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Carbohydrates for training and competition

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Abstract
An athlete's carbohydrate intake can be judged by whether total daily intake and the timing of consumption in relation to exercise maintain adequate carbohydrate substrate for the muscle and central nervous system ("high carbohydrate availability") or whether carbohydrate fuel sources are limiting for the daily exercise programme ("low carbohydrate availability"). Carbohydrate availability is increased by consuming carbohydrate in the hours or days prior to the session, intake during exercise, and refuelling during recovery between sessions. This is important for the competition setting or for high-intensity training where optimal performance is desired. Carbohydrate intake during exercise should be scaled according to the characteristics of the event. During sustained high-intensity sports lasting $\sim$1 h, small amounts of carbohydrate, including even mouth-rinsing, enhance performance via central nervous system effects. While 30–60 $g \cdot h^{-1}$ is an appropriate target for sports of longer duration, events $>$2.5 h may benefit from higher intakes of up to 90 $g \cdot h^{-1}$. Products containing special blends of different carbohydrates may maximize absorption of carbohydrate at such high rates. In real life, athletes undertake training sessions with varying carbohydrate availability. Whether implementing additional "train-low" strategies to increase the training adaptation leads to enhanced performance in well-trained individuals is unclear.

Keywords: *Glycogen, energy intake, performance, "train low"*

Introduction

During exercise, carbohydrate availability to the muscle and central nervous system can be compromised because the fuel cost of an athlete's training or competition programme exceeds endogenous carbohydrate stores. Provision of additional carbohydrate is important because carbohydrate availability limits the performance of prolonged ($>$90 min) sub-maximal or intermittent high-intensity exercise and plays a permissive role in the performance of brief or sustained high-intensity work (Hargreaves, 1999). The 2003 IOC consensus meeting on sports nutrition provided a substantial focus on carbohydrate needs of athletes with the programme involving separate reviews on pre-exercise eating (Hargreaves, Hawley, & Jeukendrup, 2004), nutrition during exercise (Coyle, 2004), post-exercise recovery (Burke, Kiens, & Ivy, 2004), and training and nutrient interactions (Spriet & Gibala, 2004). This review will focus on areas in which the guidelines produced at that meeting should be updated.

Carbohydrate for daily refuelling and recovery

The restoration of muscle and liver glycogen is a fundamental goal of recovery between training sessions or competitive events, particularly when the athlete undertakes multiple workouts within a condensed time period. Table I summarizes guidelines for refuelling, incorporating recent refinements to our knowledge. In 2003 we identified the optimal timing and amount of carbohydrate intake for glycogen storage during early recovery, and whether strategies such as altering the timing, pattern, quality, and type of carbohydrate intake can promote better glycogen synthesis when total carbohydrate intake is below the amount needed for maximal glycogen storage. This will often be the case for female athletes and others who restrict energy intake to achieve

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Table I. Updated guidelines for refuelling after exercise and in the athlete's everyday diet.

Well supported principles

- When it is important to train hard or with high intensity, daily carbohydrate intakes should match the fuel needs of training and glycogen restoration
- Targets for daily carbohydrate intake are usefully based on body mass (or proxy for the volume of active muscle) and exercise load. Guidelines can be suggested (Table II) but need to be fine-tuned according to the athlete's overall dietary goals and feedback from training
- Guidelines for carbohydrate intake should not be provided in terms of percentage contributions to total dietary energy intake
- When the period between exercise sessions is less than 8 h, athletes should consume carbohydrate as soon as practical after the first workout to maximize the effective recovery time between sessions. More importantly, in the absence of carbohydrate intake, refuelling is ineffective
- When carbohydrate intake is sub-optimal for refuelling, adding protein to a meal/snack will enhance glycogen storage (Figure 1)
- Early refuelling may be enhanced by a higher rate of carbohydrate intake, especially when consumed in frequent small feedings (Table II)
- During longer recovery periods (24 h) when adequate energy and carbohydrate is consumed, the types, pattern, and timing of carbohydrate-rich meals and snacks can be chosen according to what is practical and enjoyable
- Carbohydrate-rich foods with a moderate-to-high glycaemic index provide a readily available source of substrate for glycogen synthesis. This may be important when maximum glycogen storage is required in the hours after an exercise bout
- Nutrient-rich carbohydrate foods or other foods added to recovery meals and snacks can provide a good source of protein and other nutrients
- Adequate energy intake is needed to optimize glycogen storage; the restrained eating practices of some athletes interfere both with meeting targets for carbohydrate intake and optimizing glycogen storage from this intake
- Although there are small differences in glycogen storage across the menstrual cycle, females can store glycogen as effectively as male athletes if they consume adequate carbohydrate and energy
- Athletes should follow sensible practices regarding alcohol intake at all times, but particularly in the recovery period after exercise

