Three to four days before a marathon or ultramarathon race, many endurance athletes reduce their training volume and ingest a high carbohydrate diet. Is this practice justified?

Since the 1970's, the beneficial effects of carbohydrate (CHO) supplementation during endurance exercise have been well documented (2,3,4,5), showing low muscle glycogen or blood glucose concentrations to be associated with reduced work and endurance capacity. Carbohydrate supplementation during periods of intense training has been theorized to maintain muscle glycogen stores, lessen symptoms of fatigue, and maintain performance capacity. Therefore, nutritional strategies to increase body carbohydrate stores or carbohydrate availability are considered to be potentially beneficial for maintaining or improving athletic training and performance capabilities. Sport nutritionists, physiologists, and commercial manufacturers of sport nutrition products often recommend that athletes undergoing periods of heavy training increase consumption of carbohydrate-rich foods and/or supplement the diet with concentrated carbohydrate drinks.

The mechanisms by which carbohydrate loading affects athletic performance, however, are not well understood. Carbohydrate metabolism in exercise is subject to the mediating influences of many different parameters such as exercise duration and intensity and the type, form, and frequency of CHO ingestion. Studies have yielded varied and often conflicting results since different experimental protocols have different effects upon insulin secretion, catecholamine secretion, and carbohydrate oxidation. Here I examine the current literature on the effects of CHO supplementation—both positive and negative—and discuss the possible biochemical and physiological mechanisms by which CHO loading may exert its spectrum of effects on exercise endurance and work output.

Preexercise Carbohydrate Loading and the Role of Glycogen Stores

Many recent studies have confirmed the original studies conducted by Costill et al. (2), Coggan and Coyle (3), Coggan et al. (4), and Coyle et al. (5) that glycogen storage is important in sustaining exercise and delaying the onset of fatigue. "Glycogen-loading" regimens have been shown to increase the resting muscle glycogen content and extend the time to exhaustion during prolonged (>3 hr) submaximal exercise (17) while dietary and exercise manipulations that reduce preexercise glycogen stores are associated with an impaired ability to continue exercise at a given percentage of peak oxygen uptake (VO2max) (1).

One possibility for the ergogenic effects of CHO loading is that the higher muscle glycogen stores after CHO loading may delay the onset of fatigue resulting from muscle glycogen depletion during exercise. However, a number of studies have shown that rates of muscle glycogen utilization during exercise are increased after CHO loading in association with relative hyperglycemia and hyperinsulinemia in which case muscle glycogen depletion may not be delayed (1, 15, 19).

Alternatively, the proposed ergogenic effect of CHO loading could be due to a slowing of the rate of liver glycogen depletion because an increased availability of muscle glycogen would be expected to reduce the muscles' demand for blood glucose (15). In a study by Bosch et.al. (1), total muscle glycogen disappearance was greater in the CHO-loaded subjects compared to placebo subjects as a result of the maintenance of high rates of muscle glycogen utilization during the second hour of exercise when glycogen content was still high in the CHO-loaded subjects. It was speculated that CHO loading extends endurance by increasing the time taken for muscle glycogen to become critically low.

Carbohydrate Supplementation During Exercise and Blood Glucose Availability

Researchers have also shown that ingesting carbohydrate during prolonged, moderate-intensity exercise can improve performance by maintaining plasma glucose availability for oxidation during the later stages of exercise (4, 5, 7, 11) as well as sparing of muscle and liver glycogen. Other studies (6, 20) have indicated more optimal results with both preexercise CHO loading as well as CHO replacement during exercise than either nutritional manipulation alone. As muscle glycogen levels are reduced during exercise, the reliance on blood glucose for energy production is increased (7, 14). If carbohydrate is administered, a large percentage of it could be made available for utilization by working muscles.

Notably, in a study conducted by Fielding et al. (8), the increase in maximal performance capacity following carbohydrate feeding occurred in the absence of a significant change in plasma free fatty acids. This may suggest that the increase in performance capacity could have been mediated by changes in the availablity of plasma glucose, thus indicating that carbohydrate ingestion may have been related to the relative changes in CHO availability rather than the absolute level of blood glucose or CHO utilization per se. Blood glucose concentration reflects the equilibrium between glucose uptake by tissues and glucose output by the liver. The prior elevation of insulin in response to carbohydrate administration before exercise may have increased muscle glucose uptake during exercise and suppressed liver glucose output (6, 15). Therefore, it could be suggested that carbohydrate supplementation may have partially or completely replaced hepatic glycogenolysis and/or gluconeogenesis as a source of blood glucose.

Does CHO Really Enhance Endurance Capacity? The Effects of Insulin on Glucose Oxidation

While many studies have documented the beneficial effects of CHO supplementation, some studies have suggested, however, that glucose given before exercise may adversely affect exercise performance because of the associated hyperinsulinemia and subsequent hypoglycemia that often occurs with CHO ingestion.

