The Latest on Carbohydrate Loading: A Practical Approach

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SEDLOCK, D.A. The latest on carbohydrate loading: a practical approach. *Curr. Sports Med. Rep.*, Vol. 7, No. 4, pp. 209–213, 2008. *High dietary carbohydrate (CHO) intake for several days before competition (CHO loading) is known to increase muscle glycogen stores, with subsequent ergogenic performance benefits often seen in events longer than 90 min in duration. CHO-loading strategies vary in characteristics such as type and duration of dietary manipulation and the accompanying exercise/training activities. Additionally, glycogen concentration may remain elevated for up to 5 d. This versatility in CHO-loading strategies allows the athlete greater flexibility in tailoring pre-event preparation. Women who attempt to CHO load should be particularly attentive to both total energy intake and relative CHO intake; dietary CHO should exceed 8 g·kg body mass^{-1} ·d^{-1} or 10 g·kg lean body mass^{-1} ·d^{-1}. As long as the amount ingested is adequate for loading, the type of CHO is less important, with the exception of 1-d loading protocols where the glycemic index may be an important consideration.*

INTRODUCTION

Carbohydrate (CHO) loading, also known as glycogen loading or glycogen supercompensation, is a performance-enhancement strategy often used by endurance athletes before competition. Increased carbohydrate intake through dietary manipulation increases muscle glycogen stores (1–5) and improves performance (1,2,4,5), presumably by delaying the onset of fatigue. Pioneering work by Scandinavian researchers in the late 1960s and early 1970s (1,2) demonstrated this relationship among dietary CHO intake, muscle glycogen content, and subsequent exercise performance. Since that time, the ergogenic value of CHO for prolonged exercise, as well as the associated physiologic mechanisms, has been studied perhaps more extensively than any other singular performance-enhancing strategy.

There is little doubt as to the importance of CHO as a fuel for endurance performance. However, athletes must be cautious when assuming that CHO loading will greatly increase glycogen stores, and that this increase in glycogen will translate to improved performance. The degree to which muscle glycogen stores can be supercompensated varies considerably, with increases ranging from less than 25% (5–8) to a doubling or near-doubling (2,3,9,10) of the preloaded value. Moreover, the relationship between post-loading increases in muscle glycogen and subsequent improvements in performance is inconsistent (2,3,5,6,8). For example, performance was increased coincident with a 13% increase in muscle glycogen (5), but not with other relatively small but significant increases of 18% (6) and 23% (8). Similarly, large increases in muscle glycogen (~100%) were reported to increase (2) or have no effect upon (3) performance.

Because CHO loading can be an effective performance-enhancing strategy for some endurance athletes but perhaps not others, it is important to be aware of factors that can modify the outcome. These include, but are not limited to, loading strategy, type of CHO ingested, characteristics of the ensuing exercise performance, the presence or absence of a high fat diet/adaptation period before loading, the presence or absence of preloading glycogen-depleting exercise, timing of supercompensation relative to the performance event, and gender. Few studies regarding CHO loading were published in the last year (9,11). To incorporate this new information, this article will focus on loading strategies, preloading glycogen depleting exercise, timing of CHO loading, and CHO loading in women, with a brief mention of some issues regarding the other previously mentioned factors.

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CHO-LOADING STRATEGIES

The classic CHO-loading procedures were first reported by Scandinavian researchers (1,2) in the late 1960s and involved either a 3- or 6-d exercise and diet manipulation. The protocol involved performing prolonged (*i.e.*, glycogen-depleting [GD]) exercise followed by 3 d of a high-CHO diet with minimal to no training (3 d), or the same procedure preceded by GD exercise and subsequent 3-d low CHO diet (6 d). Although these classic exercise/dietary regimens induce increases in muscle glycogen, they may not represent the optimal way to prepare for competition. The exercise/diet manipulation is difficult to execute, especially the 6-d protocol, and may result in untoward physical and mental consequences. A GD workout just a few days before, as well as 3 consecutive days of inactivity immediately before a prolonged endurance event, may be disruptive to the usual regimen of the athlete. Moreover, the low dietary CHO phase may increase the risk for injury (12), make it difficult to adhere to an optimal training/tapering regimen, and result in manifestations of hypoglycemia such as listlessness, irritability, and diminished mental acuity. Bloating, gastrointestinal (GI) distress, and weight gain during the high CHO phase also are of concern (13).

In 1981, Sherman *et al.* (3) reported a more "user-friendly" strategy for increasing muscle glycogen stores. Briefly, they showed that muscle glycogen content could almost double by undergoing a 3-d exercise taper starting approximately 1 wk before the event while consuming a normal mixed diet (~50% of energy as CHO), then ingesting a high (70%) CHO diet for the remaining 3 d with approximately 20 min of low-intensity exercise during the first 2 d and resting on the last day. This modified regimen effectively supercompensated the muscle, yet eliminated the need to perform an exhausting exercise bout within a few days of a competitive event, allowed for a reasonable exercise taper, and relative to the classic 6-day loading protocol, avoided several days of low dietary CHO intake while simultaneously decreasing the duration of exaggerated dietary manipulation.