Equivocal evidence – requiring further study

- Training in a glycogen-depleted or fasted state can enhance the adaptive responses to exercise stimulus and increases exercise capacity in previously untrained individuals. In real life, athletes undertake training sessions with varying carbohydrate availability. Whether implementing additional ''train low'' strategies enhances the performance of well-trained individuals is unclear

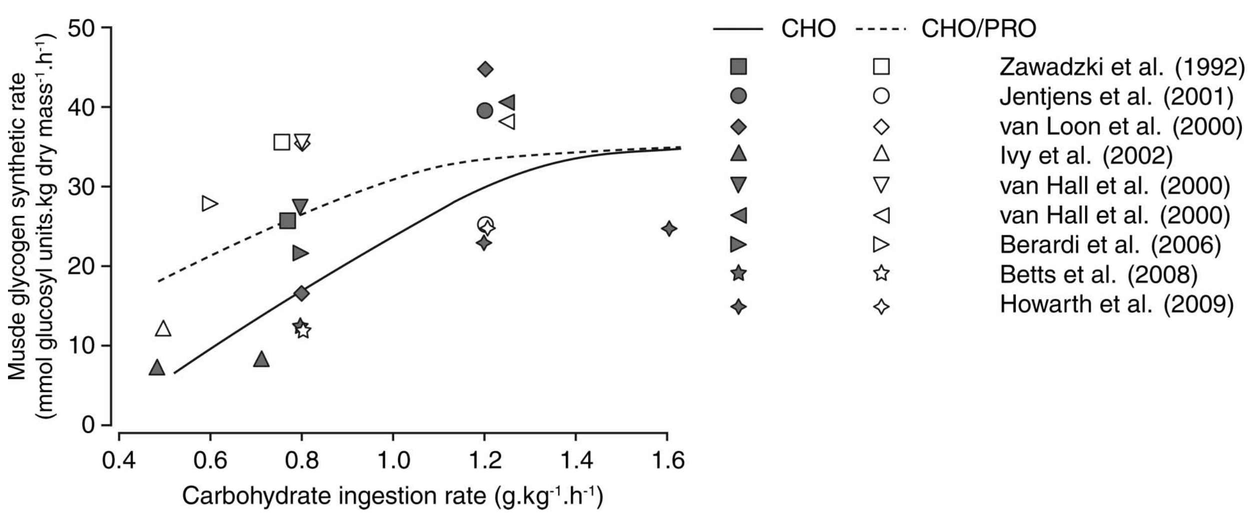

Figure 1. Reported rates of muscle glycogen resynthesis across nine studies that have compared muscle glycogen storage over > 2–6 h post-exercise with varied rates of carbohydrate (CHO) intake, with or without co-ingestion of protein (PRO). This provides evidence that when CHO intake is below refuelling guidelines (< 1.2 g.kg^{-1}.h^{-1}), the addition of protein ($\approx$20g) enhances glycogen synthesis. (adapted from Betts and Williams, 2010, with permission).

physique goals. Unfortunately, little further information is available.

Some opportunities exist, however, to enhance glycogen storage from a given amount of carbohydrate; these include use of high molecular weight glucose polymers (Piehl Aulin, Soderlund, & Hultman, 2000), co-ingestion of large amounts of caffeine (Pedersen et al., 2008), and prior creatine loading (Robinson, Sewell, Hultman, & Greenhaff, 1999). Practical implications of these strategies may limit their use. For example, reliance on glucose polymer to provide a substantial energy intake reduces the nutrient density of the diet and may impair the athlete's ability to meet other nutritional goals. Meanwhile, side-effects associated with supplementation of large doses of caffeine (e.g. interference with sleep) or creatine (e.g. weight gain) may prevent these from being routinely used. Future research should attempt to identify the situations or individuals who might benefit from enhanced glycogen storage associated with these or other strategies in spite of the potential disadvantages. The dietary strategy of true value when energy restriction or poor appetite limit carbohydrate intake is to add protein. Despite earlier debate, it is now clear that this enhances glycogen storage when carbohydrate intake is suboptimal (Figure 1).

