Fueling strategies to optimize performance: training high or training low?

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Availability of carbohydrate as a substrate for the muscle and central nervous system is critical for the performance of both intermittent high-intensity work and prolonged aerobic exercise. Therefore, strategies that promote carbohydrate availability, such as ingesting carbohydrate before, during and after exercise, are critical for the performance of many sports and a key component of current sports nutrition guidelines. Guidelines for daily carbohydrate intakes have evolved from the “one size fits all” recommendation for a high-carbohydrate diet to an individualized approach to fuel needs based on the athlete’s body size and exercise program. More recently, it has been suggested that athletes should train with low carbohydrate stores but restore fuel availability for competition (“train low, compete high”), based on observations that the intracellular signaling pathways underpinning adaptations to training are enhanced when exercise is undertaken with low glycogen stores. The present literature is limited to studies of “twice a day” training (low glycogen for the second session) or withholding carbohydrate intake during training sessions. Despite increasing the muscle adaptive response and reducing the reliance on carbohydrate utilization during exercise, there is no clear evidence that these strategies enhance exercise performance. Further studies on dietary periodization strategies, especially those mimicking real-life athletic practices, are needed.

The availability of carbohydrate as a substrate for muscle metabolism and central nervous system support is a critical factor in the performance of prolonged (>90 min) submaximal or intermittent high-intensity exercise, and plays a permissive role in the performance of brief high-intensity work (Hargreaves, 1999). Therefore, a variety of athletes are highly dependent on carbohydrate fuels: these include endurance athletes in high-intensity events conducted in the zone between the so-called “lactate threshold” and maximal aerobic capacity, and team or racquet sport players who undertake repetitive bursts of high-intensity work. It is interesting to note that even where the overall physiological demands of competition vary markedly between sports and events (e.g. competition may range from 1 to 2 min of “middle distance” swimming and track events to over 2 h in marathons and cycling road races), success in such events is typically underpinned by the athlete’s ability to sustain effort in this critical zone. Furthermore, training programs in each of these events share common elements: longer periods of work at submaximal intensities, sessions focused on sustained high-intensity work and “interval” sessions involving repeated high-intensity exercise with variable recovery periods. Because of these similarities between apparently diverse events, the focus of this review has far-reaching outcomes across sport.

It is important to note that the total body carbohydrate stores are limited, and are often substantially less than the fuel requirements of the various training and competition sessions undertaken by athletes in the range of sports noted previously. Therefore, sports nutrition guidelines promote a variety of options for acutely increasing carbohydrate availability for an exercise session, including consuming carbohydrate before, during and in the recovery period between prolonged exercise bouts (American Dietetic Association et al., 2009). When these strategies enhance or maintain carbohydrate availability, they delay the onset of fatigue, and enhance exercise capacity or endurance (Wright et al., 1991; Fallowfield & Williams, 1993; Chryssanthopoulos & Williams, 1997). Studies that show benefits of carbohydrate support to exercise performance are more appropriate to sport (Sherman et al., 1991; Below et al., 1995; Tsintzas et al., 1995; Vergauwen et al., 1998), and even include protocols in which increased carbohydrate availability has enhanced performance in field situations or actual sports competition (Karlsson & Saltin, 1971; Akerman et al., 1996; Balsom et al., 1999).
The clear benefits of an adequate carbohydrate supply for an acute bout of exercise not only form the basis of competition nutrition recommendations but also underpin the guidelines for the athlete’s everyday nutrition whereby the chronic outcomes of training are seen as an accumulation of a series of individual exercise bouts. It has been assumed that repeated training with optimal fuel support will lead to better preparation and an enhancement of competition performance (the “training better” approach). This paper will review the evolution of guidelines for the everyday or training diets of athletes, summarizing the evolution of guidelines for a carbohydrate-supported training environment and the criticism that has been leveled at these recommendations. It will also examine the emerging interest in dietary periodization in which exercising in a low fuel state is suggested to enhance the adaptations to training and result in superior performance (the “training smarter” approach).

