting carbohydrate at a rate of 40-75 g/h. It has been suggested that this is because ingestion of 40-75 g carbohydrate/h already results in optimal carbohydrate availability and ingesting carbohydrate at higher rates may not increase the bioavailability (11). 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 two different carbohydrate solutions. The overall conclusion seems to be that performance benefits can be observed with relative small amounts of carbohydrate (16 g/h). There are some indications that ingesting larger amounts of carbohydrate can result in further improvements in performance (see further). The efficacy of carbohydrate ingestion is likely to depend on the oxidation of that carbohydrate.

Oxidation of ingested carbohydrate

Several factors have been suggested to influence exogenous carbohydrate oxidation including feeding schedule, type and amount of carbohydrate ingested and the exercise intensity and these have been intensively investigated. Some of these factors have only small effects, whereas other factors have major effects on exogenous carbohydrate oxidation. For example, the timing of carbohydrate ingestion seems to have relatively little effect on exogenous carbohydrate oxidation rates. Studies in which a large bolus (100g) of a carbohydrate in solution was given (45) seem to result in similar exogenous carbohydrate oxidation rates to studies in which 100g glucose was ingested at regular intervals. With increasing exercise intensity, the active muscle mass becomes more and more dependent on CHO as a source of energy. However, exogenous carbohydrate oxidation seems to remain constant at intensities of 50-60%VO_2max or above.

Oxidation of different carbohydrates

Some types of carbohydrate are oxidized more readily than others (34). For example early studies showed that fructose was oxidized at only half the rate of glucose which was attributed to the fact that fructose

Roughly they can be divided into two categories: carbohydrates that can be oxidized at rates up to 60 g/h and carbohydrates that can be oxidized at rates up to 30 g/h (see table 1).

TABLE 1 ABOUT HERE

TABLE 1. *Oxidation of different carbohydrates*

Rapidly oxidized carbohydrates
Glucose
Sucrose
Maltose
Maltodextrins
Amylopectin
Slowly oxidized carbohydrates
Fructose
Galactose
Isomaltulose
Trehalose
Amylose

The optimal amount of carbohydrate

The optimal amount is likely to be the amount of carbohydrate that results in maximal exogenous carbohydrate oxidation rates without causing gastro-intestinal problems. Rehrer et al (53) 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 exercise) or a 17% glucose solution (220 g during 80 min of exercise). Total exogenous carbohydrate oxidation was measured and this was slightly higher (42 g versus 32 g in 80 min) with the larger carbohydrate dose. So, even though the amount of carbohydrate ingested was increased almost 4-fold, the oxidation rate was hardly affected. More recently Jeukendrup et al (37) investigated the oxidation rates of even larger carbohydrate intakes up to 180 g/h and found that this resulted in oxidation rates up to 56 g/h at the end of 120 min of cycling exercise.

The results from a large number of studies were used to construct Figure 1. The peak exogenous carbohydrate oxidation rates are plotted against the rate of ingestion. It must be concluded that the maximal rate at which a single ingested carbohydrate can be oxidized is about 60 g/h. The horizontal line depicts the absolute maximum around 60 g/h. The dotted line represents the line of identity where the rate of carbohydrate ingestion equals the rate of exogenous carbohydrate oxidation. Although the vast majority of studies was performed with men, the same conclusions seem to hold true for endurance-trained women: the highest rates of exogenous glucose oxidation and greatest endogenous carbohydrate sparing were observed when carbohydrate was ingested at moderate rates (60 g/h) during exercise (59).