A key recommendation of the 2003 guidelines centred on the terminology to describe and advise athletes about the carbohydrate content of their eating plans or post-exercise diets. We proposed that a "high carbohydrate diet", particularly when judged as a percentage of energy intake, is a nebulous term that is poorly correlated to both the amount of carbohydrate actually consumed and the fuel requirements of an athlete's training or competition demands (Burke et al., 2004). Just as "energy availability" has been coined to define an athlete's energy intake in relation to the energy costs of their specific exercise programme, we now argue that "carbohydrate availability" is a preferable way to discuss carbohydrate intake. An athlete's carbohydrate status is best considered in terms of whether their total daily intake and the timing of its consumption in relation to exercise, maintains an adequate supply of carbohydrate substrate for the muscle and central nervous system ("high carbohydrate availability") or whether carbohydrate fuel sources are depleted or limiting for the daily exercise programme ("low carbohydrate availability").

Our continued approach to setting guidelines for daily carbohydrate intake is to consider the importance of achieving high carbohydrate availability, then estimate the carbohydrate cost of the specific exercise task. There is sound evidence that high carbohydrate availability is desirable in the competition setting where it may contribute to optimal performance (Hargreaves et al., 2004; Hawley, Schabort, Noakes, & Dennis, 1997; Temesi, Johnson, Raymond, Burdon, & O'Connor, 2011), but this may not always be the case for each training session. Estimations of the amount of carbohydrate required to replenish glycogen stores and to consume during exercise as a supplementary fuel source should consider the mass of the exercising musculature (using body weight as a proxy), with a sliding scale according to the training or competition energy cost (Table II). We have expanded the suggested work-based categories since the 2003 guidelines. Unfortunately, this is not underpinned by direct knowledge of the glycogen cost of the real-life exercise programmes undertaken by athletes; such data are surprisingly limited. Rather, it is driven by pragmatic feedback from sports nutritionists that previously stated targets were impractical for athletes who are large, follow energy-restricted diets, and/or undertake predominantly skill-based or low-intensity activities. Therefore, until a better model is proposed, it is sensible to increase the flexibility of guidelines for daily fuel requirements.

Another remodelling of key messages is that the athlete's needs are not static, but rather move between categories according to changes in the daily, weekly or seasonal goals and exercise commitments in a periodized training programme. We also note that it is useful to adjust an athlete's carbohydrate intake by strategically consuming meals/snacks providing carbohydrate and other nutrients around important exercise sessions. This allows nutrient and energy intake to track with the needs of the athlete's exercise commitments as well as specifically promoting the potential for high carbohydrate availability to enhance performance and recovery at key times.

Acute strategies to promote high carbohydrate availability for exercise

Manipulating nutrition and exercise in the hours and days prior to an important exercise bout allows an athlete to commence the session with glycogen stores that are commensurate with the estimated fuel costs of the event. In the absence of severe muscle damage, glycogen stores can be normalized with 24 h of reduced training and adequate fuel intake (Burke et al., 2004) (see Table II). Events of more than 90 min duration may benefit from higher glycogen stores (Hawley et al., 1997). The evolution of "carbohydrate loading" strategies illustrates how knowledge and practice in sports nutrition often develop. The first studies (Ahlborg et al., 1967) were undertaken in physically active rather than specifically trained individuals and used dietary extremes to achieve a maximal effect rather than nutritional manipulations that would be practical in the field. The glycogen supercompensation protocol derived from this era involved a period of depletion (3 days low carbohydrate + training) followed by a 3-day loading phase (taper + high carbohydrate intake). Today we recognize the importance of considering responses in highly trained individuals and according to the requirements of real sporting events. Subsequent studies around these issues have demonstrated that high glycogen concentrations can be achieved without a depletion phase (Sherman, Costill, Fink, & Miller, 1981) and with as little as 24–36 h of high carbohydrate intake/rest (Bussau, Fairchild, Rao, Steele, & Fournier 2002). Although it seems possible for the trained muscle to supercompensate glycogen with much less effort than previously thought, one study has found that very high elevations in muscle

Table II. Summary of guidelines for carbohydrate intake by athletes.

