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ORIGINAL RESEARCH

Is There a Specific Role for Sucrose in Sports and Exercise Performance?

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The consumption of carbohydrate before, during, and after exercise is a central feature of the athlete's diet, particularly those competing in endurance sports. Sucrose is a carbohydrate present within the diets of athletes. Whether sucrose, by virtue of its component monosaccharides glucose and fructose, exerts a meaningful advantage for athletes over other carbohydrate types or blends is unclear. This narrative reviews the literature on the influence of sucrose, relative to other carbohydrate types, on exercise performance or the metabolic factors that may underpin exercise performance. Inference from the research to date suggests that sucrose appears to be as effective as other highly metabolizable carbohydrates (e.g., glucose, glucose polymers) in providing an exogenous fuel source during endurance exercise, stimulating the synthesis of liver and muscle glycogen during exercise recovery and improving endurance exercise performance. Nonetheless, gaps exist in our understanding of the metabolic and performance consequences of sucrose ingestion before, during, and after exercise relative to other carbohydrate types or blends, particularly when more aggressive carbohydrate intake strategies are adopted. While further research is recommended and discussed in this review, based on the currently available scientific literature it would seem that sucrose should continue to be regarded as one of a variety of options available to help athletes achieve their specific carbohydrate-intake goals.

Keywords: carbohydrate, exercise test, muscle fatigue

Carbohydrate is recommended for and consumed by athletes to support the energy requirements of training and competition. Athletes are generally advised to obtain their carbohydrates from a variety of foods including bread, cereals and grains, legumes, milk/alternatives, vegetables, and fruit (Rodruigez et al., 2009) where the predominant carbohydrate, other than in fruit and milk products, will invariably be starch (i.e., a polysaccharide of glucose where the degree of polymerization is >9, FAO/WHO, 1998). More specific guidelines have been developed for optimal carbohydrate fueling pre, during and postexercise or competition to optimize muscle and liver glycogen stores, maintain blood glucose levels and offset the reduction in endogenous glycogen stores during exercise (e.g., glucose-fructose mixtures for ultra-endurance exercise or moderate-to-high glycemic index [GI] carbohydrates for rapid postexercise glycogen restoration; Burke et al., 2011).

Sucrose or table sugar is a widely known and available carbohydrate and is a disaccharide composed of glucose and fructose monomers and with a moderate GI (60–65; Foster-Powell et al., 2002). While studies examining the sugar content of athlete's diets often suffer from unclear or lack of definition as to what exactly is meant by sugar or sugars, the former is usually defined as sucrose and the latter as both mono- and disaccharides, naturally occurring or added to food/drink in the diet (Hess et al., 2012). Dietary surveys show sugars to contribute anything from 4 to 25% and 5–60% to total dietary energy and carbohydrate intake, respectively, suggesting that sugars intake varies widely and within that probably sucrose consumption (Beis et al., 2011; Burke & Read, 1987; Garcia-Roves et al., 2000; Onywera et al., 2004; Ziegler et al., 2001). It is not clear if sucrose intake is specifically planned in athletes although it seems unlikely as athletes have reported their intention to reduce dietary sucrose consumption for apparent though unnamed health reasons (Burke & Read, 1987), which may reflect the common negative perceptions of sugar in the general public. Sucrose is widely used in caloric soft drinks globally although its inclusion in commercial sports food and drinks at the present time varies by region and manufacturer (e.g., Gatorade contains sucrose in products available globally; Powerade sold in Australia contains sucrose but not in Europe or USA; Lucozade Sport, predominantly available in Europe does not contain sucrose).

Due to its component monosaccharides, sucrose could be specifically suited to meet certain aspects of the carbohydrate nutrition guidelines for athletes. However, to the authors' knowledge, comparatively few studies have examined the relative effectiveness of sucrose for sports and exercise performance. It is not entirely clear

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why sucrose has not been as extensively investigated as other carbohydrates such as glucose, glucose polymers, or fructose in the context of exercise performance. Nonetheless, specific ingestion of sucrose particularly in close temporal association with exercise could be warranted if it is equal or superior to other forms of carbohydrate. Therefore, the purpose of this narrative review is to summarize the current scientific literature with respect to the role of sucrose in sport and exercise performance. Specifically, we have tried to ascertain if sucrose confers any specific advantages or disadvantages relative to other carbohydrate types in relation to sport and exercise performance or its underlying metabolic basis. In undertaking the review we have identified gaps in the literature and the review concludes with future directions for research. The limited evidence suggests that in the context of pre-, during, and postexercise fueling, sucrose may continue to be employed as a viable option to help athletes achieve their carbohydrate intake goals.

The review was preceded by a comprehensive literature search of bibliographic databases (PubMed, Web of Science and Sport Discuss) using the Medical Subject Heading (MeSH) search terms *(sucrose* or *fructose)* and *(sports* or *exercise* or *exercise test* or *motor skills* or *muscle strength* or *muscle fatigue* or *fatigue)*. Fructose was included in the search terms to identify studies that employed equimolar amounts of fructose and glucose in combination with the assumption that this could yield insights that are relevant to the effects of sucrose. The electronic search was complemented by manual search of relevant cross-references. Only papers on human participants and reported in English, with the exception of one study, (Massicotte et al., 1996) were included for efficacy comparisons. The review is mainly focused on studies that included sucrose (or equimolar combinations of glucose and fructose) as one of a number of carbohydrate interventions to gain insight as to the relative impact of sucrose in relation to sport and exercise performance. Studies were included regardless of whether sucrose was provided in food or beverage form. However, since most studies provided the sucrose, or comparison carbohydrate(s), in beverage form, it should be assumed that all interventions were provided as beverages unless informed to the contrary. No studies were found which compared the effect of sucrose relative to other carbohydrates on motor skills or strength. The review therefore specifically examines studies on the relative effects of sucrose in relation to its consumption before, during, and after endurance-type exercise.