More recently, researchers have shown increases in muscle glycogen stores with a single day of high CHO consumption (10,14). Bussau *et al.* (10) found that physical inactivity coupled with ingestion of a high CHO diet ($10\ g \cdot d^{-1} \cdot kg^{-1}$ high CHO and high glycemic index food and beverage) increased muscle glycogen stores by 90% after only 1 d, with no additional significant increase after 2 more days of the diet and inactivity intervention. Subjects in this study performed a normal training workout on the day preceding the intervention. In a related study (14), endurance-trained men increased muscle glycogen content by an average of 82% after performing a short-term, high-intensity cycling exercise (150 s at 130% $\dot{V}O_{2max}$ followed by an all-out 30-s sprint) with a subsequent day of inactivity and ingestion of a similarly high-CHO diet ($12\ g \cdot kg^{-1}$ lean body mass or $\sim 10\ g \cdot kg^{-1}$ body mass).

Each of the previously mentioned CHO-loading protocols can increase muscle glycogen to some extent. However, other factors must be considered if maximal levels of intramuscular glycogen are to be attained, some of which are discussed below.

PRELOADING GLYCOGEN DEPLETION

Findings from some (7,15) but not all (3) research suggest that a greater amount of glycogen storage occurs when performing GD exercise rather than lighter exercise bouts (*e.g.*, exercise tapering) before ingesting a high-CHO diet. Although the modified loading protocol of Sherman *et al.* (3) produced muscle glycogen concentrations similar to the classic protocol, other studies yielded equivocal findings regarding the ability to maximize muscle glycogen concentration without initially depleting those stores. Roedde *et al.* (15) reported muscle glycogen concentrations of $174\ mmol \cdot kg^{-1}$ following a 6-d classic loading regimen compared to $115\ mmol \cdot kg^{-1}$ following a modified procedure. Goforth *et al.* (7) used ^{13}C magnetic resonance spectroscopy to measure the pattern of muscle glycogen concentration after CHO loading with or without a preceding GD exercise. After a GD exercise or non-GD (20 min of moderate-intensity cycling) exercise, subjects consumed a high-CHO (80%) diet for 3 d and then a normal mixed diet (56% CHO) for an additional three days with 20 min of moderate intensity (65% $\dot{V}O_{2peak}$) cycling performed daily. Muscle glycogen increased significantly in both the GD (38%) and non-GD (24%) groups after the high-CHO diet phase. During the mixed diet phase, glycogen concentration continued to increase in the GD group, whereas glycogen peaked after the first day and then decreased gradually back to the baseline value over the next 3 d in the non-GD group (Figure).

The larger increases in muscle glycogen observed after preloading GD exercise are suggested to result from factors such as a faster rate of glycogen resynthesis (16), greater glycogen synthase activity (17,18), and enhanced glucose transport (19). This enhanced muscle sensitivity to

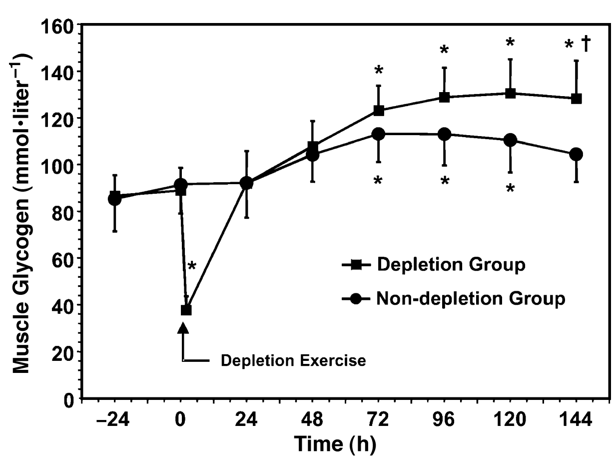

Figure. Profile of muscle glycogen during depletion and nondepletion exercise regimens. Measurements were made daily between 8:00 A.M. and 12:00 noon for depletion group (N = 15) and nondepletion group (N = 10). *P < 0.01 versus baseline; †P < 0.001 versus nondepletion group. (Reprinted from Goforth, H.W., D. Laurent, W.K. Prusaczyk, *et al.* Effects of depletion exercise and light training on muscle glycogen supercompensation in men. *Am J Physiol Endocrinol Metab* 285:E1304–1311, 2003. Copyright © 2003 The American Physiological Society. Used with permission.)