	Situation	Carbohydrate targets	Comments on type and timing of carbohydrate intake
DAILY NEEDS FOR FUEL AND RECOVERY: *these general recommendations should be fine-tuned with individual consideration of total energy needs, specific training needs, and feedback from training performance*			
Light	• Low-intensity or skill-based activities	3–5 g · kg^{-1} of athlete's body mass per day	• Timing of intake may be chosen to promote speedy refuelling, or to provide fuel intake around training sessions in the day. Otherwise, as long as total fuel needs are provided, the pattern of intake may simply be guided by convenience and individual choice • Protein- and nutrient-rich carbohydrate foods or meal combinations will allow the athlete to meet other acute or chronic sports nutrition goals
Moderate	• Moderate exercise programme (i.e. ~1 h · day^{-1})	5–7 g · kg^{-1} · day^{-1}	
High	• Endurance programme (e.g. moderate-to-high intensity exercise of 1–3 h · day^{-1})	6–10 g · kg^{-1} · day^{-1}	
Very high	• Extreme commitment (i.e. moderate-to-high intensity exercise of >4–5 h · day^{-1})	8–12 g · kg^{-1} · day^{-1}	
ACUTE FUELLING STRATEGIES: *these guidelines promote high carbohydrate availability to promote optimal performance in competition or key training sessions*			
General fuelling up	• Preparation for events <90 min exercise	7–12 g · kg^{-1} per 24 h as for daily fuel needs	• Athletes may choose compact carbohydrate-rich sources that are low in fibre/residue and easily consumed to ensure that fuel targets are met, and to meet goals for gut comfort or lighter "racing weight"
Carbohydrate loading	• Preparation for events >90 min of sustained/ intermittent exercise	36–48 h of 10–12 g · kg^{-1} body mass per 24 h	
Speedy refuelling	• <8 h recovery between two fuel demanding sessions	1.0–1.2 g · kg^{-1} · h^{-1} for first 4 h then resume daily fuel needs	• There may be benefits in consuming small regular snacks • Compact carbohydrate-rich foods and drinks may help to ensure that fuel targets are met
Pre-event fuelling	• Before exercise >60 min	1–4 g · kg^{-1} consumed 1–4 h before exercise	• The timing, amount, and type of carbohydrate foods and drinks should be chosen to suit the practical needs of the event and individual preferences/ experiences • Choices high in fat/protein/fibre may need to be avoided to reduce risk of gastrointestinal issues during the event • Low GI choices may provide a more sustained source of fuel for situations where carbohydrate cannot be consumed during exercise
During brief exercise	• <45 min	Not needed	
During sustained high-intensity exercise	• 45–75 min	Small amounts including mouth rinse	• A range of drinks and sports products can provide easily consumed carbohydrate
During endurance exercise including "stop and start" sports	• 1.0–2.5 h	30–60 g · h^{-1}	• Opportunities to consume foods and drinks vary according to the rules and nature of each sport • A range of everyday dietary choices and specialised sports products ranging in form from liquid to solid may be useful • The athlete should practice to find a refuelling plan that suits their individual goals including hydration needs and gut comfort
During ultra-endurance exercise	• >2.5–3.0 h	Up to 90 g · h^{-1}	• As above • Higher intakes of carbohydrate are associated with better performance • Products providing multiple transportable carbohydrates (glucose:fructose mixtures) will achieve high rates of oxidation of carbohydrate consumed during exercise

glycogen could not be repeated when a second protocol was undertaken immediately after a 48-h loading and glycogen-depleting exercise test (McInerney et al., 2005). Nevertheless, the well-trained athletes in this study were able to maintain performance on the successive endurance exercise protocols when a high carbohydrate diet was consumed between trials. Although laboratory studies provide evidence that exercise of more than 90 min duration can cause glycogen depletion, and thus benefit from strategies to supercompensate stores prior to the protocol (Hawley et al., 1997), more field research is needed to define the range of sporting events in which this might be of advantage. Sports-specific investigations have shown that carbohydrate loading can enhance performance of distance running $\geq$30 km (Karlsson & Saltin, 1971) and prolonged team games involving repeated high-intensity sprints such as ice hockey (Akermark, Jacobs, Rasmusson, & Karlsson, 1996) and soccer (Balsom, Wood, Olsson, & Ekblom, 1999). Current recommendations for pre-event carbohydrate intake are summarized in Table II and recognize the specificity of the needs and logistics of each sporting event, as well as the personal preferences and experience of the individual athlete.

Glycaemic index and exercise

The concept of the glycaemic index (GI) was first introduced in the early 1980s as a method of functionally ranking carbohydrate-rich foods, based on measured blood glucose responses to the intake of the test food compared with a reference food such as glucose or white bread (Jenkins et al., 1981). Although nutritional recommendations to improve exercise capacity and performance are often based on information related to the GI of carbohydrate sources, there is some debate about the consistency of the outcomes of implementing this advice.