Preexercise Sucrose Feeding

Preexercise Meal

In terms of preparation for endurance exercise, it is typically recommended that a meal providing 1–4 g/kg body weight of carbohydrate but relatively low in fat, protein or fiber (to reduce the risk of gastro-intestinal upset) is consumed 1–4 hr before the commencement of exercise (Burke et al., 2011). This will help to ensure that body carbohydrate availability, and particularly liver glycogen after an overnight fast, is replete for the onset of exercise. The specific role that sucrose, within foods or beverages, can play in this component of preparation for exercise has not been systematically investigated. Nonetheless, there are two areas where sucrose could make beneficial contributions. The first is that sucrose contains both a source of fructose and glucose. Results of intravenous infusion studies indicate that the primary target organ depot for storage may be different for glucose and fructose. It has been shown that intravenous fructose infusion at rest in the postabsorptive state is superior to glucose at increasing liver glycogen stores (Nilsson & Hultman, 1974), whereas intravenous infused glucose is preferentially stored as muscle glycogen compared with fructose following exercise (Bergstom & Hultman, 1967). The results of intravenous infusion studies may not be directly comparable to those of ingestion, with the latter necessitating intestinal absorption and delivery via the portal vein to the liver, giving rise to a possible greater potential for preferential first-pass hepatic metabolism, and furthermore, with ingestion resulting in a greater insulin response (Féry et al., 2001). However, data from oral consumption of fructose at rest do support its predominant hepatic metabolism (Delarue et al., 1993). Therefore, sucrose as a component of a preexercise meal may, by virtue of its fructose component facilitate greater liver glycogen storage during the preexercise period as compared with a meal with a relatively low proportion of fructose. The potential for enhanced liver glycogen storage along with the assessment of metabolic and performance consequences of increasing the sucrose component of the preexercise meal warrants further investigation.

The second area that may be of relevance is the impact of sucrose on the GI of the ingested preexercise meal. The GI of a food is an index of the 2-hr blood glucose response to consuming carbohydrates and carbohydrate containing foods compared with a reference food (typically glucose defined as a GI of 100). As already stated, sucrose has a moderate glycemic index of ~60–65 due to the presence of the fructose moiety which has a very low GI (~19; Foster-Powell et al., 2002). Low GI meals have been shown to enhance lipid oxidation, reduce muscle glycogen degradation, maintain blood glucose, and even extend endurance during exercise as compared with high GI preexercise meals (Wee et al., 2005; Wu & Williams, 2006). Although there is currently insufficient evidence for the benefits of low GI meals for exercise performance particularly when carbohydrate is subsequently ingested during exercise (Burke et al., 1998), it has nonetheless been suggested that low GI choices may provide a useful prolonged release of energy for exercise situations where carbohydrate provision during competition itself is not freely available (Burke et al., 2011). Sucrose being a moderate GI carbohydrate may therefore provide a useful source of carbohydrate as part of a lower GI meal, as compared with higher GI carbohydrates such as glucose. However, inclusion of free fructose within a low GI meal has been observed to result in a paradoxical increase in carbohydrate oxidation and reduction in fat oxidation to the extent that substrate utilization, at least during low-intensity exercise, is similar to that seen following a high GI meal (Sun et al., 2012). Therefore, the effect of inclusion of sucrose within a low GI meal, as compared with a low GI meal without sucrose, needs to be evaluated with respect to the potential to maintain a sustained release of energy (relative to high GI meal ingestion) in exercise situations where additional carbohydrate provision is not readily available.

Sucrose Ingestion in the Hour Before Exercise

The ingestion of high glycemic carbohydrates in the hour before exercise has long been anecdotally considered to compromise exercise performance as a result of rebound hypoglycemia. This state was thought to arise from a high-GI carbohydrate induced hyperglycemia and hyperinsulinemia, followed by, on commencement of exercise, a dramatic reduction in blood glucose levels, with high rates of glycogenolysis and reduced lipolysis and fat oxidation. However, a recent review of the evidence does not provide support for either clinically diagnosed hypoglycemia or negative effects on performance and suggested any effect to be highly individual (Jeukendrup & Killer, 2010). Such individuals considered more susceptible to the development of rebound hypoglycemia following preexercise carbohydrate ingestion have been advised to choose low-GI carbohydrates (Jeukendrup & Killer, 2010) and/or consume the carbohydrate during a preexercise warm-up period (Brouns et al., 1989). Preexercise sucrose ingestion has been shown to improve exercise tolerance (manifest through reductions in heart rate and perceived exertion during 15 min constant workload cycle ergometry) in patients with McArdles disease (a disease characterized by exercise intolerance due to an inability to breakdown muscle glycogen; Vissing & Haller, 2003). However, the metabolic and performance response to sucrose ingestion within foods or beverages in the hour before exercise has not been compared with other carbohydrate types with differing GI's in healthy exercise trained individuals. Sucrose as a moderate GI carbohydrate may be expected to result in different metabolic responses during exercise as compared with low or high GI carbohydrates although further research is needed to fully elucidate its potential role in preexercise nutrition.

