CARBOHYDRATE NUTRITION AND EXERCISE PERFORMANCE

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Summary

During prolonged, strenuous exercise, muscle glycogen and blood glucose are major substrates for contracting skeletal muscle and fatigue often coincides with depletion of these carbohydrate reserves. Thus, the goals of carbohydrate nutritional strategies for exercise are: (1) to optimise the availability of muscle and liver glycogen and blood glucose prior to exercise, and (2) to maintain an adequate supply of carbohydrate to contracting skeletal muscle and a high rate of carbohydrate oxidation during the latter stages of prolonged exercise. These goals are achieved by ensuring that athletes consume a diet high in carbohydrate during periods of intense training and supplement their endogenous carbohydrate reserves, by ingesting carbohydrate, during prolonged, strenuous exercise. Such nutritional strategies are associated with enhanced endurance exercise performance.

I. INTRODUCTION

Muscle glycogen and blood glucose, derived from liver glycogen, are important substrates for contracting skeletal muscle during prolonged, strenuous exercise. Fatigue during such exercise is often associated with muscle glycogen depletion and hypoglycemia (Coggan and Coyle 1987; Vøllestad et al. 1984). The observation of an increase in ATP breakdown products (IMP, hypoxanthine, NH_3) in glycogen-depleted muscle cells (Broberg and Sahlin 1989) suggests impaired ATP resynthesis in such cells. This appears to be due to a relative pyruvate deficiency, which results in reduced substrate for reactions that supply tricarboxylic acid (TCA) cycle intermediates necessary for the oxidation of acetyl CoA (Sahlin et al. 1990). Increasing carbohydrate availability, by ingesting glucose during exercise, attenuates the rise in IMP, maintains TCA cycle intermediates and enhances endurance performance (Spencer et al. 1991). Thus, in view of the importance of carbohydrate for endurance exercise performance, the goals of nutritional strategies before and during exercise are to optimise the supply of muscle and liver glycogen and blood glucose, with a view to maintaining a high rate of carbohydrate oxidation, particularly during the latter stages of prolonged exercise.

(a) Carbohydrate loading prior to exercise

The classic studies of Christensen and Hansen in the 1930s demonstrated that endurance exercise performance was enhanced following several days on a high carbohydrate diet. This was associated with a higher respiratory exchange ratio during exercise, suggesting a high rate of carbohydrate oxidation. The application of the percutaneous muscle biopsy procedure to exercise studies on human volunteers confirmed this early work and demonstrated a direct relationship between the pre-exercise muscle glycogen level and exercise time to fatigue at 70-75% of maximal oxygen uptake (Bergstrom et al. 1967). This observation led to the development of an exercise-diet regimen, commonly known as "glycogen loading", in which extemes of exercise and dietary carbohydrate were used to obtain pre-exercise muscle glycogen levels two to three times those observed under "normal" conditions. In recent years, it has been shown that trained athletes need only taper their training and increase dietary carbohydrate to 60-70% of total energy intake to achieve similar increases in muscle glycogen

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(Sherman et al. 1981). This is probably due, in part, to an increase in muscle glycogen synthase activity following training. The high carbohydrate intake designed to increase muscle glycogen will also elevate liver glycogen reserves; however, athletes should also consume an easily digested, high carbohydrate meal three to four hours prior to competition, especially if they have fasted overnight. Such a meal will ensure adequate liver glycogen stores and may increase muscle glycogen levels if they are less than optimal (Coyle et al. 1985). Athletes who fail to increase their carbohydrate intake prior to exercise may experience a premature lowering of blood glucose during prolonged, strenuous exercise. The metabolic effects of a high carbohydrate meal prior to exercise persist for up to six hours (Montain et al. 1991); nevertheless, ingestion of carbohydrate several hours prior to exercise results in improved endurance exercise performance (Sherman et al. 1989). The increase in exercise performance is enhanced if, in combination with the pre-exercise meal, carbohydrate is ingested before and/or during exercise (Neufer et al. 1987; Wright and Sherman 1989). Although glycogen loading has mainly been of interest to endurance athletes, there are reports of increased high-intensity exercise performance following glycogen loading (Greenhaff et al. 1987). Such an observation may be due as much to a slight metabolic alkalosis resulting from three days on a high carbohydrate diet, as to an increase in muscle glycogen availability. Further work is required to clarify the influence of muscle glycogen levels on maximal exercise performance.