The 1990s – the high-carbohydrate approach to training nutrition

Official guidelines for athletes prepared during the 1990s were unanimous in their recommendation of high-carbohydrate intakes in the everyday or training diet, based on the perceived benefit of promoting muscle glycogen recovery on a daily basis (Devlin & Williams, 1991; American Dietetic Association, 1993; Ekblom & Williams, 1994; Maughan & Horton, 1995). Most guidelines took a “one size fits all” approach, or at best a two-tier approach that divided athletes into “endurance” and “general” categories. In addition, the guidelines were commonly expressed in terms of the percentage of energy intake that should be contributed by carbohydrate in the training diet. A typical summary of these early sports nutrition guidelines was that athletes should consume diets providing at least 55% of energy from carbohydrate (Maughan & Horton, 1995) or 60–65% of energy from carbohydrate (American Dietetic Association, 1993). In the case of endurance athletes, carbohydrate intake recommendations were set variously at >60% of dietary energy (Ekblom & Williams, 1994) and 65–70% of dietary energy (American Dietetic Association, 1993).

This advice was criticized both outside and within sport science circles on two accounts. The first criticism was the apparent failure of athletes to achieve such carbohydrate-rich diets in training, with the rationale that if it were advantageous to training adaptations and performance, we would expect athletes to follow the practice (Noakes, 1997). Indeed, a review of the dietary surveys of serious athletes published since the announcement of the 1991 sports nutrition guidelines found that the mean values for the reported daily carbohydrate intakes of endurance athletes were ~ 50–55% of total energy intake (Burke et al., 2001), compared with the 60–70% of energy intake suggested by various expert groups. Second, it was suggested that the available literature failed to provide a clear support for the benefits of chronic high-carbohydrate intakes on training adaptations and performance of athletes undertaking intensive daily workouts. These both concerns were addressed when dietary guidelines for athletes were updated in the following decade (Burke et al., 2004; American Dietetic Association et al., 2009).

The new millennium – carbohydrate needs of athletes re-examined and re-modeled

In the recent decade, updated dietary guidelines have examined both the science underpinning the daily carbohydrate requirements for athletes and the terminology used to define these needs. These approaches have simultaneously addressed the criticisms of the previous recommendations for the athlete’s training diet, as well as produced a more practical education message.