Sucrose Feeding During Exercise

The primary purpose of carbohydrate feeding during exercise is to provide an exogenous fuel source for the body, primarily working muscles and central nervous system. It follows that for an ingested carbohydrate source to be effective it should be readily available for utilization during exercise. In this context, many studies have used stable ^{13}C or radioactive ^{14}C isotope methods to assess exogenous carbohydrate delivery as measured by end-point oxidation (total exogenous carbohydrate oxidation, for review see Jeukendrup & Jentjens, 2000). Exogenous carbohydrate oxidation rates may vary from study to study depending on the choice of isotope method with stable ^{13}C isotope methods typically resulting in higher oxidation rates than those observed when using radioactive ^{14}C isotopes (Hawley et al., 1992; Moseley et al., 2005). Nonetheless, the methods can be useful for making relative comparisons of feeding strategies within studies and assessing directional consistencies and differences between studies. Two early studies using isotope labeled carbohydrate ingestion techniques clearly demonstrated that sucrose ingested during exercise is oxidized (Benade et al., 1973; Gerard et al., 1986). It should be noted that while we and others refer to sucrose oxidation, it is not the direct oxidation of sucrose per se that is being measured but rather exogenous carbohydrate oxidation that reflects the oxidation of the glucose and fructose liberated from the hydrolysis of sucrose. Regardless, the relative effectiveness of sucrose as an exogenous fuel source for use during exercise as compared with other carbohydrate types was not investigated until later. We have summarized these studies in Table 1 and described them in further detail below. It appears that during exercise sucrose is oxidized at similar rates to glucose when provided at moderate ingestion rates (0.5–1.0 g/min), though higher than glucose at large ingestion rates (>1.0–1.5 g/min). Similarly, sucrose appears to be oxidized at similar rates to glucose polymers at both moderate and large ingestion rates.

Sucrose Versus Glucose

Moodley and colleagues (Moodley et al., 1992) compared the oxidation of sucrose with glucose (and glucose polymers) during exercise at 3 different ingestion rates (0.75, 1.0 and 1.5 g/min) during 90 min of cycle ergometer exercise at 70% VO_{2max}. When the data were combined for all doses, ingested glucose and sucrose were oxidized at similar average rates during exercise. However, although the exact data were not presented and thus caution should be exercised in interpretation, in a separate analysis of the Moodley data, Hawley and coworkers (Hawley et al., 1992) report that instantaneous exogenous carbohydrate oxidation rates measured at the final time point during exercise (i.e., 90 min) were higher for sucrose than glucose at an ingestion rate of 1.5 g/min. Similar oxidation rates between ingested sucrose and glucose have also been observed during 60 min of fixed intensity (75% VO_{2max}) treadmill exercise when carbohydrate was ingested at an average rate corresponding to 1.0 g/min during exercise (Leese, Thompson, Scrimgeour, & Rennie, 1996) and when carbohydrate was ingested at ~0.8 g/min during 120 min of cycling exercise at ~60%VO_{2max} (Massicotte et al., 1996). Interestingly, Jentjens and colleagues (Jentjens et al., 2005) found that sucrose was oxidized at significantly higher rates (~34% higher during the last 60 min of exercise) than glucose when ingestion rates of 1.2 g/min were employed during a 2 hr cycle bout at an intensity of ~63% VO_{2max}. While comparisons between metabolic

Table 1 Summary of Studies Examining the Effect of Sucrose Consumption on Exogenous Carbohydrate Oxidation During Exercise in Comparison with Other Carbohydrates

Study	Exercise protocol	Comparator (Ingestion rate, g/min)	Relative sucrose effect <, =, > (Effect size, classification)
Jentjens et al. (2005)	120 min continuous cycling @63% VO_{2max}	glucose (1.2)	> (2.1, very large)
Achten et al. (2007)	150 min steady state cycling @59% VO_{2max}	isomaltulose (1.1)	> (9.5, extremely large)
Hawley et al. (1992)	90 min continuous cycling @70% VO_{2max}	glucose (1.5)	>*(NR)
		glucose (0.75, 1.0)	=*(NR)
Wagenmakers et al. (1993)	120 min continuous cycling @70% W_{max}	glucose polymer (1.2)	= (0.4, small)
Leese et al. (1996)	60 min continuous walking @75% VO_{2max}	glucose (1.0)	= (0.6, small)
		glucose polymer (1.0)	= (0.4, small)
Moodley et al. (1992)	90 min continuous cycling @70% VO_{2max}	glucose (0.75, 1.0, 1.5)	= (0, trivial)
Moodley et al. (1992)	90 min continuous cycling @70% VO_{2max}	glucose polymer (0.75, 1.0, 1.5)	= (NR)
		glucose polymer (0.75, 1.0, 1.5)	<* (NR)
Massicotte et al. (1996)	120 min continuous cycling @60% VO_{2max}	glucose (0.8)	= (–0.5, small)
		free glucose-fructose (0.8)	= (-1.1, moderate)

Note. < , = or >, denotes where the effect of sucrose (relative to its comparator) appears to be less advantageous, similar, or advantageous with respect to exogenous carbohydrate oxidation during exercise based on traditional significance testing (i.e., *p*-value). Modified Cohen effect size classification also provided to provide indicative size of treatment effects (standardized difference in means; trivial ~0.0–0.2, small ~0.2–0.6, moderate ~0.6–1.2, large ~1.2–2.0, very large ~2.0–4.0, and extremely large >4.0 (Hopkins et al., 2009). NR denotes that sufficient data to calculate effect sizes were not reported. Inferences on the likelihood of outcomes could not be calculated due to insufficient reporting of data.*Effect observed was an instantaneous measurement of exogenous carbohydrate oxidation rate taken at end exercise (i.e., 90-min time point).

responses in the aforementioned studies should be made with some caution due to variable experimental designs (e.g., exercise mode, intensity, duration and participant training status), it would appear that when glucose and sucrose are ingested at moderate rates during exercise (0.5–1.0 g/min) they may be oxidized at similar rates. However, at large ingestion rates (>1.0–1.5 g/min), sucrose may confer benefits over glucose in terms of exogenous carbohydrate delivery and this could be due to greater total carbohydrate absorption with sucrose due to its properties as a multiple transportable carbohydrate as will be discussed further.

Sucrose Versus Glucose Polymers

Moodley and coworkers (Moodley et al., 1992) also revealed that the instantaneous exogenous carbohydrate oxidation rate measured at the end of exercise (i.e., 90 min time point) was higher for glucose polymers than for sucrose when the data for all three ingestion rates were combined. However, this statistical difference was not apparent when the average oxidation rates over the entire 90-min exercise period were considered. Subsequent studies (Leese et al., 1996; Wagenmakers et al., 1993) observed similar oxidation rates from sucrose and glucose polymers ingested during exercise ranging from 1 to 2 hr duration and spanning moderate (1.0 g/min) and large (1.2 g/min) ingestion rates. On balance, and under the conditions studied to date, provision of both sucrose and glucose polymers appear equally effective at delivering exogenous fuel for oxidation during exercise.

