

Pre-exercise carbohydrate and fat ingestion: effects on metabolism and performance

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A key goal of pre-exercise nutritional strategies is to maximize carbohydrate stores, thereby minimizing the ergolytic effects of carbohydrate depletion. Increased dietary carbohydrate intake in the days before competition increases muscle glycogen levels and enhances exercise performance in endurance events lasting 90 min or more. Ingestion of carbohydrate 3–4 h before exercise increases liver and muscle glycogen and enhances subsequent endurance exercise performance. The effects of carbohydrate ingestion on blood glucose and free fatty acid concentrations and carbohydrate oxidation during exercise persist for at least 6 h. Although an increase in plasma insulin following carbohydrate ingestion in the hour before exercise inhibits lipolysis and liver glucose output, and can lead to transient hypoglycaemia during subsequent exercise in susceptible individuals, there is no convincing evidence that this is always associated with impaired exercise performance. However, individual experience should inform individual practice. Interventions to increase fat availability before exercise have been shown to reduce carbohydrate utilization during exercise, but do not appear to have ergogenic benefits.

Keywords: fatigue, free fatty acids, glucose uptake, insulin, muscle glycogen.

Introduction

The importance of carbohydrate for exercise performance has been recognized since the classic respiratory exchange studies of Christensen and Hansen in the late 1930s and the biopsy studies of Bergstrom and colleagues (Bergstrom *et al.*, 1967), who measured muscle glycogen during various dietary and exercise interventions. Since then, considerable attention has focused on nutritional strategies to maximize endogenous carbohydrate stores (liver and muscle glycogen), thereby minimizing the potential ergolytic effects of carbohydrate depletion (Coyle *et al.*, 1986). In this review, attention will focus on dietary carbohydrate during training in the days (1–7) leading up to competition and on carbohydrate and fat ingestion in the hours immediately before exercise and their effects on exercise metabolism and performance.

Carbohydrate loading in the days before exercise

In the classic carbohydrate loading study of Bergstrom *et al.* (1967), the ingestion of a high carbohydrate diet, following a period of relative carbohydrate deprivation, resulted in a marked increase (supercompensation) in muscle glycogen (to as high as 200 mmol·kg⁻¹ wet mass) and enhanced subsequent endurance exercise performance. More recently, a less extreme diet-exercise regimen was found to be equally effective in elevating pre-exercise muscle glycogen to these levels (Sherman *et al.*, 1981), but had no effect on subsequent 21-km running performance lasting ~80 min. Trained athletes were shown to increase their muscle glycogen to 180 mmol·kg⁻¹ wet mass in as little as one day by ingesting 10 g carbohydrate·kg⁻¹ BM (where BM = body mass) and remaining inactive (Bussau *et al.*, 2002). Muscle glycogen did not increase further during another 2 days of rest and high carbohydrate intake. There is also evidence that well-trained athletes can maintain, or even increase, their muscle glycogen stores to 170–180 mmol·kg⁻¹ wet mass in less than 24 h while training (~67% $\dot{V}O_{2peak}$) 2 h per day and

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consuming 10–12.5 g carbohydrate · kg⁻¹ BM · day⁻¹ (Coyle *et al.*, 2001). It has even been suggested that trained athletes can greatly increase their muscle glycogen stores in less than 24 h by performing only 3 min of supramaximal exercise and then consuming a high carbohydrate diet (Fairchild *et al.*, 2002). This protocol potentially represents an improvement over previous regimens that have been tested extensively under laboratory and/or field conditions and further study is warranted. The mechanisms that allow trained individuals to rapidly increase muscle glycogen stores remain to be elucidated, but are likely to be related to their higher GLUT-4 concentrations and glycogen synthase activities (Hickner *et al.*, 1997).

Despite a greater reliance on muscle glycogen when pre-exercise concentrations are elevated (Gollnick *et al.*, 1972; Bosch *et al.*, 1993; Hargreaves *et al.*, 1995), increased dietary carbohydrate in the 1–7 days before exercise is generally associated with enhanced performance when exercise duration exceeds about 90 min (Galbo *et al.*, 1979; Brewer *et al.*, 1988; Fallowfield and Williams, 1993; Rauch *et al.*, 1995; Hawley *et al.*, 1997b; Pitsiladis and Maughan, 1999; Walker *et al.*, 2000), probably due to a delay in the point at which muscle glycogen availability is limiting for optimal exercise performance. The largest effects are observed during exercise trials to exhaustion (often referred to as endurance ‘capacity’) and, while still apparent, they are smaller in magnitude during tests of endurance ‘performance’ that are not open-ended such as total work output in a given time or time taken to complete a certain distance or amount of work (Jeukendrup *et al.*, 1996). During prolonged, strenuous exercise, rates of carbohydrate oxidation can be as high as 3–4 g · min⁻¹, derived primarily from muscle glycogen (Angus *et al.*, 2002). Assuming an active muscle mass of ~10 kg during cycling, one could argue that endurance athletes should ensure their pre-event muscle glycogen concentrations are at least in the range of 150–200 mmol · kg⁻¹ wet mass, even when carbohydrate is to be supplemented during exercise. Interestingly, carbohydrate loading has also been associated with increased exercise performance in the heat (Pitsiladis and Maughan, 1999), a condition where carbohydrate availability is not usually thought to limit exercise performance. Carbohydrate loading does not appear to further increase exercise performance when carbohydrate availability is maintained high with a pre-exercise carbohydrate meal and carbohydrate ingestion during exercise (Burke *et al.*, 2000b). Furthermore, while two studies have observed no additional benefit of carbohydrate ingestion during exercise in carbohydrate-loaded individuals (Flynn *et al.*, 1987; Widrick *et al.*, 1993), one study has observed potentiation (Kang *et al.*, 1995). A key factor may be the extent to which blood glucose