Some studies focusing on the composition of a pre-exercise meal have provided evidence that a benefit exists in relation to metabolism and substrate utilization during subsequent exercise when low GI carbohydrate-rich foods are compared with a high GI meal (for a review, see Burke, 2010b). The primary benefit is that the attenuated post-prandial hyperglycaemia and hyperinsulinaemia of the low GI carbohydrate source reduces the suppression of free fatty acid oxidation that normally accompanies carbohydrate feeding, and possibly achieves better maintenance of plasma glucose concentrations and more sustained carbohydrate availability during exercise. However, although a few studies have reported enhanced endurance following the consumption of low GI carbohydrate sources in the pre-exercise meal (Thomas, Brotherhood, & Brand, 1991; Wong et al., 2008; Wu & Williams, 2009), most studies have failed to find that metabolic differences arising from the GI of carbohydrates consumed before exercise translate into better exercise capacity or performance in subsequent exercise (for a review, see Burke, 2010b). Furthermore, when carbohydrate is ingested during endurance exercise, it negates the effect of glycaemic characteristics of the pre-exercise meals (Burke, Claassen, Hawley, & Noakes, 1998; Chen et al., 2009; Wong et al., 2009). Altering the GI of meals consumed before exercise may offer benefits for some situations (when it is difficult to consume carbohydrate during exercise) or individuals (those who are sensitive to a hyperinsulinaemic response to carbohydrate feedings). However, further research is needed before systematic manipulation of the GI of carbohydrate-rich foods in the athlete's diet can be recommended. In any case, like all aspects of the pre-event meal, the type, timing, and amount of carbohydrate in the competition menu needs to be individualized to the athlete's specific event, their gut comfort, and their individual preferences.

Carbohydrate intake during exercise

The consumption of carbohydrate immediately before and during exercise represents an effective strategy to provide an exogenous fuel source to the muscle and central nervous system. Reviews of this topic (Karelis, Smith, Passe, & Péronnet, 2010; Jeukendrup, 2011) identify a range of potential mechanisms by which supplementary carbohydrate during exercise can enhance performance. These include provision of an additional muscle fuel source when glycogen stores become depleted, muscle glycogen sparing, prevention of low blood glucose concentrations, and effects on the central nervous system. Given the potential for a variety of different, overlapping, and combined benefits on performance, and the variety of ways that fatigue or physiological limitations can manifest in different sports and exercise activities, it seems naive to think that a "one size fits all" recommendation for carbohydrate intake during exercise is sufficient. Yet it is only recently that guidelines were made available.

Both the 2003 IOC consensus view and the more recent ACSM position stand (2007) replaced relatively rigid guidelines of the American College of Sports Medicine (1996) with a more pragmatic approach to the different characteristics of each sport. Namely, for sports of more than 60 min duration in which fatigue would otherwise occur, athletes were encouraged to develop a personalized exercise nutrition plan that combined carbohydrate intake of 30–60 $g \cdot h^{-1}$ and adequate rehydration with the practical opportunities for intake during the event or session (Coyle, 2004). Opportunities for a more systematic approach to specific carbohydrate needs for different types of situations, however, were discouraged by prevailing beliefs, including the capping of the oxidation rate of exogenous carbohydrate at 60 $g \cdot h^{-1}$, the concern that larger intakes might cause gastrointestinal distress, and the lack of evidence of a dose response to carbohydrate intake during exercise. Recent field and laboratory evidence supports an updating of this view.

Carbohydrate intake during prolonged exercise

Surveys of competitive to elite athletes have noted high ($\sim$90 $g \cdot h^{-1}$) intakes of carbohydrate during exercise (Kimber, Ross, Mason, & Speedy, 2002; Saris, Van Erp-Baart, Brouns, Westerterp, & ten Hoor, 1989). These have been reported during endurance cycling events (Tour de France, Ironman triathlon) in which a relative ease of consuming foods and fluids while exercising combines with extreme fuel requirements, and where energy support may be an additional nutritional goal. Nevertheless, these observations have led to questions of whether it is the guidelines (30–60 $g \cdot h^{-1}$) or athlete practices that are wrong.