While preexercise CHO loading has the potential to increase muscle glycogen levels before the onset of exercise, CHO loading also increases CHO oxidation, especially muscle glycogen breakdown, due to the enhanced insulin action. A recent study conducted by Okano et al. (16) compared the effects of giving a single four-hour preexercise high carbohydrate meal (HCM) to a high fat meal (HFM) and found that there was no difference in endurance capacity between the two different trials. One reason for this may be that, in most of the preexercise CHO loading studies discussed earlier, trials with CHO loading were compared to non-caloric placebo control trials following an overnight fasting (2, 6, 9, 14, 17). When the subjects begin the non-caloric control trial following overnight fasting, their body’s CHO availability during the exercise is expected to be less than that of the CHO trial. Thus, preexercise HCM ingestion several hours before prolonged exercise is not necessarily more effective for endurance capacity when compared with HFM feeding with the same amount of calories. Another reason may be due to the effects of insulin on CHO oxidation. The respiratory exchange ratios in the Okano study showed that the four-hour preexercise HCM ingestion lead to a higher CHO oxidation in the early stages of exercise, as compared with HFM ingestion (16).

Some studies have examined the effects of CHO sources other than glucose ingested prior to exercise in an attempt to alleviate hyperinsulinemia and hypoglycemic responses (8, 12, 13, 18, 19). It is now recognized that different forms of carbohydrates have different rates of digestion and provide varying rates of release of glucose into the blood, with or without stimulating insulin secretion (19). Foods such as legumes and pasta give a slow but sustained release of glucose to the blood (low glycemic index) without an accompanying insulin surge. In comparison, foods such as potato, bread and many breakfast cereals give glycemic and insulin responses almost as high as an equivalent amount of glucose (high glycemic index). The glycemic index (GI) of food is defined as the degree to which it raises the plasma glucose concentration relative to glucose, which has been assigned the arbitrrary value of 100 (19).

While the verdict on glucose—a high GI food—is still unclear, glucose polymer feedings during exercise are able to maintain blood glucose and delay fatigue by providing a carbohydrate source to the exercising muscles when glycogen levels are low (5). In a study conducted by Thomas et al. in which trained cyclists pedalled to exhaustion one hour after ingestion of equal carbohydrate portions of four test meals—lentils (low GI), potato (high GI), and glucose and water, it was shown that endurance time in the lentils trial was significantly longer than in the potato, glucose, and water trials. The low GI meal of lentils prolonged endurance at 67% VO2max by 20 minutes compared to the high GI meal of potatoes. Lentils produced less hyperglycemia and less hyperinsulinemia before exercise but maintained plasma glucose and resulted in higher plasma free fatty acid levels during exercise. The average respiratory exchange ratio value during the 90 minutes of exercise was lower in the low GI trial than in the high GI potato and glucose trials, indicating that less glucose was being oxidized. This suggests that glycogen stores were possibly being depleted at a slower rate after consumption of the low GI food, since muscle glycogen is the preferred CHO fuel at the onset of exercise. The results also showed that blood lactate levels during exercise may be influenced by the GI of the pre-game CHO. Plasma lactate levels in the potato and glucose trials were highly elevated, presumably a result of increased glycolysis in tissues such as muscle, a further indication that high GI foods may be undesireable in the hour before exercise.

Goodpastor et al. (9) also showed that ingestion of a starch consisting primarily of amylopectin prior to exercise provided an ergogenic effect equal to the pre-exercise ingestion of an isocaloric amount of glucose. This conflicts with the above results by Thomas et al. One possible reason for the discrepancies was that the Thomas et al. study administered starches in solid form while the Goodpastor et al. study administered starches in solution. The form as well as the type of ingested starch could influence its digestion and oxidation, leading to different blood glucose responses. Furthermore, different intensities of exercise may influence insulin secretion and thus glucose oxidation. In a recent study by Gozal et al. (10), it was suggested that the magnitude of insulin surge after acutely increased glucose before exercise in glycogen-depleted subjects may exert dissociative effects on adrenal-dependent glycogenolysis and on catecholaminergic responses. Catecholamine response and glucose turnover are known to increase with exercise intensity, possible resulting in an over-riding influence on plasma glucose concentrations.

In summary, the benefits of CHO loading regimens are still unclear. CHO loading has been shown to both increase endurance and work output as well as to attenuate endurance due to hyperinsulinemia. Conflicting results between studies indicate the complexity of the mechanisms involved in carbohydrate metabolism in relation to exercise. While diet certainly plays an important role athletic performance, the "ideal" diet for any sport still cannot be determined.

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