Support for the chronic benefits of training with high-carbohydrate availability on performance outcomes is reliant on a small number of training studies comparing groups or trials with “moderate”- and “high”-carbohydrate intakes (see Table 1). It is unfortunate but not surprising that this literature is so sparse, because such studies require painstaking control over a long duration. Nevertheless, there is clear evidence of superior restoration of muscle glycogen stores when athletes consume a higher-carbohydrate intake. However, the evidence for performance gains is equivocal: only three studies have shown enhancement of performance following a period of fuel-supported training (Simonsen et al., 1991; Achten et al., 2004; Halson et al., 2004), while another shows a potential for better performance via better running economy (Kirwan et al., 1988). An important finding from two of these investigations was that a higher daily carbohydrate intake was able to reduce, but not entirely prevent, the development of over-reaching symptoms (fatigue, impaired performance, sleep and mood disturbance, altered hormonal responses to stress, etc.), which can occur when a period of intensified training is undertaken (Achten et al., 2004; Halson et al., 2004). The notable characteristics of the other study that favored high-carbohydrate availability in training were the use of highly trained athletes, a longer duration of intervention and the blinding of dietary treatments (Simonsen et al., 1991).
<table>
<thead>
<tr>
<th>Study</th>
<th>Athletes</th>
<th>Duration of study (days)</th>
<th>Daily CHO intake (g/kg/day)</th>
<th>Effect on muscle glycogen</th>
<th>Performance protocol</th>
<th>Performance advantage with HCHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costill et al. (1988)</td>
<td>Well-trained swimmers (12 M)</td>
<td>10 days Subjects self-selected into dietary groups (eight HCHO and four MCHO)</td>
<td>8.2 vs 5.3</td>
<td>Declined in MCHO Maintained in HCHO</td>
<td>Training: doubling of usual 1.5 h/day training program Performance battery: power (swim bench); 2 × 25 yards freestyle swim with 2–3 min recovery interval; VO₂max in pool; swimming efficiency at submaximal pace</td>
<td>No for final performance No difference between 25-year swim, swim power, VO₂max from pre-trial and between groups. However, stroke efficiency reduced in MCHO Yes for training performance MCHO group reported “chronic fatigue” during training program</td>
</tr>
<tr>
<td>Lamb et al. (1990)</td>
<td>Well-trained swimmers (14 M)</td>
<td>9 days Cross-over design</td>
<td>12.1 vs 6.5</td>
<td>NA</td>
<td>2 × daily training sessions: intervals over variety of distances + 1500 m and 3000 m timed for afternoon sessions during last 5 days</td>
<td>No No difference in mean swimming times over range of distances between diets</td>
</tr>
<tr>
<td>Kirwan et al. (1988)</td>
<td>Well-trained runners (10 M)</td>
<td>5 days Cross-over design</td>
<td>8.0 vs 3.9</td>
<td>Declined in both groups but greater reduction in MCHO</td>
<td>Training increased by 150% for 5 days Economy tested on treadmill at two speeds on Days 4 and 6 Overnight fasted</td>
<td>Reduction in running economy with MCHO</td>
</tr>
<tr>
<td>Sherman et al. (1993)</td>
<td>Trained runners (nine M + nine M)</td>
<td>7 days Parallel group design</td>
<td>10 vs 5</td>
<td>Declined in MCHO Maintained in HCHO</td>
<td>2 × time to exhaustion on a treadmill at 80% VO₂max with 5-min recovery period Trials undertaken at the end of day after 1-h training</td>
<td>No No difference between groups on endurance during either run. Sum time = 613 ± 38 and 580 ± 108 s for MCHO and HCHO, respectively, NS</td>
</tr>
<tr>
<td>Achten et al. (2004)</td>
<td>Well-trained runners (seven M)</td>
<td>4 days +7 days intensified training Cross-over design</td>
<td>8.5 vs 5.4</td>
<td>Decrease in muscle glycogen utilization during training sessions at 58% and 77% VO₂max during MCHO trial compared with HCHO</td>
<td>Pre-load +8 km treadmill TT on days on days 1, 5, 8 and 11 16 km road TT on days 6, 7, 9 and 10 Overnight fasted</td>
<td>Yes Intensified training lead to deterioration of 8 km TT performance by 61 s in HCHO and 155 s in MCHO, and deterioration in 16 km TT performance in MCHO only. HCHO reduces symptoms of over-reaching during intensified training compared with MCHO but does not prevent it entirely</td>
</tr>
<tr>
<td>Halson et al. (2004)</td>
<td>Trained cyclists (six M)</td>
<td>7 days +8 days intensified training + 14 days recovery training Cross-over design</td>
<td>9.4 vs 6.4 in intensified training period (additional CHO consumed before/during/after training sessions)</td>
<td>Not measured but inferred that HCHO achieved better maintenance of muscle glycogen stores during intensified training</td>
<td>Time to exhaustion on cycle ergometer at 74% VO₂max Overnight fasted</td>
<td>Yes Period of intensified training reduced time to exhaustion and increased rating of perceived exertion in both trials, although impairment was attenuated in trial in HCHO trial with higher CHI and energy intake. After 2 weeks recovery, cycling capacity was still below baseline in MCHO trial (– 13%) but was supercompensated (10%) in HCHO</td>
</tr>
<tr>
<td>Study</td>
<td>Athletes</td>
<td>Duration of study (days)</td>
<td>Daily CHO intake (g/kg/day)</td>
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<tr>
<td>Simonsen et al. (1991)</td>
<td>Collegiate rowers (12 M, 10 F)</td>
<td>28 days</td>
<td>10 vs 5</td>
<td>MCHO allowed maintenance of muscle glycogen stores, while HCHO allowed an increase in stores</td>
<td>3 × 2500 m rowing ergometer TT with 8-min recovery interval undertaken on days 1, 3 and 5 of each week</td>
<td>Yes</td>
</tr>
<tr>
<td>Sherman et al. (1993)</td>
<td>Trained cyclists (nine M-nine M)</td>
<td>7 days</td>
<td>10 vs 5</td>
<td>Declined in MCHO Maintained in HCHO</td>
<td>2 × time to exhaustion on cycle ergometer at 80% VO₂ max with 5-min recovery period</td>
<td>No</td>
</tr>
<tr>
<td>Vogt et al. (2003)</td>
<td>Well trained duathletes (11 M)</td>
<td>35 days</td>
<td>6.9 vs 3.6</td>
<td>Maintained on both diets</td>
<td>VO₂ max cycling TT undertaken after progressive submaximal pre-load; outdoor 21 km run (all undertaken on separate days)</td>
<td>No</td>
</tr>
<tr>
<td>Cox et al. (2010)</td>
<td>Well trained cyclists/triathletes (16 M)</td>
<td>28 days</td>
<td>8 vs 5.2 (additional CHO consumed during/after training sessions)</td>
<td>Maintained on both diets</td>
<td>100 min at 70% VO₂ max + ~ 25-min TT</td>
<td>No</td>
</tr>
</tbody>
</table>