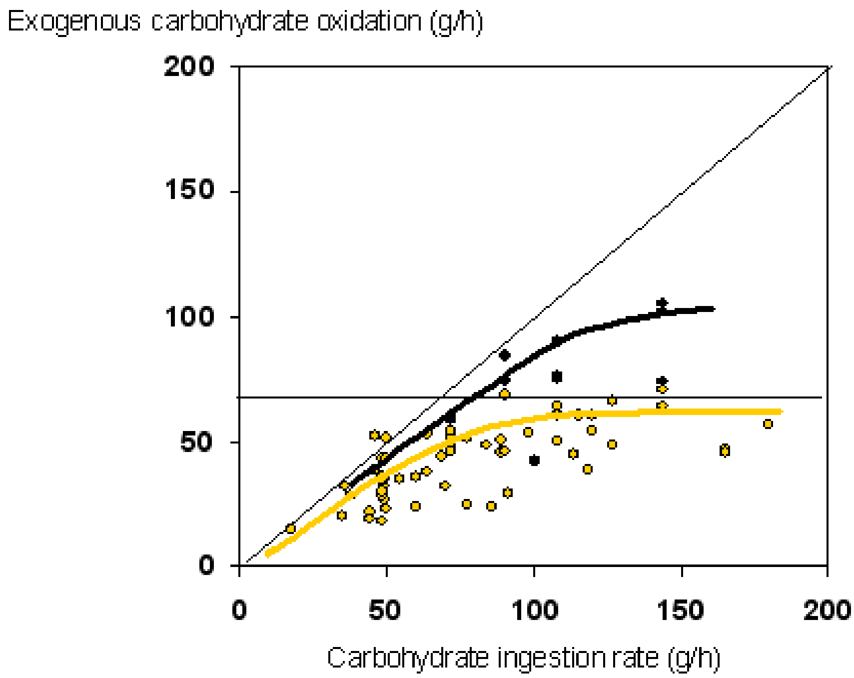

FIGURE 1. *Oxidation of ingested carbohydrate.* This figure is complied from a large number of studies investigating exogenous carbohydrate during exercise. The oxidation rate of ingested carbohydrate is plotted as a function of the ingestion rate (both have been expressed in g/h). In grey are the values from studies in which one type of carbohydrate was investigated. In black are the oxidation rates from combinations of multiple transportable carbohydrates. The grey line is an estimation of the average from all studies of single carbohydrates, the black line for multiple transportable carbohydrates. As the amounts ingested increase, the oxidation rate increases up to a certain point. Ingesting more than 60-70 g/h does not further result in an increase in the oxidation of the ingested carbohydrate and the excess carbohydrate is likely to accumulate in the intestine (Modified from (32)). However if multiple transportable carbohydrates are ingested at high rates very high rates of exogenous carbohydrate oxidation can be achieved.

From this graph it can be concluded that oxidation of orally ingested carbohydrate may already be optimal at ingestion rates around 60-70 g/h. This implies that athletes should ensure a carbohydrate intake of about 60-70 g/h for optimal carbohydrate delivery. Ingesting more than this will not increase carbohydrate oxidation rates any further, and is more likely to be associated with gastro-intestinal discomfort. In a review (34) we introduced the term oxidation efficiency to describe the percentage of the ingested carbohydrate that is oxidized. High oxidation efficiency means that smaller amounts of carbohydrate remain in the gastro-intestinal tract reducing the risk of developing gastro-intestinal complaints during prolonged exercise (4, 51).

Multiple transportable carbohydrates

The reason that exogenous carbohydrate oxidation is limited to approximately 60 grams per hour is most likely due to intestinal absorption (for review and detailed discussions see (32)). It is suggested that by feeding a single carbohydrate source (for example glucose or maltodextrin) at high rates the sodium dependent glucose transporters (SGLT1) become saturated. Once these transporters are saturated feeding more of that carbohydrate will not result in greater absorption and increased oxidation rates. It was suggested by intestinal perfusion studies that the ingestion of carbohydrates that use different transporters might increase total carbohydrate absorption (58). We used dual tracer techniques to study the oxidation of glucose and fructose mixtures during exercise. In the first study subjects ingested a drink containing glucose and fructose. 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). It was found that the ingestion of glucose at a rate of 72 g/h resulted in oxidation rates around 48 g/h. Ingesting more glucose did not increase the oxidation. However, ingesting glucose+fructose the total exogenous carbohydrate oxidation rate 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 of carbohydrates and also different amounts in an attempt to see what the maximal contribution could be of exogenous carbohydrate (22-28, 30, 35, 59). We observed that very high oxidation rates were reached with combinations of glucose+fructose, maltodextrin+fructose and glucose+sucrose+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 CHO oxidation peaked at 105 g/h! This is 75% higher than what was previously though to be the absolute maximum!

The increased oxidation of ingested carbohydrate has been suggested to be beneficial but concrete evidence for this has not yet been published. From a laboratory study in which subjects cycled for 5 h with water, glucose or glucose+fructose there are some indications that drinks with multiple carbohydrates could improve performance (35). In this study carbohydrate was ingested at a rate of 90 g/h. The first indication of improved performance was that RPE tended to be lower with glucose+fructose compared with glucose, which in turn was lower than water placebo. In fact with water not all participants were able to complete the 5 h at 50%. In addition the self selected cadence dropped significantly with water, which is generally seen as an indication of developing fatigue. With glucose this was somewhat prevented but with glucose+fructose cadence was highest and remained almost unchanged from the beginning of exercise (35). We have since performed a study to confirm the beneficial effects of glucose+fructose drinks compared with glucose on prolonged exercise performance (Currell et al unpublished findings).