Sucrose Versus Fructose

There are no direct reports comparing the oxidation of sucrose with fructose during exercise although it is worthy of discussion as fructose comprises one of the monosaccharides constituting sucrose. Fructose ingested in isolation has a low oxidation rate compared with glucose due to a relatively low absorption rate and the necessity for hepatic conversion to glucose (or lactate) before oxidation by skeletal muscle (Adopo et al., 1994; Massicotte et al., 1986). There is evidence for malabsorption of fructose when ingested in isolation (Rumessen, 1986) and this may have consequences for exercise performance (Murray et al., 1989a). The presence of glucose with fructose appears to overcome this malabsorption (Rumessen, 1986). Coingestion of 50 g glucose with 50 g fructose at the beginning of a 2 hr cycle bout at 61% VO_{2max} elicited higher oxidation rates during exercise than equivalent total amounts (i.e., 100 g) of fructose alone (Adopo et al., 1994). While Adopo and colleagues employed coingestion of equimolar quantities of free glucose and free fructose and not sucrose, their results would suggest that sucrose should also elicit higher oxidation rates than equivalent amounts of fructose ingested during exercise.

Sucrose Versus Glucose and Fructose

As already discussed, sucrose is a disaccharide comprised of glucose and fructose. Sucrose is digested by sucrase at the brush border of the intestinal epithelium to glucose and fructose. The Michaelis constant (K_m) for sucrase in-vitro is 20 mM (Conklin et al., 1975) although the K_m for sucrose hydrolysis in-vivo in humans has been estimated to be much greater, approximating 142 mM (Gray & Ingelfinger, 1966). On the basis of this latter observation, combined with similar monosaccharide absorption from sucrose compared with equimolar mixtures of free glucose-fructose (Gray & Ingelfinger, 1966; Shi et al., 1995), the inference from intestinal perfusion studies is that digestion is unlikely to be limiting for the absorption of monosaccharides derived from sucrose ingestion. Whether sucrose digestion can become limiting to monosaccharide absorption when carbohydrate is ingested during exercise, particularly at high carbohydrate ingestion rates, has not been directly studied. There is some evidence that sucrose may escape hydrolysis and pass directly into the body although an intestinal sucrose transporter has not been identified in humans and direct sucrose transfer to the circulation occurs in very small quantities in healthy individuals (Tasevska et al., 2005).

Therefore the major pathway for sucrose entry into the circulation is via hydrolysis to glucose and fructose for subsequent absorption. The transport of glucose and fructose released from sucrose appears to occur via the same mechanisms responsible for free glucose and free fructose transport (Davidson & Leese, 1977; Gray & Ingelfinger, 1966). That is glucose (and galactose) is transported from the intestinal lumen into intestinal epithelial cells by the sodium-dependent glucose transporter (SGLT1) whereas the sodium-independent glucose transporter 5 (GLUT5) transports fructose. All three monosaccharides are subsequently transported into the hepatic circulation by GLUT2 located on the basement membrane of the epithelial cell (Ferraris, 2001). In addition to the classical SGLT1 and GLUT5 transport mechanism, there is now evidence from animal studies that additional proteins may be involved in the intestinal transport of glucose and fructose, and by inference the transport of glucose and fructose derived from sucrose hydrolysis. This includes a role for glucose or sugar-induced trafficking of intracellular GLUT2 to the apical membrane which would facilitate both glucose and fructose transport (for review see Kellett et al., 2008) in addition to a newly identified role for GLUT8 in the regulation of mammalian intestinal fructose transport (DeBosch et al., 2012).

To our knowledge, Massicotte and colleagues (Massicotte et al., 1996) are the only investigators to directly compare the oxidation of sucrose with equimolar free glucose-fructose. This group reported no differences in total exogenous carbohydrate oxidation rates when carbohydrate was ingested at moderate rates (~0.8 g/min) during 120 min of cycling exercise at ~60%VO_{2max}. However, it should be noted that further examination of the results suggests a moderate effect size (1.1, see legend in Table 1 for effect size classifications) for the differences between free glucose-fructose and sucrose favoring free glucose-fructose ingestion. This observation requires clarification before strong conclusions can be drawn as to whether there are meaningful differences in exogenous carbohydrate oxidation from sucrose versus equimolar ratios of its constituent monosaccharides.

Sucrose as a Multiple Transportable Carbohydrate

Interestingly, Burke and colleagues (Burke et al., 2011) recently recommended the ingestion of multiple transportable carbohydrates (i.e., glucose and fructose) at rates up to 1.5 g/min (90 g/h) to maximize carbohydrate availability and oxidation for competition or training for athletes participating in ultra-endurance exercise (>2.5–3.0 hr). This is based on the premise that absorption is a key-limiting factor for total exogenous carbohydrate oxidation and multiple transportable carbohydrate ingestion facilitates greater total carbohydrate absorption through the non-competitive absorption of glucose and fructose via different intestinal transport mechanisms (Jeukendrup, 2010). Indeed, Shi and colleagues (Shi et al., 1995) demonstrated that perfusion of solutions containing glucose-fructose or sucrose results in higher carbohydrate absorption than glucose alone under resting conditions. Furthermore, sucrose and free glucose-fructose solutions were equally effective at stimulating carbohydrate, water, and total solute absorption (Shi et al., 1995). Moreover, a comprehensive series of studies by Jeukendrup and colleagues established that the utilization (i.e., oxidation) of ingested carbohydrate during exercise can be elevated substantially above the previously reported upper limit of 1.0 g/min for glucose (up to 1.75 g/min) by the coingestion of large to very large quantities (>1.5–2.4 g/min) of combined glucose and fructose carbohydrate sources and this includes blends of glucose and sucrose or glucose, fructose and sucrose (for review see Jeukendrup, 2010)). As the absorption and subsequent oxidation of monosaccharides from sucrose is largely similar to that of free glucose-fructose, it seems reasonable to conclude that sucrose can be considered a source of multiple transportable carbohydrates and therefore a viable option to achieve the high oxidation rates expected from large carbohydrate intakes.