M, male; F, female; NA, not available; TT, time trial.
It is curious that benefits from high-carbohydrate eating have not been a universal outcome from training studies. However, several methodological issues may explain the unclear findings, including an overlap between what was considered a moderate- and high-carbohydrate diet in various studies. It is possible that the “moderate”-carbohydrate diets used in some studies provided sufficient fuel to meet training requirements, in such a situation, additional benefit would not be expected from higher-carbohydrate intakes. Another consideration is whether sufficient time was allowed for differences in the training responses of athletes to lead to significant differences in the study performance outcome. After all, studies on tapering and reduced training show that the performance of some types of exercise may be maintained for up to 3 weeks, despite a reduced training stimulus (Mujika & Padilla, 2000a, b). A further consideration is how carbohydrate intake is spread over the day in relation to training sessions, and whether simply reporting the total daily intakes of carbohydrate masks how well carbohydrate is consumed before, during and after exercise to best promote fuel availability. Finally, the protocols used to measure performance in studies should be scrutinized to see if they are sufficiently reliable to detect small but real improvements that would be significant to a competitive athlete (Hopkins et al., 1999). It is possible that present studies suffer from type II errors, in that they fail to recognize potential performance improvements because of variability of performance measures, small sample sizes and the reliance on traditional probability-based statistics to interpret the results (Hopkins et al., 2009).

One possible conclusion from the available studies of chronic dietary patterns and exercise performance is that athletes adapt to lower muscle glycogen stores resulting from moderate carbohydrate intake so that there is no impairment of training or competition outcomes. This shall be discussed further below. However, in setting the most recent dietary guidelines, it was noted that no study shows that a moderate carbohydrate intake promotes superior training adaptations and performance compared with higher-carbohydrate diets (Burke et al., 2004). Thus, the guidelines continued to support the concept of training with high-carbohydrate availability.

The apparent mismatch between sports nutrition guidelines and the real-life dietary patterns of athletes is interesting to explore, although of course, it is difficult to establish cause and effect just from examining the practices of successful athletes. After all, it is likely that talented athletes can excel in spite of their practices just as well as because of them. In addition, the literature is largely devoid of studies of truly elite athletes; in fact, the few studies of the most highly successful athletes such as Kenyan middle-distance and distance runners (Onywera et al., 2004) report intakes of carbohydrate that are high when judged per kilogram of body mass (BM) (~ 10 g/kg) and as a percentage of dietary energy (> 70% of energy). Nevertheless, the apparently low carbohydrate intakes reported by most other groups of (typically sub-elite) athletes can be largely explained as a result of confusion arising from the terminology used to make sports nutrition guidelines (Burke et al., 2001).