Important answers come from a series of studies that systematically tracked the oxidation rates of various sources, forms, and combinations of carbohydrate consumed during exercise (Jeukendrup, 2010). The major finding from this body of work is that the rate limiting step in the oxidation of ingested carbohydrate is its intestinal absorption, with limits on absorption of glucose in its various forms by the sodium-dependent glucose transporter SGLT1 at $\sim$1 $g \cdot min^{-1}$. However, when consumed in combination with a carbohydrate that is absorbed by a different transport mechanism (e.g. fructose, using GLUT5), rates of ingested carbohydrate can exceed 1.5 $g \cdot min^{-1}$ (Jentjens, Moseley, Waring, Harding, & Jeukendrup, 2004; Jentjens et al., 2006). The various interests of gastrointestinal comfort, opportunity to consume carbohydrate while exercising, and the high rates of exogenous carbohydrate oxidation required to maintain power output when glycogen becomes depleted, converge at a carbohydrate ingestion rate of $\sim$80–90 $g \cdot h^{-1}$, at least when glucose and fructose are co-ingested in a 2:1 ratio (Jeukendrup, 2010). Athletic practice has both preceded and now benefited from these findings, since sports nutrition companies now produce a range of carbohydrate-containing fluids/gels/bars with this ratio of the so-called "multiple transportable carbohydrates". A variety of forms of these products, ranging from liquid to solid, appear to deliver high rates of carbohydrate (Pfeiffer, Stellingwerff, Zaltas, & Jeukendrup, 2010a, 2010b) and can be tolerated in the field (Pfeiffer, Stellingwerff, Zaltas, Hodgson, & Jeukendrup, 2011)

Added to the support for a revision of the guidelines for prolonged sporting activities, is emerging evidence of a dose–response relationship between carbohydrate intake and performance of events longer than 2.5 h in which the optimal rate of intake appears to be within the range of 60–90 $g \cdot h^{-1}$ (Smith et al., 2010a, 2010b). Finally, studies using multiple transportable carbohydrates have shown benefits to the performance of exercise activities of $\sim$3 h duration compared with the ingestion of glucose alone (Currell & Jeukendrup, 2008; Triplett, Doyle, Rupp, & Benardot, 2010). Therefore, new guidelines to promote individual experimentation with carbohydrate intakes of up to 90 $g \cdot h^{-1}$ in ultra-endurance sports are warranted (see Table II). We have provided these guidelines in absolute amounts, based on the evidence that there is little difference in the oxidation of exogenous carbohydrate according to body size/body mass (see Figure 2). Instead, factors such as the carbohydrate content of the habitual diet or intake during training sessions (Cox et al., 2010) may play a role in determining capacity for oxidizing carbohydrate ingested during exercise.

Carbohydrate intake in sports lasting $\sim$1 h

Sports involving $\sim$1 h of sustained or intermittent high-intensity exercise are not limited by the availability of muscle glycogen stores given adequate nutritional preparation. Therefore, evidence of enhanced performance when carbohydrate is consumed during a variety of such exercise protocols is perplexing (for a review, see Burke, Wood, Pyne, Telford, & Saunders, 2005). Findings of a lack of improvement of a 1-h cycling protocol with glucose *infusion* (Carter, Jeukendrup, Mann, & Jones, 2004b) but benefits from carbohydrate *ingestion* (Carter, Jeukendrup, & Jones, 2004a) created an intriguing hypothesis that the central nervous system might sense the presence of carbohydrate via receptors in the mouth and oral space, promoting an enhanced sense of well-being and improved pacing. This theory was subsequently confirmed by observations that simply rinsing the mouth with a carbohydrate solution can also enhance performance of the cycling bout (Carter et al., 2004a). A number of studies have now investigated this phenomenon, including several in which functional magnetic resonance imaging technology has tracked changes in various areas of the brain with carbohydrate mouth sensing (Chambers, Bridge, & Jones, 2009). In these studies, both sweet and non-sweet carbohydrates were shown to activate regions in the brain associated with reward and motor control.

There is now robust evidence that in situations when a high power output is required over durations of about 45–75 min, mouth rinsing or intake of very