concentrations are maintained during exercise in the carbohydrate-loaded state without carbohydrate ingestion. In shorter, more intense exercise bouts lasting about 60–90 min, the benefits of glycogen loading are not apparent (Sherman *et al.*, 1981; Madsen *et al.*, 1990; Hawley *et al.*, 1997a,b), possibly due to muscle glycogen availability not being a limiting factor in the non-carbohydrate-loaded trial in this type of exercise.

During single bouts of high-intensity exercise, the effects of carbohydrate loading are somewhat equivocal. Some studies have observed enhanced performance with elevated muscle glycogen concentrations after increased dietary carbohydrate intake (Maughan and Poole, 1981; Maughan *et al.*, 1997), while others have observed no benefit of elevated pre-exercise muscle glycogen (Vandenbergh *et al.*, 1995; Hargreaves *et al.*, 1997). In studies by Maughan and colleagues, the differences in performance were most obvious at the extremes of diet and may have been due as much to deleterious acid–base disturbances following consumption of a high fat–protein diet as to increased muscle glycogen availability following the high carbohydrate diet (Maughan *et al.*, 1997). With repeated bouts of high-intensity exercise, increased muscle glycogen availability is associated with enhanced intermittent exercise performance (Balsom *et al.*, 1999). Furthermore, increasing dietary carbohydrate intake from ~300 to ~600 g · day⁻¹ in the 2 days before exercise improved long-term, intermittent exercise performance (Bangsbo *et al.*, 1992), while ingestion of 10 g carbohydrate · kg⁻¹ BM improved intermittent running capacity during 22 h of recovery when compared with an isoenergetic diet without additional carbohydrate (Nicholas *et al.*, 1997).

It has been suggested that females may have a reduced ability to increase muscle glycogen during a period of dietary carbohydrate loading (Tarnopolsky *et al.*, 1995), although this observation may have been due to a lower energy intake in the female participants (Tarnopolsky *et al.*, 2001). Other studies have not observed reduced muscle glycogen storage in female athletes (Walker *et al.*, 2000; James *et al.*, 2001). Thus, with adequate energy and carbohydrate intake, female athletes benefit from carbohydrate loading as much as male athletes.

Carbohydrate ingestion 3–4 h before exercise

Ingestion of a carbohydrate-rich meal (containing about 140–330 g carbohydrate) 3–4 h before exercise has been shown to increase muscle glycogen (Coyle *et al.*, 1985) and enhance exercise performance (Sherman *et al.*, 1989; Wright *et al.*, 1991; Schabort *et al.*, 1999). An increase in pre-exercise muscle glycogen is one ex-

planation for the enhanced performance. Alternatively, because liver glycogen concentrations are substantially reduced after an overnight fast, ingestion of carbohydrate may increase these reserves and contribute, together with any ongoing absorption of the ingested carbohydrate, to the maintenance of blood glucose concentrations and improved performance during subsequent exercise (Casey *et al.*, 2000). In contrast, other studies have observed no benefit to exercise performance of a high carbohydrate meal 4 h before exercise (Okano *et al.*, 1996; Whitley *et al.*, 1998).