Earlier guidelines for daily carbohydrate intake for athletes follow the traditional terminology used in population dietary guidelines, where recommendations for the intake of macronutrients are expressed as the proportion of dietary energy that they should typically contribute. However, population guidelines for carbohydrate result from taking a group of issues into account for a generic group of people (e.g. meeting requirements for protein, achieving benefits from reducing fat intake) rather than trying to meet specific muscle fuel needs for a specialized sub-group, or more particularly, for an individual. The athlete’s fuel needs are better estimated from more direct information, such as the carbohydrate intake required for optimal glycogen recovery, or the carbohydrate expenditure of the training program. Such estimates of carbohydrate needs should be provided relative to the BM of the athlete to roughly account for the size of the muscle mass that must be fueled. General guidelines derived from such information have been included in the updated guidelines for athletes (American College of Sports Medicine et al., 2000; Burke et al., 2004; American Dietetic Association et al., 2009). Even these guidelines (summarized in Table 2) should also be considered as “ball-park” ranges, which can be fine-tuned for the individual athlete with more specific knowledge of their actual training program, past and present response to training and their total energy budget. A re-examination of the dietary surveys of athletes published between 1990 and 2000 shows mean values of reported daily carbohydrate intake (g/kg BM) to be 7.6 and 5.8 for male endurance and non-endurance athletes, and 5.7 and 4.6 for their female counterparts (Burke et al., 2001). These values suggest that the daily carbohydrate intakes of the typical male athlete fell within the suggested ranges for fuel needs for at least a moderate training load, particularly if these athletes have under-reported by 10–20% as is common with dietary records (Burke et al., 2001). Of course, these mean estimates do not guarantee that all athletic groups or specific athletes met these recommended intakes, or indeed met their actual fuel requirements; such determinations can only be made on an individual basis. Female athletes appeared to be at a higher risk of carbohydrate intakes below these ranges, largely as a result of lower energy intakes.
Newer guidelines for sports nutrition have specifically stated the disadvantages of using percentage of energy terminology to provide advice to athletes about their carbohydrate needs (Burke et al., 2004; American Dietetic Association et al., 2009), noting that it is not practical or user-friendly to people with a simple knowledge of nutrition. To convert existing information from food labels and food composition into a percentage of energy (particularly over a day’s intake) requires some expertise and mathematical skill. Most important, however, the review of dietary surveys of athletes (Burke et al., 2001) provided clear evidence that the two methods of describing carbohydrate intake are not interchangeable and percentage of energy intake can be misleading. Among groups of male athletes, there was evidence of a loose but positive correlation between reported intakes of carbohydrate (g/kg) and the energy contributed by carbohydrate in the diet. In other words, male athletes who change their eating patterns to increase the energy contribution of carbohydrate in their diets are likely to increase their carbohydrate intake per kilogram of BM. Nevertheless, the correlation was too low to guarantee that a particular target for grams of carbohydrate intake based on specific fuel needs translates into a certain percentage of dietary energy. Furthermore, in the case of female endurance athletes, the correlation between the carbohydrate–energy ratio and total carbohydrate intake (g/kg BM) was minimal. This is because of the confounding issue of restricted energy intake in some individuals or groups. These athletes may consume 70–75% of total energy from carbohydrate in an energy-restricted diet (i.e. meet old guidelines) but still only achieve 3–4 g of carbohydrate per kilogram of BM (fall below fuel-based targets).

In summary, the current sports nutrition guidelines for the daily training environment encourage strategies to promote carbohydrate availability for the majority of training sessions as is practical and within the athlete’s total energy budget (Table 2). These recommendations are based on plentiful evidence that strategies enhancing carbohydrate availability also enhance endurance and performance during a single session of exercise. They concede that the literature fails to provide a clear support that long-term high-carbohydrate intakes enhance the training adaptations and performances of endurance athletes, but challenges sport scientists to undertake well-controlled studies that will better test this hypothesis.