CHO after GD exercise may be analogous to muscle adaptations that occur from training. For example, Hansen *et al.* (20) examined muscle glycogen content in response to knee extensor training 5 d·wk^{-1} for 10 wk in untrained young men. Subjects trained one leg for 1 h·d^{-1} (high glycogen) and trained the other leg every other day for two 1-h sessions separated by a 2-h recovery (low glycogen). This protocol equated workload and training volume for both legs throughout the training program; however, the leg in the high glycogen condition always began training with relatively high glycogen stores, whereas the second hour of training for the leg in the low glycogen condition always began with significantly reduced glycogen. Muscle glycogen increased in both legs in response to training, but the increase was significant only for the leg that trained using the low glycogen protocol.

Preloading GD exercise is not a prerequisite for supercompensating the muscle with glycogen (3,5,21,22). However, evidence regarding the importance of a preloading GD exercise (or at least significantly reducing in muscle glycogen content) (12) for maximizing increases in glycogen storage is sufficient to warrant further study.

TIMING OF CHO LOADING

Regardless of the type and duration of CHO-loading protocols used, research examining the relationship between CHO loading, muscle glycogen content, and exercise performance includes consumption of a high-CHO diet up until the day of the performance event. This is because the length of time muscle glycogen concentration remained elevated was largely unknown, unlike supercompensated liver glycogen, which is relatively short-lived (23). Researchers have since shown that muscle glycogen stores can remain elevated for several days after being supercompensated (7,18,23). In one study (23), endurance-trained men underwent a classic 6-d loading regimen, followed by a 3-day postloading phase consisting of moderate CHO intake (~60% total energy) and limited physical activity. Muscle glycogen remained significantly elevated above baseline throughout the postloading phase. In the previously mentioned study by Goforth *et al.* (7), muscle glycogen significantly increased after 3 d of high CHO intake (~9.0 g·kg^{-1}; 80% total energy) and remained elevated for an additional 3 d when CHO ingestion was more moderate (~6.5 g·kg^{-1}; 56% total energy) and coupled with 20 min of moderate intensity cycling each day. More recently, Arnall *et al.* (9) found that, after GD exercise with subsequent CHO loading, muscle glycogen remained significantly elevated for 5 d with a CHO intake of approximately 60% total energy and limited physical activity.

A variety of CHO-loading regimens can produce supercompensated muscle glycogen, and the elevated glycogen content may persist for up to 5 d. Thus athletes have a variety of strategies to explore regarding the type and timing of the loading protocol that would result in minimal disruption to their personal training/tapering schedules and pre-event preparation.

CHO LOADING IN WOMEN

Relative to the preponderance of research in men, little information exists on CHO loading in women. For example, the link between CHO loading and performance has been well documented in men (1,2,13,22,24), but this relationship in women is tenuous at best (4,5,25,26). Tarnopolsky *et al.* (4) reported no significant increase in muscle glycogen or performance in trained women after CHO loading (75% CHO for 4 d), whereas similarly trained men exhibited a 41% increase in glycogen and a 45% improvement in cycling time trial performance. In contrast, women in a study by Walker *et al.* (5) were able to increase significantly both glycogen (13%) and performance (~8%) in response to CHO loading (75%–80% CHO for the final 3–4 d of a 7-d diet/exercise taper). Others reported significant increases in muscle glycogen from CHO loading but no subsequent increase in performance (11,27). Factors that seem to determine the efficacy of CHO loading in women are total energy intake, amount of CHO ingested, and menstrual cycle phase. Tarnopolsky *et al.* (28) suggested that energy intake influences the ability of women to glycogen supercompensate. Increasing fractional CHO intake from 58% to 75% significantly increased muscle glycogen in men but not in women. However, by increasing energy intake of women by approximately 34% (the difference in habitual energy intake between the men and women) while keeping fractional CHO intake at 75% did result in increased glycogen stores. Other research suggests that the important factor governing the ability of muscle to store additional glycogen is CHO intake relative to body mass (BM) or lean body mass (LBM). Significant increases in muscle glycogen in women were reported when CHO intake was 8.4 g·kg BM^{-1}·d^{-1} (11), 8.2 g·kg BM^{-1}·d^{-1} (10.1 g·kg LBM^{-1}·d^{-1}) (5), 11.2 g·kg LBM^{-1}·d^{-1} (27), and 12.3 g·kg LBM^{-1}·d^{-1} (29). In the previously mentioned study by Tarnopolsky *et al.* (28), CHO intake was 8.8 g·kg BM^{-1}·d^{-1} during the increased energy trial in which glycogen increased, but only 6.4 g·kg BM^{-1}·d^{-1} with the isocaloric high-CHO diet. Thus it seems that women have the capacity to increase muscle glycogen stores provided CHO intake exceeds approximately 8 g·kg BM^{-1}·d^{-1} or approximately 10 g·kg LBM^{-1}·d^{-1}. Although this recommendation seems scientifically reasonable, the practical aspect is more daunting because this dose amounts to ingesting more than 93% of total energy as CHO for a 60-kg woman with a caloric intake of 2000 kcal·d^{-1} (28). Hence, women who attempt to CHO load should be particularly attentive to both total energy intake and relative CHO intake.