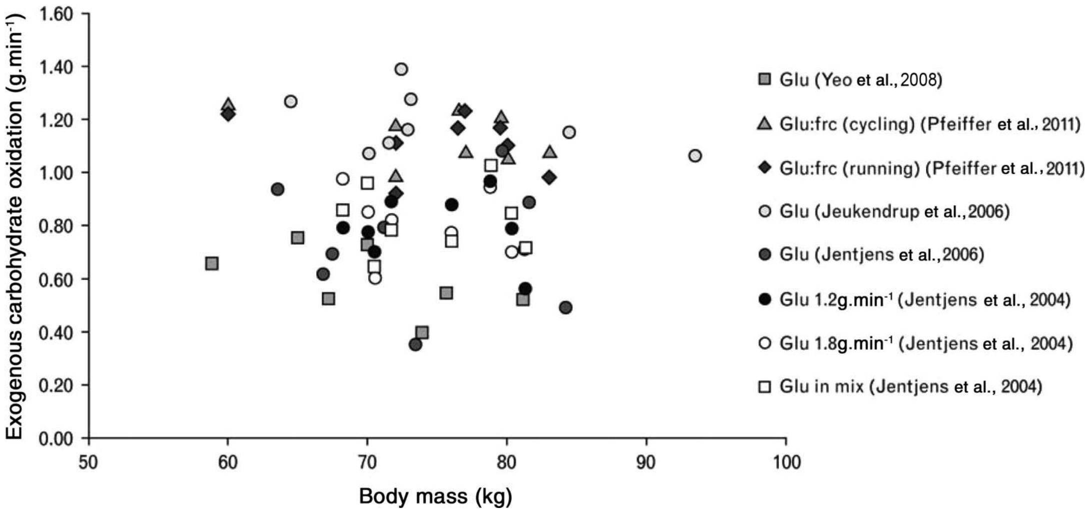

Figure 2. Results of peak oxidation rates of exogenous carbohydrate consumed during exercise versus body mass for individuals involved in a number of studies. These data show that there is no correlation between exogenous fuel use and body size, and suggest that guidelines for carbohydrate intake during exercise can be provided in absolute amounts rather than scaled to body mass (adapted from Jeukendrup et al., 2006, with permission). Glc = glucose, frc = fructose.

small amounts of carbohydrate play a largely non-metabolic role involving the central nervous system in enhancing performance by 2–3% (Jeukendrup & Chambers, 2010). Not all studies have reported this effect, however, possibly because a carbohydrate-rich pre-event meal is associated with a dampening of the effect (Beelen et al., 2009). These findings have been incorporated into updated guidelines for carbohydrate intake during exercise (Table II).

Train low/compete high – a new paradigm for training adaptations?

Although we have previously encouraged athletes to follow a training diet based on the fuel cost of their exercise load, evolving research into exercise and nutrient interactions has identified that an alternative approach might be of value. From a cellular perspective, training adaptations are the consequence of the accumulation of specific proteins required for sustaining energy metabolism during and after a series of exercise sessions (Hawley & Burke, 2010). However, it has been uncertain whether it is a lack or surplus of a substrate that triggers the training adaptation (Coyle, 2000). New molecular insights show that compared with high muscle glycogen content, an acute bout of (endurance) exercise commenced with low muscle glycogen results in a greater transcriptional activation of enzymes involved in carbohydrate metabolism (i.e. the AMP-activated protein kinase [AMPK], GLUT-4, hexokinase, and the pyruvate dehydrogenase [PDH] complex), and an increase in adaptive responses favouring fat metabolism (see Hawley & Burke, 2010; Hawley, Burke, Phillips, & Spriet, 2011). Based on convincing evidence of enhanced muscle markers of cellular signalling and metabolic adaptation following training in a low carbohydrate environment, a new concept of dietary periodization has been promoted whereby the athlete should "train low" to promote a greater training response, before switching to high carbohydrate availability for competition when optimal performance is required (Baar & McGee, 2008).

The watershed investigation of Hansen and colleagues (2005) provides apparent evidence to support such dietary periodization. The 10-week training study required previously sedentary men to train one leg with a "two a day" training protocol every second day, while the contralateral leg undertook the same workouts, spread over a daily training schedule (Hansen et al., 2005). Maximal power output increased equally in each leg, but the leg that trained twice-a-day, commencing 50% of its training sessions with a low glycogen concentration, showed greater increases in kicking endurance accompanied by greater maximal activity of an "aerobic" enzyme. These findings have significant scientific merit and possible application for exercise programmes targeting metabolic improvements and health outcomes. However, there are some caveats that must be applied in relation to sports performance.