Another important observation is that the oxidation efficiency of drinks containing carbohydrates that use different transporters for intestinal absorption was higher than drinks with a single carbohydrate. The amount of carbohydrate remaining in the intestine is therefore smaller and osmotic shifts and malabsorption may be reduced. This probably means that drinks with multiple transportable carbohydrates are less likely to cause gastro-intestinal distress. Interestingly, this is a consistent finding in studies that have attempted to register gastro-intestinal discomfort during exercise (22-28, 30, 35, 59). Subjects tended to feel less bloated with the glucose+fructose drinks versus glucose drinks. A larger scale study into the effects of drinks with different types of carbohydrates on gastro-intestinal discomfort has not yet been conducted.

Gastro-intestinal discomfort during exercise

Gastro-intestinal discomfort is very common during exercise, especially in endurance and ultra endurance sports. Peters et al (47) used a mail questionnaire on 600 runners, cyclists and triathletes to assess the prevalence of gastro-intestinal problems as well as their training background and nutrition habits. Symptoms of upper (nausea, vomiting, belching, heartburn, chest pain) and lower gastro-intestinal tract (bloating, abdominal cramps, side ache, urge to defecate, diarrhea) were evaluated in all participants. Prevalences of 45 and 79% were reported for lower gastro-intestinal symptoms and 36-67% for upper gastro-intestinal symptoms. Symptoms are generally; more severe during running compared with cycling, are more prevalent in women than men and seem to be more prevalent in more prolonged exercise. In an extreme long distance triathlon event 93% of the participants reported some problem and 45% of these problems were classified as serious (36).

The occurrence of problems has been related to carbohydrate intake during exercise (4). A relatively high carbohydrate intake during exercise may increase the incidence of GI symptoms like diarrhea and abdominal cramps, either by inducing osmotic flows (4) or by malabsorption. The fact that mesenteric blood flow is reduced during high intensity exercise and even more with dehydration (4) is probably responsible for the fact that symptoms seem to be more prevalent if exercise is more prolonged and performed in hot conditions. Although the occurrence of GI distress has been related to carbohydrate intake during exercise, this may be more related to the hyperosmolality of solutions than the actual carbohydrate content (52). In fact, in a laboratory study, 7% hypotonic carbohydrate drinks did not result in significantly greater discomfort during 2.5 h running and cycling compared with water (48, 49). 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, would result in increased incidence of GI problems. It is also likely, however, that the GI discomfort is mainly dictated by the oxidation efficiency. It is therefore tempting to speculate that multiple transportable carbohydrates ingested at high rates will result in vastly reduced discomfort whilst providing carbohydrate at high rates. The tolerance of carbohydrate drinks and development of GI distress seems highly individual and therefore strategies for carbohydrate intake will always have to be developed on an individual basis.

Carbohydrate and fluid delivery

Another reason to avoid the intake of highly concentrated carbohydrate solutions is that these solutions have been shown to delay gastric emptying and fluid absorption. Although there is a lot of evidence to support this there are also observations that impairment of fluid delivery is minimized when combinations of multiple transportable carbohydrate are ingested. Fluid delivery with a glucose+fructose solution has been shown to be greater than fluid delivery from a glucose solution (26). Both these carbohydrate solutions were about 15% and such highly concentrated carbohydrate solutions would normally result in severely impaired fluid delivery. Interestingly fluid delivery with the glucose+fructose drink was closer to water than it was to glucose. Nevertheless in situations where fluid delivery is more important than carbohydrate delivery, it would be recommended to consume less concentrated carbohydrate solutions. During prolonged exercise in hot conditions when sweat rates are usually high fluid delivery is important to maintain fluid balance. On the other hand, carbohydrate needs are fairly constant in different environmental conditions although it has been shown that carbohydrate oxidation rates are increased in the heat. This increased carbohydrate oxidation is mainly from muscle glycogenolysis and the contribution from exogenous carbohydrate may actually be decreased (29). The most logical explanation for this decrease is a redistribution of blood flow to the skin and muscle, with a reduction in mesenteric blood flow. This has consequences for carbohydrate absorption. However, recently we have demonstrated that 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 (29).

CHO and training adaptations

Recently is has also been suggested that carbohydrate ingestion during exercise may suppress the gene expression of oxidative enzymes and may therefore interfere with the process of adaptation. It has been shown that the transcription of several metabolic genes is transiently induced post exercise when no feeding is provided during exercise. However, Cluberton et al (10) demonstrated that glucose ingestion attenuated the exercise-induced increase in PDK-4 and UCP3 mRNA. In another study it was shown that carbohydrate ingestion during exercise mainly affects genes involved in fat metabolism with minimal changes in genes involved with carbohydrate metabolism (8). This would at least in theory suggest that carbohydrate ingestion during exercise would impair the adaptation. However, there may be a flaw in this extrapolation to the practical implications for the athlete as 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 draw any conclusions and base practical advice on the small number of laboratory studies currently published (19).

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