In addition to optimising carbohydrate stores prior to competition, athletes in heavy training should ensure their diet contains sufficient carbohydrate to allow significant muscle glycogen resynthesis between training sessions. It is possible that the feelings of tiredness associated with "overtraining" are related, in part, to lowered carbohydrate reserves (Costill et al. 1988; Kirwan et al. 1988). The carbohydrate needs of athletes may be as high as 8-10 g/kg body weight or 65-70% of total energy intake. In order, to achieve this level of carbohydrate intake, it may become necessary for athletes to supplement their diet with carbohydrate-rich drinks (Saris et al. 1989). The complete restoration of muscle glycogen following intense training or competition may require as long as 20-24 hours, assuming a rate of resynthesis of 5-6 mmol/kg muscle/hr (Coyle 1991). Although exercise alone will activate muscle glycogen synthase (Bak and Pedersen 1990), post-exercise muscle glycogen resynthesis is critically dependent upon the ingestion of carbohydrate. The rate of resynthesis is faster if carbohydrate is ingested immediately after exercise, rather than delayed by two hours (Ivy et al. 1988a). The optimal amount of carbohydrate intake appears to be about 50 g every two hours (Blom et al. 1987; Ivy et al. 1988b), aiming for a total intake of 600 g in 24 hours. In the early post-exercise period (6-8 hours), simple sugars may be more beneficial than complex carbohydrates in promoting muscle glycogen resynthesis (Kiens et al. 1990). Furthermore, ingestion of carbohydrate foods with a high glycemic index results in a greater muscle glycogen storage in 24 hours than ingestion of foods with a low glycemic index (Burke et al. unpublished observations). Glucose and sucrose result in faster muscle glycogen resynthesis than fructose (Blom et al. 1987), although fructose may benefit restoration of liver glycogen. Muscle glycogen resynthesis is reduced following activities that produce muscle damage and soreness (Costill et al. 1990; Sherman et al. 1983). This is probably due, in part, to disruption of the muscle sarcolemma and the presence of inflammatory cells with a large capacity for glucose oxidation, which will reduce glucose availability to glycogen-depleted muscle cells. The effect of muscle damage on glycogen synthesis can be partially overcome by increased carbohydrate intake (Costill et al. 1990).

(b) Carbohydrate supplementation during exercise

Numerous studies over the years have demonstrated the ergogenic benefits of carbohydrate supplementation during exercise. These studies have observed increased exercise time to exhaustion (Bjorkman et al. 1984; Coggan and Coyle 1987, 1989; Coyle et al. 1983, 1986), enhanced work output (Coggan and Coyle 1988; Ivy et al. 1979; Mitchell et al. 1989a) and improved sprint performance following prolonged exercise (Hargreaves et al. 1984) when carbohydrate is ingested. The benefit of carbohydrate supplementation is its ability to maintain carbohydrate availability at a time when endogenous carbohydrate stores are reduced (ie. muscle and liver glycogen depletion and hypoglycemia). Thus, carbohydrate ingestion maintains blood glucose levels and a high rate of carbohydrate oxidation during the latter stages of prolonged, strenuous exercise. At this point, muscle glucose utilization may be as high as 1-1.5 g/min (Coggan and Coyle 1987). Carbohydrate ingestion has no effect on the rate of muscle glycogenolysis during exercise (Coyle et al. 1986; Hargreaves and Briggs 1988); even elevation of blood glucose to 10-12 mmol/l, by intravenous glucose infusion, fails to alter muscle glycogen usage (Coyle et al. 1991). There may well be sparing of liver glycogen utilization, since the exercise-induced increase in counterregulatory hormones is attenuated by carbohydrate ingestion (Mitchell et al 1990). Indeed, a recent preliminary report has observed a 59% reduction in endogenous liver glucose production during prolonged exercise when carbohydrate is ingested (Bosch et al. 1991). Carbohydrate ingestion at the point of fatigue increases blood glucose levels, carbohydrate oxidation and exercise performance initially, but these effects are soon reversed as glucose utilization exceeds glucose absorption from the gut (Coggan and Coyle 1987). In contrast, carbohydrate ingestion 30 min prior to the point of fatigue is more effective in maintaining blood glucose, carbohydrate oxidation and increasing exercise time (Coggan and Coyle 1989). Thus, while it may not be necessary to ingest carbohydrate throughout exercise, athletes should ingest enough carbohydrate prior to the point of fatigue to ensure adequate carbohydrate availability late in exercise. Based on a number of studies, it appears that athletes need to ingest 45-60 g carbohydrate per hour to meet carbohydrate requirements late in exercise. This can be achieved by ingestion of 600-1000 ml/hr of drinks containing 6-10% carbohydrate (Coyle 1991). More concentrated solutions (15-20%), although maximising carbohydrate delivery, may impair gastric emptying and rehydration (Mitchell et al. 1989b). Solutions containing up to 10% carbohydrate, however, are as effective as water in minimising dehydration during prolonged exercise, while still providing sufficient carbohydrate to maintain blood glucose and carbohydrate oxidation (Kingwell et al. 1989; Owen et al. 1986). There is little difference between maltodextrins, glucose and sucrose in their metabolic and performance effects during exercise, although 10% maltodextrin solutions tend to be less sweet, and therefore more palatable, than solutions of simple sugars. In contrast, fructose ingestion does not appear to enhance exercise performance (Bjorkman et al. 1984; Murray et al. 1989). Since there are likely to be individual differences between athletes in the response to carbohydrate ingestion during exercise, carbohydrate feeding regimes should be tested in training prior to competition.

In summary, in view of the importance of carbohydrate for exercise performance, the goal of carbohydrate nutritional strategies is to optimise the availability of muscle and liver glycogen and blood glucose. Maintenance of carbohydrate availability and a high rate of carbohydrate oxidation during exercise is associated with improved performance.

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