### Table 2. Summary of current guidelines for carbohydrate intake by athletes (adapted from Burke, 2007)

<table>
<thead>
<tr>
<th>Situation</th>
<th>Recommended carbohydrate intake</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acute situation</strong></td>
<td></td>
</tr>
<tr>
<td>Optimal daily muscle glycogen storage (e.g. for post-exercise recovery or to fuel up or carbohydrate load before an event)</td>
<td>7–12 g/kg body mass/day</td>
</tr>
<tr>
<td>Rapid post-exercise recovery of muscle glycogen, where recovery between sessions is &lt; 8 h</td>
<td>1–1.2 g/kg immediately after exercise; repeated each hour until meal schedule is resumed. There may be some advantages to consuming carbohydrate as a series of small snacks every 15–60 min in the early recovery phase</td>
</tr>
<tr>
<td>Pre-event meal to increase carbohydrate availability before prolonged exercise session</td>
<td>1–4 g/kg eaten 1–4 h before exercise</td>
</tr>
<tr>
<td>Carbohydrate intake during exercise</td>
<td></td>
</tr>
<tr>
<td>Sustained high-intensity exercise ～ 1 h when muscle fuel stores are not limiting</td>
<td>Small amounts, including swilling in mouth</td>
</tr>
<tr>
<td>Moderate-intensity or intermittent high-intensity exercise of &gt; 1 h</td>
<td>0.5–1.0 g/kg/h (30–60 g/h)</td>
</tr>
<tr>
<td>Prolonged exercise (2–3 h’’)</td>
<td>80–90 g/h</td>
</tr>
<tr>
<td><strong>Chronic or everyday situation</strong></td>
<td></td>
</tr>
<tr>
<td>Daily recovery or fuel needs for athletes with very light training program (low-intensity exercise or skill-based exercise). These targets may be particularly suited to athletes with large body mass or a need to reduce energy intake to lose weight</td>
<td>3–5 g/kg/day*</td>
</tr>
<tr>
<td>Daily recovery or fuel needs for athlete with moderate exercise program (i.e. 60–90 min)</td>
<td>5–7 g/kg/day*</td>
</tr>
<tr>
<td>Daily recovery or fuel needs for endurance athlete (i.e. 1–3 h of moderate- to high-intensity exercise)</td>
<td>7–12 g/kg/day*</td>
</tr>
<tr>
<td>Daily recovery or fuel needs for athlete undertaking extreme exercise program (i.e. &gt; 4–5 h of moderate- to high-intensity exercise such as Tour de France)</td>
<td>≥ 10–12 g/kg/day*</td>
</tr>
</tbody>
</table>

*Note that this carbohydrate intake should be spread over the day to promote fuel availability for key training sessions – i.e. consumed before, during or after these sessions.
Training with low-carbohydrate availability

Discovery of nutrient–gene interactions and cellular signaling pathways has allowed scientists to identify a range of muscular adaptations to training and form new hypotheses about the best strategies to promote these adaptations. Some studies have found that when exercise is undertaken with low muscle glycogen content, the transcription of a number of genes involved in training adaptations is enhanced (for review, see Hawley et al., 2006; Baar & McGee, 2008). It appears that several transcription factors have glycogen-binding domains, and when muscle glycogen is low, these factors are released to associate with different targeting proteins. Indeed, exercising with low muscle glycogen stores amplifies the activation of the signaling proteins, AMP-activated protein kinase and p38 mitogen-activated protein kinase, which have direct roles in controlling the expression and activity of several transcription factors involved in mitochondrial biogenesis and other training adaptations (Hawley et al., 2006; Baar & McGee, 2008).

Equally, exercise in a fasted state has been shown to promote different cellular signaling responses to exercise undertaken with carbohydrate intake before and during the session (Civitarese et al., 2005). This information underpins the recently described “train low, compete high” protocol – training with low glycogen/carbohydrate availability to enhance the training response, but competing with high-fuel availability to promote performance. There are a number of potential ways to reduce carbohydrate availability for the training environment (see Table 3), and it should be pointed out that these do not always promote a low carbohydrate diet per se nor restrict carbohydrate availability for all training sessions.