Despite plasma glucose and insulin concentrations returning to basal levels, ingestion of carbohydrate in the hours before exercise often results in a transient fall in glucose with the onset of exercise, increased carbohydrate oxidation and a blunting of free fatty acid (FFA) mobilization (Coyle *et al.*, 1985; Sherman *et al.*, 1989). These metabolic perturbations can persist for up to 6 h after carbohydrate ingestion (Montain *et al.*, 1991), but are not detrimental to exercise performance, with an increased carbohydrate availability apparently compensating for the greater carbohydrate utilization. No differences in exercise performance have been observed after ingestion of meals that produced marked differences in plasma glucose and insulin concentrations (Wee *et al.*, 1999). The effects of a high carbohydrate meal 3–4 h before exercise on subsequent performance may be equivalent to those observed with carbohydrate ingestion during exercise (Chryssanthopoulos *et al.*, 1994), although this is not always the case (Wright *et al.*, 1991) and there may be some important metabolic differences. The combination of a pre-exercise carbohydrate meal and carbohydrate ingestion during exercise may further enhance exercise performance (Wright *et al.*, 1991; Chryssanthopoulos and Williams, 1997). From a practical perspective, if access to carbohydrate during exercise is limited or non-existent, ingestion of 200–300 g carbohydrate 3–4 h before exercise may be an effective strategy for enhancing carbohydrate availability during the subsequent exercise period. Furthermore, ingestion of carbohydrate may be effective in enhancing subsequent exercise performance when the recovery period is relatively short (~4 h; Fallowfield *et al.*, 1995).

Carbohydrate ingestion 30–60 min before exercise

The ingestion of carbohydrate in the hour before exercise results in a large increase in plasma glucose and insulin concentrations. With the onset of exercise, however, there is a rapid fall in blood glucose concentration as a consequence of the combined stimulatory effects of hyperinsulinaemia and contractile

activity on muscle glucose uptake and inhibition of the exercise-induced rise in liver glucose output (Marmy-Conus *et al.*, 1996; Febbraio *et al.*, 2000a,b), despite ongoing absorption of the ingested carbohydrate. An enhanced uptake and oxidation of blood glucose by skeletal muscle may account for the increased carbohydrate oxidation often observed after pre-exercise carbohydrate ingestion (Costill *et al.*, 1977; Febbraio and Stewart, 1996; Coyle *et al.*, 1997; Horowitz *et al.*, 1997). In addition, an increase in muscle glycogenolysis has been reported by some researchers (Costill *et al.*, 1977; Hargreaves *et al.*, 1985; Febbraio *et al.*, 2000b), although others have not observed such an effect (Levine *et al.*, 1983; Fielding *et al.*, 1987; Hargreaves *et al.*, 1987; Febbraio and Stewart, 1996). The increase in plasma FFA concentrations with exercise is attenuated following pre-exercise carbohydrate ingestion, as a consequence of insulin-mediated inhibition of lipolysis (Horowitz *et al.*, 1997). Fat oxidation is reduced because of the lower plasma FFA availability, but also as a result of inhibition of lipid oxidation within muscle (Coyle *et al.*, 1997), since restoration of plasma FFA availability does not completely return fat oxidation to values seen during exercise in the fasted state (Horowitz *et al.*, 1997). Co-ingestion of medium-chain triglyceride with carbohydrate, as a strategy to increase plasma FFA, has no effect on muscle glycogen use during subsequent exercise (Horowitz *et al.*, 2000). Since these metabolic effects of pre-exercise carbohydrate ingestion are a consequence of hyperglycaemia and hyperinsulinaemia, there has been interest in strategies that minimize the changes in plasma glucose and insulin before exercise. These have included the ingestion of fructose (Levine *et al.*, 1983; Hargreaves *et al.*, 1985, 1987) or carbohydrate types other than glucose with differing glycaemic indices (Thomas *et al.*, 1991; Febbraio and Stewart, 1996; Kirwan *et al.*, 1998, 2001a,b; Sparks *et al.*, 1998; DeMarco *et al.*, 1999; Febbraio *et al.*, 2000b; Jentjens and Jeukendrup, 2003), varying the carbohydrate load (Seifert *et al.*, 1994; Jentjens *et al.*, 2003) and ingestion schedule (Moseley *et al.*, 2003; Short *et al.*, 1997), the addition of fat (Horowitz and Coyle, 1993), or the inclusion of warm-up exercise in the pre-exercise period (Brouns *et al.*, 1989). In general, while these various interventions modify the metabolic response to exercise, there appears to be no great advantage for exercise performance in blunting the pre-exercise glycaemic and insulinaemic responses.

The glycaemic responses during exercise preceded by carbohydrate ingestion are determined by several factors. These include the combined stimulatory effects of insulin and contractile activity on muscle glucose uptake, the balance of inhibitory and stimulatory effects of insulin and catecholamines, respec-

tively, on liver glucose output, and the magnitude of ongoing intestinal absorption of glucose from the ingested carbohydrate (Kuipers *et al.*, 1999). The occurrence of rebound hypoglycaemia in susceptible individuals does not appear to be related to insulin sensitivity (Jentjens and Jeukendrup, 2002) or to the exercise intensity (Achten and Jeukendrup, 2003). Thus, the aetiology of rebound hypoglycaemia remains unknown and susceptibility to this condition must be determined by personal experience. Since the inhibition of lipolysis and fat oxidation occurs with only small increases in plasma insulin – for example, after fructose (low glycaemic index) ingestion – it could be argued that if pre-exercise carbohydrate ingestion is the only mechanism by which an athlete can increase carbohydrate availability during exercise, they would be well advised to ingest a reasonable amount of carbohydrate (perhaps as much as 100 g), without undue gastrointestinal distress, so as to compensate for the suppressed fat oxidation and to provide a pool of glucose that becomes available for use during the later stages of exercise.