The first problem is the misconception that all "train low" techniques require chronic adherence to a low carbohydrate diet. Exposure to a high-fat, low-carbohydrate diet causes differences in the metabolic outcomes associated with repeated exercise, both in short-term fat adaptation protocols (Burke & Hawley, 2002) and longer-term training studies (Helge, 2002). Although training on a high-fat diet is associated with an increased ability to oxidize fat during exercise and a decreased reliance on muscle glycogen utilization (Helge, Watt, Richter, Rennie, & Kiens, 2001; Burke et al., 2002), there are also indications that it can reduce the chronic adaptations to training (Helge, Richter, & Kiens, 1996) and impair carbohydrate utilization (Stellingwerff et al., 2006) and the ability to sustain high-intensity exercise performance (Havemann et al., 2006). Therefore, the more recent train low protocols have utilized a different approach to reducing carbohydrate availability for training. In fact, the protocol used in the primary study used the placement of training sessions rather than dietary manipulation to achieve low glycogen levels for specific workouts. Other ways to selectively reduce carbohydrate availability for training include exercising after an overnight fast, consuming water during prolonged workouts, withholding carbohydrate in the hours after exercise, and restricting carbohydrate below the fuel requirements of the training load (Burke, 2010a). Such protocols differ in the duration of exposure to a low carbohydrate environment as well as the focus on reducing endogenous and/or exogenous carbohydrate stores.

The second issue involves direct translation of research on exercise metabolism into the outcomes of sport or athletic performance. Characteristics that have been questioned include the transfer of information from previously untrained individuals to well-trained populations and the use of a "clamped" training programme (training at the same power-specific output for each session) compared with the principles of progressive overload and self-pacing that underpin the training programmes of athletes (Hawley & Burke, 2010). Further studies utilizing the "two a day training" model of low glycogen training (Hulston et al., 2010; Morton et al., 2009; Yeo et al., 2008), or manipulation of exogenous carbohydrate availability via the presence or absence of carbohydrate intake before and during exercise (De Bock et al., 2008; Cox et al., 2010; Nybo et al., 2009; Van Proeyen, Szlufcik, Nielens, Ramaekers, & Hespel, 2011), have been undertaken. Given the large number of study characteristics that can be manipulated, it is not surprising that the sparse literature has only just scratched the surface of the potential areas of interest and application. Nevertheless, there is consistent evidence that undertaking some exercise sessions with low glycogen/exogenous carbohydrate availability can enhance the metabolic adaptations associated with training, even in well-trained individuals.

It is important to recognize, however, that no sporting medals are awarded for the muscle with highest concentration of cellular signalling molecules or metabolic enzymes. Instead, victory goes to athletes who are the swiftest, highest, strongest or otherwise best able to perform in their event. Muscular adaptations achieved by training provide part of the process by which athletes improve their ability to perform. However, changes in muscle physiology are not, *per se*, a proxy for performance and currently there is no convincing evidence that train low strategies achieve an enhancement of performance over a conventional diet/training approach (Hawley & Burke, 2010). Furthermore, several disadvantages are associated with train low techniques, including an impairment of the ability to train at high intensities; this is not insignificant because it is a cornerstone of the principles of preparation for elite sport.

In summary, further research on this topic is needed, but a pragmatic commentary on practices in the field is that athletes already periodize the carbohydrate availability for their training sessions. By design or by accident, some workouts are undertaken with reduced carbohydrate availability (the second or third session of a day during high-volume periods, early morning sessions undertaken before breakfast, training during a period of energy restriction for weight loss) while others are undertaken with good carbohydrate support (quality sessions scheduled during lower volume periods, sessions undertaken after a meal). Thus the real question is not whether there is a role for dietary periodization with carbohydrate availability, but whether it should be exploited in a different way. For the moment, it makes sense to focus on good carbohydrate availability for sessions requiring high intensity or high levels of technique and skill, while noting that it is less important during lower intensity workouts or the conditioning sessions at the beginning of a season.

Summary and future directions for research

It is encouraging that even in areas that have benefited from nearly a decade of sports science research, new ideas continue to emerge and add value to the practice of sports nutrition. Quantitative and qualitative guidelines for carbohydrate intake over the day and in relation to exercise, based on our updated knowledge, are summarized in Tables I and II. Questions for future research include:

1. Can manipulation of nutrition characteristics promote better glycogen storage from a given carbohydrate intake, particularly in cases where energy restrictions or practical challenges cause sub-optimal carbohydrate intake.
2. Can strategies to "train low" with low availability of endogenous and/or exogenous carbohydrate availability be further incorporated into the periodized training programme to enhance

competition performance? In particular, researchers need to employ practical and sensitive measures of performance to determine whether metabolic differences in the muscle translate into functional changes that are worthwhile in determining the outcomes of sport.

3. Can a better understanding of the effects of carbohydrate on the central nervous system help us to exploit an ergogenic effect?

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