Great interest in this new hypothesis of “train low, compete high” was generated by a study by Hansen et al. (2005). In this investigation, seven untrained males undertook a 10-week program of leg knee extensor “kicking” exercise. In an ingenious experimental design, each subject’s legs undertook the same training program (5 h/week) but received a

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Table 3. Strategies to reduce carbohydrate availability to alter the molecular responses to endurance-based training sessions

<table>
<thead>
<tr>
<th>Exercise-diet strategy</th>
<th>Main outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronically low carbohydrate diet (carbohydrate intake less than fuel requirements for training)</td>
<td>Chronic reduction in muscle carbohydrate availability (endogenous and potentially exogenous sources) for all training sessions, depending on degree of fuel mismatch. Chronic whole-body effects of low carbohydrate availability including impairment of immune system and central nervous system function.</td>
</tr>
<tr>
<td>Twice a day training (low endogenous carbohydrate availability for the second session in a day achieved by limiting the duration and carbohydrate intake in recovery period after the first session)</td>
<td>Reduction in endogenous and exogenous carbohydrate availability for the muscle during the second training session. Acute reduction in carbohydrate availability for immune system and central nervous systems depending on duration of carbohydrate restriction and muscle fuel requirements of second session.</td>
</tr>
<tr>
<td>Training after an overnight fast</td>
<td>Reduction in exogenous carbohydrate availability for the muscle for the specific session. Potential reduction in endogenous carbohydrate availability if there is inadequate glycogen restoration from previous day’s training. Acute reduction in carbohydrate availability for immune system and central nervous systems depending on duration of carbohydrate restriction and fuel requirements of the session.</td>
</tr>
<tr>
<td>Prolonged training with or without an overnight fast and/or withholding carbohydrate intake during the session</td>
<td>Reduction in exogenous carbohydrate sources for the muscle for the specific session. Acute reduction in carbohydrate availability for immune and central nervous systems depending on duration of carbohydrate restriction and fuel requirements of the session.</td>
</tr>
<tr>
<td>Withholding carbohydrate during the first hours of recovery</td>
<td>Could provide adequate fuel availability for the specific session but amplify post-exercise signaling due to the short but targeted time of low carbohydrate availability – theoretically achieves both a “training harder” and “training smarter” effect. Could interfere with re-fuelling for subsequent training sessions if total carbohydrate intake is reduced rather than just delayed. Given limits in the total rate of glycogen synthesis, delaying the timing of intake may reduce the potential for total glycogen storage between two sessions that are &lt;8 h apart, regardless of total carbohydrate intake. May reduce immune system function or accentuate the immune suppression that occurs after exercise.</td>
</tr>
</tbody>
</table>

*Note that permutations and combinations of these strategies could alter exogenous and endogenous carbohydrate supplies independently or interactively.
different daily schedule: one leg was trained twice-a-day, every second day, whereas the contralateral leg was trained daily. The consumption of a carbohydrate-rich diet (\( \sim 8 \, \text{g/kg/day} \)) meant that one leg exercised with full restoration of glycogen each day, while the “twice a day” leg undertook the second session with depleted muscle glycogen stores. Compared with the leg that performed daily training with normal glycogen reserves, the leg that commenced half of training sessions with low muscle glycogen levels had a more pronounced increase in resting glycogen content (when training and dietary factors were organized to promote re-fueling) and citrate synthase activity. Although the increase in maximal power was similar in each leg, there was an almost twofold greater training-induced increase in one-legged exercise time to fatigue in the “train low” leg compared with the leg trained in a glycogen-replete state.

Some caveats were identified in applying the results of this study to real-life athletes. First, the subjects were untrained and the results may not apply to the training adaptation and performance in already well-trained athletes. Second, the training sessions undertaken by subjects in that study were “clamped” at a fixed submaximal intensity for the duration of the training program: athletes typically periodize their programs to incorporate a “hard–easy” pattern to the overall organization of training, as well as progressive overload. Third, the mode of training (one-legged knee kicking) and the exercise “performance” task (submaximal kicking to exhaustion) bear little resemblance to the whole-body training modes and performance tasks undertaken by the majority of competitive athletes. These issues have been partially addressed by some more recent studies.