Recently, the Rowland's laboratory has provided insights into the specific fructose-glucose ratio, among a variety of multiple transportable carbohydrate solutions, which could elicit the highest rates of exogenous carbohydrate oxidation. Across three separate studies (O'Brien & Rowlands, 2011; O'Brien et al., 2013; Rowlands et al., 2008), these researchers demonstrated that higher rates of exogenous carbohydrate oxidation could be elicited when consuming fructose-glucose source solutions with a 0.8 fructose-glucose source ratio as compared with a ratio of 0.5 or 1.2–1.25. From these data it would appear that fructose-glucose ratios approaching unity (i.e., consistent with the constituent carbohydrate ratio of sucrose) might yield the highest exogenous carbohydrate oxidation rates during exercise when large amounts of carbohydrate are consumed.

Sucrose Versus Isomaltulose

Isomaltulose is a disaccharide composed of glucose and fructose linked by a 1,6-glycosidic bond, as compared with the 1,2-glycosidic bond linking glucose and fructose in sucrose. It is naturally occurring or can be produced by enzymatic conversion of sucrose. Disaccharides with 1,6-glycosidic bonds are hydrolyzed at low rates (Goda & Hosoya, 1983) and thus isomaltulose displays a slower rate of digestion, absorption and subsequent glycemic and insulinemic response as compared with sucrose (Lina et al., 2002; van Can et al., 2009). The potential impact of slower digestion and absorption of isomaltulose compared with sucrose on total exogenous carbohydrate oxidation during exercise has been investigated by Achten and colleagues (Achten et al., 2007). These workers observed that exogenous carbohydrate oxidation rates from ingested isomaltulose were only 59% of that of sucrose during a 2.5 hr cycle bout at ~59%VO_{2max}. This is perhaps not unexpected as intestinal absorption is a potential rate-limiting step in the oxidation of orally ingested carbohydrates during exercise (Jeukendrup, 2010). Thus, although recent studies indicate that the absorption profile of isomaltulose can favorably influence glycemic responses to exercise (vs. glucose) in people with Type 1 diabetes (West et al., 2011), sucrose would be more advantageous to the healthy athlete if the goal is to maximize rates of ingested carbohydrate utilization during exercise.

Sucrose Consumption During Exercise and Performance

It is clear that sucrose ingestion during exercise can offer benefits to exercise performance relative to water or a nonnutritive placebo (Abbiss et al., 2008; Murray et al., 1989a; Murray et al., 1989b; van Essen & Gibala, 2006). However, a limitation of previous studies comparing sucrose with other carbohydrates is the general focus on metabolic outcomes and to our knowledge only one study has directly compared the performance benefits of sucrose versus other carbohydrates. Murray and colleagues (Murray et al., 1989a) investigated the effect of consuming a 6% carbohydrate-electrolyte solution containing glucose, sucrose or fructose at moderate intake rates of ~0.66 g/min on high intensity cycle performance following 115 min of incremental intermittent cycle exercise (65–80% VO_{2max}). The time to complete 600 cycle pedal revolutions was not different between sucrose (419.4 ± 21.0s) and glucose (423.9 ± 21.2 s) but both were significantly faster (13–14%) than when fructose was ingested. The relatively poor performance when fructose was consumed was associated with higher ratings of stomach upset and perceived exertion and lower overall beverage acceptance (Murray, Paul, et al., 1989); the former might be due to poor absorption when fructose is ingested alone which does not appear to occur when fructose is consumed as a constituent of sucrose (Murray et al., 1989a; Rumessen, 1986). Thus, although the evidence is limited, it seems there are no discernable differences in the efficacy of sucrose as compared with glucose under the conditions studied.

Several recent studies have demonstrated the superiority of multiple versus single transportable carbohydrates for prolonged endurance exercise performance when carbohydrate is consumed in large quantities (Currell & Jeukendrup, 2008; Rowlands et al., 2012; Triplett et al., 2010). Undoubtedly, some of the benefit of ingesting multiple transportable carbohydrates can be attributed to increased exogenous fuel provision during exercise as compared with single transportable carbohydrates. In addition, improved gastro-intestinal comfort with multiple transportable carbohydrates has been identified as a possible mediating mechanism in explaining the endurance performance benefits of multiple over single transportable carbohydrates (Rowlands et al., 2012). This is perhaps not surprising given the use of highly concentrated-hypertonic glucose-only control solutions which can demonstrably induce severe gastro-intestinal distress during prolonged exercise (Triplett et al., 2010). Regardless of the mechanism, it might be expected that sucrose as a multiple transportable carbohydrate source would confer performance benefits over single transportable carbohydrates when large amounts of carbohydrate are consumed during exercise.

With respect to the consumption of large amounts of carbohydrate, Smith and colleagues recently demonstrated a curvilinear dose-response relationship of carbohydrate intake (fructose-glucose source ratio of 0.5, carbohydrate ingested in the range of 0–2.0 g/min) with endurance exercise performance with optimal performance identified at an ingestion rate of ~1.3 g/min (range 1.1–1.5 g/min) and decrements in performance observed at higher ingestion rates (Smith et al., 2013). Although not reported, it is possible that gastro-intestinal symptoms were influential in the reduction in performance at very high ingestion rates (i.e., >1.5 g/min). Indeed, superior endurance performance has been demonstrated when consuming fructose-glucose source solutions with a ratio of 0.8 and 1.25 as compared with 0.5 (ingestion rates 1.8 g/min; O'Brien & Rowlands, 2011). The authors attributed this benefit to the improvements in perceptions of gut comfort observed with the 0.8 (highest level of gut comfort) and 1.25 (second highest level of gut comfort) ratios, and suggested gut comfort had a clearer relationship with performance than could be explained by differences in exogenous carbohydrate oxidation.