The metabolic alterations associated with ingestion of carbohydrate in the 30–60 min before exercise have the potential to influence exercise performance. It has been postulated that the increase in muscle glycogenolysis observed previously (Costill *et al.*, 1977) would result in an earlier onset of fatigue during exercise, as was suggested in a subsequent study (Foster *et al.*, 1979). In contrast, every study since has shown either unchanged (Hargreaves *et al.*, 1987; Febbraio and Stewart, 1996; Sparks *et al.*, 1998; Febbraio *et al.*, 2000b; Jentjens and Jeukendrup, 2003; Jentjens *et al.*, 2003; Moseley *et al.*, 2003) or enhanced (Gleeson *et al.*, 1986; Sherman *et al.*, 1991; Thomas *et al.*, 1991; Kirwan *et al.*, 1998) endurance exercise performance after the ingestion of carbohydrate in the hour before exercise. Thus, notwithstanding the well-documented metabolic effects of pre-exercise carbohydrate ingestion, and the possible negative consequences of hypoglycaemia in susceptible individuals, on balance there appears to be little evidence to support the practice of avoiding carbohydrate ingestion in the hour before exercise, provided sufficient carbohydrate is ingested. Having said that, individual practice must be determined on the basis of individual experience with various pre-exercise carbohydrate ingestion protocols. Finally, when carbohydrate is ingested during prolonged exercise, the glycaemic index of pre-exercise carbohydrate feedings has no effect on performance (Burke *et al.*, 1998); indeed, carbohydrate ingestion during exercise may be a more effective strategy for enhancing exercise performance (Febbraio *et al.*, 2000a) if this is the only option available to an athlete.

Increased fat availability before exercise

Another potential strategy to enhance endurance exercise performance is to increase fat availability acutely, with a view to reducing carbohydrate utilization during exercise, thereby delaying the onset of carbohydrate depletion and fatigue. Increased dietary fat intake over a 24-h period increased muscle triglyceride stores, but reduced cycling time-trial performance, compared with a high carbohydrate diet (Starling *et al.*, 1997). A longer period of ‘fat adaptation’ (5 days + 1 day carbohydrate intake to normalize muscle glycogen) resulted in marked carbohydrate sparing during exercise bouts lasting 2–4 h, but subsequent exercise performance was not altered (Burke *et al.*, 2000a; Carey *et al.*, 2001). Furthermore, although trained athletes were able to perform intense interval training sessions on such a dietary regimen, they were associated with increased ratings of perceived exertion (Stepito *et al.*, 2002). Ingestion of high fat meals and infusion of Intralipid, both in combination with heparin administration, are effective in raising plasma FFA concentrations and have been associated with reduced muscle glycogen utilization (Costill *et al.*, 1977; Vukovich *et al.*, 1993) and carbohydrate oxidation (Hawley *et al.*, 2000). One study has observed increased endurance with elevated plasma FFA before exercise (Pitsiladis *et al.*, 1999), while others have not seen any benefit (Okano *et al.*, 1996, 1998; Whitley *et al.*, 1998; Hawley *et al.*, 2000). Thus, it would appear that while such a strategy can have a marked effect on exercise metabolism (i.e. reduced carbohydrate utilization), there is no beneficial effect on exercise performance.

Summary

Increasing dietary carbohydrate intake to $\sim 10 \text{ g} \cdot \text{kg}^{-1}$ BM in the days leading up to athletic competition increases muscle glycogen stores and is associated with enhanced endurance exercise capacity and performance in events lasting more than 90 min. While the performance of a single high-intensity effort does not appear to be improved by carbohydrate loading, intermittent high-intensity performance may be enhanced. Female and male athletes benefit equally from carbohydrate loading, provided energy and carbohydrate intake are adequate. Ingestion of a carbohydrate-rich (about 200–300 g carbohydrate) meal after an overnight fast and 2–4 h before exercise can replenish endogenous carbohydrate reserves and is associated with improved performance. On balance, the literature indicates that ingestion of carbohydrate in the hour before exercise does not impair exercise performance. However, there may be individuals who are susceptible

to hypoglycaemia and its negative consequences. There are no clear indicators of susceptibility to rebound hypoglycaemia during exercise and this should be assessed by individual experience. Increasing fat availability before exercise reduces carbohydrate utilization during subsequent exercise, but does not alter exercise performance.

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