Menstrual cycle phase also may play a role in the effectiveness of CHO loading. Women have higher uncompensated glycogen levels (11,30) and a greater capacity for storing glycogen (11,26) during the luteal phase than the follicular phase. The natural fluctuations of female reproductive hormones throughout the menstrual cycle may be a critical factor for the difference in CHO sensitivity between cycle phases. Without these hormonal fluctuations, James *et al.* (29) were unable to detect a difference in glycogen content during the follicular versus luteal phase in response to CHO loading in women who were taking oral contraceptives that resulted in similar values for progesterone, estradiol, luteinizing hormone, and follicle-stimulating hormone at the time glycogen was measured.

OTHER FACTORS

Type of CHO

Combinations of simple, complex, solid, and liquid CHO are most often used by athletes who CHO load. It is accepted widely that the type of CHO ingested is not as important for supercompensating muscle if the amount is adequate. The quantity of food that must be ingested to attain the proper dose of CHO depends on its CHO content, with a smaller amount required if the food has a relatively high CHO content (*e.g.*, pasta or rice) rather than a relatively low CHO content. High-CHO beverages can provide at once much of the additional CHO needed for loading without adding extra "bulk" to the diet. However, the glycemic index (GI) of ingested CHO may play a role in some loading protocols. High-GI food was reported to result in a greater restoration of glycogen than low-GI food in the first 24 h after a GD exercise (31). Additionally, both Bussau *et al.* (10) and Fairchild *et al.* (14) used high-GI food and beverages for their 1-d loading protocols. Thus GI may be an important consideration when using short duration (*i.e.*, 1-d) CHO loading protocols or when relatively rapid glycogen restoration is needed.

Preloading Fat Adaptation

The ability to enhance lipid oxidation may be beneficial for prolonged endurance events during which fat utilization would spare CHO oxidation. Several days or weeks of ingesting a high-fat diet produces metabolic alterations during exercise that favor increased fat oxidation (32,33). Subsequent restoration of muscle glycogen with a day of rest and high-CHO intake does not abolish this adaptation (34,35). In theory, this CHO-sparing effect should manifest in improved endurance performance. However, research is unclear in this regard, with some (33,35–37) but not all (38,39) investigators reporting no improvement in performance. It has been suggested that interindividual variability of subjects as well as small sample sizes (40) preclude more definitive conclusions regarding the utility of preloading fat adaptation for performance enhancement, especially if the exercise necessitates high-intensity bursts, such as when encountering elevations in terrain (39).

Characteristics of the Exercise

Athletes participate in numerous types of competitive events that are either multi-mode (*e.g.*, duathlons or triathlons) or single mode (*e.g.*, cycling or running), with durations ranging from a few seconds (*e.g.*, sprints) to hours (*e.g.*, ultra-endurance) or days (*e.g.*, Tour de France). Hawley *et al.* (22) suggest that performance benefits of CHO loading are most likely to occur in events lasting more than 90 min. For athletes who participate in these events, precompetition preparation is discussed in several recent reviews (12,41).

Any CHO-loading strategy used by an athlete should be one that is well tolerated by the individual. Ingesting CHO in amounts adequate to elevate muscle glycogen, which is not as difficult a task for men as it may be for women, as well as tolerating side effects such as bloating and general GI discomfort that often accompany high-CHO intake, are important considerations. Glycogen is stored with water in a ratio of approximately 1:3–5 (22), so the extra weight and feelings of "fullness" and "heaviness" experienced with CHO loading also must be considered, especially if the events are weight-bearing (*e.g.*, running or cross-country skiing) as opposed to weight-supported (*e.g.*, cycling or swimming).

CONCLUSION

The ergogenic benefit of CHO loading for endurance performance is a widely accepted tenet. Several strategies can be used to supercompensate muscle glycogen, many of which vary in duration, extent of dietary manipulation, and the amount and intensity of any accompanying exercise. Reports of successful single-day loading protocols as well as the duration that glycogen remains elevated allow athletes many permutations of loading strategies with which to experiment. The greatest challenge for women to successfully elevate muscle glycogen seems to be the ability to ingest an appropriate amount of CHO without incurring a large disruption to daily energy requirements. Because CHO loading is most likely to provide ergogenic effects in competitive events exceeding approximately 90 min in duration, athletes who have a low tolerance for fluid or CHO consumption during competition are likely to derive the greatest benefits.

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