More recently, O'Brien and colleagues confirmed superior endurance performance from ingesting fructose-glucose source solutions (ingestion rates 1.5 g/min) with a ratio of 0.8 over 0.5 (O'Brien et al., 2013). In contrast to their previous report, advantages of the 0.8 ratio over a 1.25 ratio were also observed and the advantage of the 0.8 ratio was characterized by higher absolute rates of exogenous carbohydrate oxidation and exogenous carbohydrate oxidation efficiency (i.e., % ingested carbohydrate oxidized) rather than a clear influence of gut comfort. Differences between the studies (O'Brien et al., 2013; O'Brien & Rowlands, 2011) in the relative influence of factors (i.e., metabolic vs. perceptual) mediating the benefits of multiple transportable carbohydrates is likely influenced by ingested carbohydrate dose (1.5 vs. 1.8 g/min) and performance protocol (repeated sprints vs. incremental exercise to exhaustion) but what appears consistent, as stated above for exogenous carbohydrate oxidation, is that fructose-glucose source ratio's approaching unity (i.e., 0.8–1.0) appear to offer the greatest benefit to prolonged-high intensity endurance performance. More broadly, the collective data suggest that even recommendations for aggressive strategies of multiple transportable carbohydrate intakes, which could include the use of sucrose, directed at enhancing exogenous substrate supply should be cognizant of the potential negative performance impact of gastro-intestinal distress associated with high rates of carbohydrate intake.

Postexercise Sucrose Feeding

It is well established that the consumption of carbohydrate after exhaustive exercise is essential for the replenishment of liver and muscle glycogen stores. Refueling recommendations are necessarily generic but the advice that carbohydrate-rich foods with a moderate-to-high GI will provide a readily available source of substrate for glycogen synthesis provides general support that sucrose can be an effective carbohydrate to facilitate postexercise refueling (Burke et al., 2011). This advice is suggested to be more critical when the recovery between intense exercise efforts is short (i.e., <8 hr; Burke et al., 2011). In the early postexercise period and indeed, at least during the short-term (i.e., <8 hr) recovery period after exhaustive exercise, sucrose has been shown to promote storage of both liver and muscle glycogen (Casey et al., 2000; van Hall, Shirreffs, & Calbet, 2000). However, the effectiveness of sucrose relative to other carbohydrate types in terms of postexercise glycogen resynthesis has not received a great deal of attention. As already discussed with respect to preexercise feeding, the primary target organ depot for glycogen storage may differ for fructose versus glucose which suggests the potential for sucrose, by virtue of its component monosaccharides, to be a particularly beneficial carbohydrate for postexercise recovery through the optimization of both liver and muscle glycogen synthesis. However, with the exception of fructose, the studies that have investigated the effects of sucrose relative to other carbohydrates in the context of postexercise recovery have generally not been able to discern meaningful differences with respect to liver glycogen restoration and results are inconsistent for muscle glycogen restoration (Table 2).

Table 2 Summary of Studies Examining the Effect of Sucrose Consumption on Glycogen Storage After Strenuous Endurance Exercise in Comparison with Other Carbohydrates

Study	Exercise protocol	Comparator (Ingestion regimen)	Relative sucrose effect <, =, > (Effect size, classification)
Blom et al. (1987)	~91 min cycling @ 75% $\text{VO}_{2\text{max}}$, 6-hr recovery period.	fructose (~50 g [0.7 g/kg bw] provided immediately, 2 and 4 hr postexercise)	> (5.0, extremely large)
	muscle glycogen content from muscle biopsies	glucose (~50 g [0.7 g/kg bw] provided immediately, 2 and 4 hr postexercise)	= (0.5, small)
Moriarty et al. (1994)	~78 min constant cycling @ 75% $\text{VO}_{2\text{max}}$, 5-hr recovery period	glucose (~76 g [~2.5 g/kg bw)] provided as a bolus immediately postexercise)	liver, = (NR)
	liver and muscle glycogen content from ^{13}C-MRS		muscle, = (NR)
Casey et al. (2000)	~83 min constant cycling @ 70% $\text{VO}_{2\text{max}}$, 4-hr recovery period	glucose (~76 g [1 g/kg bw] provided as a bolus immediately postexercise)	liver, = (0.03, trivial)
	liver and muscle glycogen content from ^{13}C-MRS		muscle, = (–0.2, trivial)
Bowtell et al. (2000)	30 min + 45 min constant cycling @ 70% $\text{VO}_{2\text{max}}$, separated by 6 high-intensity 1-min sprints, 2-hr recovery period.	glucose polymer (~61 g [~0.8 g/kg bw] provided as a bolus immediately postexercise)	< (–0.4, small)
	muscle glycogen content from muscle biopsies		

Note. < , = or >, denotes where the effect of sucrose (relative to its comparator) appears to be less advantageous, similar or advantageous with respect to postexercise glycogen storage based on traditional significance testing (i.e., *p*-value). Modified Cohen effect size classification also provided to provide indicative size of treatment effects (standardized difference in means; trivial ~0.0–0.2, small ~0.2–0.6, moderate ~0.6–1.2, large ~1.2–2.0, very large ~2.0–4.0, and extremely large >4.0 (Hopkins et al., 2009). NR denotes that sufficient data to calculate effect sizes were not reported. Inferences on the likelihood of outcomes could not be calculated due to insufficient reporting of data.

Postexercise Liver Glycogen With Sucrose Versus Glucose

Two studies have directly compared the effect of sucrose and glucose provision as a single beverage dose immediately after exhaustive exercise on postexercise liver glycogen concentration using ^{13}C-magnetic resonance spectroscopy (^{13}C-MRS; Casey et al., 2000; Moriarty et al., 1994). The study by Casey et al. provided ~76 g of carbohydrate whereas Moriarty et al., provided ~177 g with both studies monitoring liver glycogen concentration during subsequent 4–5 hr of recovery. Contrary to their hypothesis, Casey and coworkers reported that both sucrose and glucose resulted in similar increases in liver glycogen during 4 hr of recovery. The relatively low dose of carbohydrate provided (average ingestion rate of ~19 g/h) may have been preferentially stored as liver glycogen and at such a low carbohydrate dose muscle glycogen may have been a lower priority (Casey et al., 2000). Alternatively, while the differences were trivial (effect size = 0.03), given the numerical differences reported for the change in liver glycogen with sucrose and glucose (25 ± 5 g vs. 13 ± 8 g, respectively), the small sample size ($n = 6$) may have limited the power to detect meaningful differences between conditions. Interestingly, liver glycogen concentration was not observed to change from postexercise values when a larger dose of 177 g of glucose or sucrose was consumed during recovery in a study performed by Moriarty and colleagues (Moriarty et al., 1994). As discussed by Casey and colleagues, the failure of Moriarty and coworkers to detect any increase in liver glycogen during recovery may be due to methodological problems resulting in highly variable liver glycogen responses. For example, preexercise nutrient intake was not controlled for in the study by Moriarty and colleagues, nor did these investigators benefit from the use of magnetic resonance imaging for accurate placement of ^{13}C-MRS probes and broadband proton decoupling to increase the signal-to-noise ratio of the ^{13}C glycogen signal. This suggests the liver glycogen measurements in the study by Moriarty et al. (1994) should be interpreted with some caution although it is interesting to note that there was a trend ($p = .06$) for an increase in liver glycogen with sucrose ingestion after exercise, albeit again the study had low statistical power with a limited sample size ($n = 5$). Therefore, the available data do not support a significant difference in postexercise liver glycogen synthesis between sucrose and glucose ingestion. Nonetheless, due to study limitations further investigation of the potential for sucrose to contribute to optimal liver glycogen resynthesis is warranted.

Postexercise Muscle Glycogen With Sucrose Versus Other Carbohydrate Types

Blom et al. (Blom et al., 1987) investigated the effects of consuming glucose, sucrose or fructose on muscle glycogen concentrations during postexercise recovery. Volunteers were provided with ~50 g of the respective carbohydrate immediately, 2 hr and 4 hr after exercise (i.e., total ~150 g, or ~25 g/h over 6 hr). Muscle glycogen concentration was determined from muscle biopsy samples of the *vastus lateralis* at the same time points with the addition of a final sample at 6 hr post exercise. While muscle glycogen concentration increased during recovery with carbohydrate ingestion, these authors observed no statistically significant differences in the change in muscle glycogen concentration between glucose and sucrose, although both increased muscle glycogen concentrations to a greater extent than fructose. Consistent with this study, similar muscle glycogen concentration has been reported when determined noninvasively using ^{13}C-MRS during 4–5 hr recovery periods from exhaustive exercise when sucrose or glucose were provided as single doses (~76 g or ~177 g) immediately after exhaustive exercise (Casey et al., 2000; Moriarty et al., 1994). In contrast, Bowtell and colleagues reported that muscle glycogen concentration increased over a 2 hr recovery period after exhaustive exercise to a significantly greater extent (although with a small effect size, 0.4) with glucose polymer ingestion compared with sucrose when a single bolus of ~61 g of carbohydrate was ingested immediately after exercise (Bowtell et al., 2000). Bowtell et al. suggested that the greater metabolic availability of ingested carbohydrate as indicated by higher plasma glucose levels and the higher insulin response with glucose polymer ingestion may have favorably enhanced the increase in muscle glycogen concentration as compared with sucrose. However, this finding is difficult to reconcile with the previous observation that glucose and sucrose elicit similar benefits to muscle glycogen concentration, even over a 2 hr recovery period despite inducing differential glycemic and insulinemic responses (Blom et al., 1987).

The similarity between sucrose and glucose in increasing postexercise muscle glycogen concentration has been suggested to be somewhat surprising since sucrose contains equimolar amounts of glucose and fructose and therefore only half the quantity of glucose is available for direct incorporation into muscle glycogen (Blom et al., 1987; Jentjens & Jeukendrup, 2003). Nonetheless, several possibilities exist that may explain how a smaller amount of total glucose ingested as sucrose does not attenuate the rate of increase in muscle glycogen concentration. For instance, fructose is predominantly metabolized in the liver following intestinal absorption (Delarue et al., 1993) and this might reduce the requirement for and/or inhibit hepatic glucose uptake (Blom et al., 1987) and thus more glucose liberated from sucrose hydrolysis would be available for muscle glycogen. In addition, the predominant metabolism of fructose in the liver has in various contexts (e.g., rest, during exercise) been shown to contribute substantially to systemic blood glucose and lactate production (Delarue et al., 1993; Jandrain et al., 1993; Lecoultre et al., 2010), which directly or indirectly (i.e., lactate, via gluconeogenesis) could be used to synthesize muscle glycogen. Furthermore, liver glycogen turnover has been shown to occur even in the face of net liver glycogen synthesis (Magnusson et al., 1994), and therefore the potential on-going contribution of liver glucose production to muscle glycogen concentration should not be discounted. Finally, it is possible that under conditions of liver glycogen depletion with low rates of exogenous fuel provision that the liver preferentially retains an equal proportion of carbohydrate ingested regardless of the source (Casey et al., 2000), such that carbohydrate availability for incorporation into muscle glycogen is similar between carbohydrate types.

Potential for Sucrose to Promote Optimal Glycogen Storage

The studies presented thus far used relatively low and arguably suboptimal average rates of carbohydrate intake (0.3–0.5 g/kg body weight/h) compared with the recommended strategies for maximizing the rate of postexercise glycogen synthesis (i.e., 1.0–1.2 g/kg body weight/h for the first 4 hr after exercise)(Burke et al., 2011). One recent study concluded, which also used ^{13}C-MRS methodology, that the rate of net liver glycogen synthesis was faster when maltodextrin-fructose or maltodextrin-galactose (net liver glycogen synthesis rate 8.1 ± 0.6 and 8.6 ± 09 g/h, respectively) beverages were consumed at ingestion rates corresponding to ~1 g/kg/h during a 6.5h post exercise period as compared with maltodextrin consumption alone (net liver glycogen synthesis rate = 3.7 ± 0.5 g/h; Decombaz et al., 2011). Interestingly, Wallis and coworkers (Wallis et al., 2008) observed that glucose-fructose or glucose only ingestion at high rates (90 g/h for 4 hr) resulted in similar rates of postexercise muscle glycogen synthesis. We may surmise therefore that when carbohydrate is ingested at high rates equivalent to those recommended to maximize glycogen storage after exercise, it could be preferable to include a carbohydrate type that undergoes predominant hepatic metabolism (i.e., fructose, galactose) and thus optimize liver glycogen storage alongside a glucose source that can be directly incorporated into muscle glycogen. In this respect it may be that larger and more frequent dosing of sucrose is required to elicit the most beneficial responses and it would therefore be interesting to assess the relative efficacy of sucrose or carbohydrate blends containing sucrose (e.g., sucrose and glucose) versus glucose or glucose polymers on postexercise glycogen synthesis rates (in liver and skeletal muscle) under conditions recommended to optimally promote short-term glycogen storage.

Sucrose and Recovery of Exercise Capacity

It is clear that prevention of hypoglycemia can help sustain the capacity to perform prolonged strenuous exercise (Coyle et al., 1986) . As the liver is the primary source of glucose available for the maintenance of blood glucose concentration, a higher preexercise liver glycogen content before the commencement of a 2nd exercise bout could result in an improved performance. However, the literature regarding the relative effectiveness of sucrose ingestion versus other carbohydrates for the recovery of the capacity to undertake intense exercise is limited to one study. Casey et al. (2000) investigated the recovery of endurance exercise capacity in healthy but not specifically endurance-trained adults when either sucrose or glucose were provided as a single bolus (~76 g) immediately after an initial exhaustive exercise bout. Time to exhaustion during cycle exercise at 70% VO_{2max} was assessed after 4 hr of recovery; there was no significant difference between glucose and sucrose (40 ± 5 and 46 ± 6 min, respectively). As previously described, liver (and muscle) glycogen concentration was not significantly different between the sucrose and glucose trials at the commencement of the second exercise bout, which may in part explain the similar responses with respect to the recovery of exercise capacity. However, in the study of Casey et al. (2000), a weak but statistically significant relationship between the change in liver glycogen ($r = .53$, $p < .05$) or liver plus muscle glycogen ($r = .55$, $p < .05$) content during recovery and endurance exercise capacity was observed suggesting that a greater short-term resynthesis of liver and/or whole body glycogen storage could result in enhanced recovery of performance. Nonetheless, the contribution of on-going carbohydrate absorption to fuel provision during a subsequent exercise bout cannot be ruled out and therefore further work in this area is warranted.

Summary and Future Directions

The influence of sucrose, relative to other carbohydrates, on exercise metabolism and performance has been studied to varying degrees. A specific role for sucrose in preexercise nutrition has not been established and further research is warranted in this area. During exercise, carbohydrate from sucrose ingestion at moderate intakes (0.5–1.0 g/min) appears to be oxidized at similar rates to other highly metabolizable carbohydrates (e.g., glucose and glucose polymers) though more effectively than carbohydrates with predominant hepatic metabolism or slower absorption (e.g., fructose, isomaltulose). There are clear advantages to exogenous carbohydrate delivery and gut comfort from the ingestion of multiple versus single transportable carbohydrates when carbohydrate is ingested at larger intakes during exercise (e.g., ~1.5 g/min) and recent research indicates that fructose-glucose ratio's approaching unity and consistent with sucrose (i.e., spanning 0.8–1.0, O'Brien et al., 2013) represent the most advantageous carbohydrate blends. During recovery from exercise, sucrose appears to be equally effective as glucose in the restoration of liver and muscle glycogen synthesis.

In the small number of studies conducted to date, the performance benefits of sucrose either ingested during exercise or in the context of the recovery of exercise capacity have been shown to be similar to other highly metabolizable carbohydrates. Nonetheless, it is clear that there are gaps in the literature and this review has revealed several unanswered questions with respect to the role of sucrose in sport and exercise performance. To summarize:

1. Does the inclusion of sucrose within a low-GI preexercise meal result in maintained blood glucose concentration, enhanced fat oxidation, and reduced muscle glycogen degradation of sufficient magnitude to improve prolonged endurance exercise performance relative to high GI preexercise meals?
2. Can sucrose ingested during exercise at high rates (i.e., 1.5 g/min) elicit the benefits to exogenous carbohydrate delivery, gut comfort and prolonged endurance performance seen observed with free fructose-glucose source ingestion at ratio's that approach unity as compared with more disparate free fructose-glucose source ratio carbohydrate blends?
3. Can postexercise sucrose ingestion at recommended carbohydrate intakes increase whole body (liver and muscle) glycogen storage to an extent that the short-term recovery of endurance performance would be improved relative to consumption of singly transportable carbohydrates?

Clearly sugars, including sucrose per se, feature in the diets of athletes but this is most likely part of the normal pattern of food consumption. Sucrose provision, at least in beverage form, is effective as an exogenous fuel source during and postexercise. Whether sucrose can provide additional performance benefits over other highly metabolizable carbohydrate types or blends will require answers to the questions posed above.

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