Yeo et al. (2008) completed a 3-week training study using a parallel group design in which endurance-trained cyclists consumed diets providing \( \sim 8 \, \text{g/kg/day} \) carbohydrate, while completing six training sessions per week (\( \sim 8 \, \text{h/week} \)) divided into three steady-state cycling sessions (100 min at 70% \( \text{VO}_{2\text{peak}} \)) and three sessions of high-intensity intervals (8 \( \times \) 5 min at maximal sustained power, with 1 min recovery). One group of seven subjects alternated between one of these sessions each day (high group), while another seven subjects trained every second day, with the steady-state session followed an hour later by the interval session (low group). Training intensity was measured as the self-selected power outputs achieved in the interval session, while performance was measured before and after the training block via a 1-h time trial completed after an hour of steady-state cycling. They found that resting muscle glycogen concentrations, rates of whole-body fat oxidation during steady-state cycling and muscle activities of the mitochondrial enzymes citrate synthase and \( \beta \)-hydroxyacyl-CoA-dehydrogenase (HAD) were increased only in the group that undertook the interval sessions with low glycogen. However, total work completed in the interval sessions was less in the low group compared with the high training group. Nevertheless, 1-h cycling performance improved similarly (\( \sim 10\% \) increase in power) in both groups. Although it is tempting to suggest that the low group made the same performance gains with less training stimulus, it must be remembered that both groups trained for the same duration of time and to their maximum effort. In fact, the low group experienced difficulty in undertaking the interval training.

The findings of this study were confirmed by another similarly designed 3-week investigation (Hulston et al., 2010) in which participants undertook 90-min aerobic sessions and interval training sessions (8 \( \times \) 5 min at self-selected highest sustained intensity) either on alternative days (high group) or in succession on the same day (low group). Mean training intensity during the interval training sessions was again lower in the low group (297 \( \pm \) 8 W) compared with the high group (323 \( \pm \) 9 W, \( P<0.05 \)). In addition, various measurements of metabolic adaptation were evident only in the low group; there was increased mitochondrial content of the enzyme HAD and increased fat oxidation during submaximal exercise, principally from muscle-derived triacylglyceride. Once again, despite these apparently different training experiences, both groups achieved an equal improvement of performance from the 3-week training block, with \( \sim 10\% \) reduction in time to compete a time trial lasting about 60 min.

An additional variation to the “train low” approach was investigated by Morton et al. (2009). Three groups of recreationally active men undertook four sessions of fixed-intensity high-intensity running over a 6-week period with either high-carbohydrate availability (single day training), train low (two training sessions twice a week, such that the second training session was undertaken with low glycogen), or train low+glucose (as for the previous group, but with glucose intake before and during the second session). All groups recorded a similar improvement in \( \text{VO}_{2\text{max}} \) (\( \sim 10\% \)) and distance run during a YoYo intermittent Recovery Test 2 protocol (\( \sim 18\% \)), although the group who trained with low availability of exogenous and endogenous carbohydrate sources showed greater metabolic advantages such as increased activity of the mitochondrial enzyme succinate dehydrogenase.

The provision of carbohydrate during workouts during 6 weeks of matched training (three sessions per week for 1–2 h) in moderately active men has been separately studied by De Bock et al. (2008). A group who did the same training in the fasted state...
showed increases in proteins involved in fat utilization and a decrease in muscle glycogen utilization when exercise was undertaken in a fasted state. However, increases in exercise capacity were similar in both groups and fat utilization during exercise with carbohydrate intake was not different. Additionally, the group who undertook the first “train low” study have completed a further 10-week training study in previously untrained subjects, with one leg training in the fasted state, while the contralateral leg undertook training while consuming a carbohydrate drink (Akerstrom et al., 2009). Both legs responded equally to the training in terms of increases in muscle concentrations of glycogen and the enzymes citrate synthase and HAD, as well as increases in exercise power and endurance. Finally, another study followed cyclists/triathletes who completed 15–20 h/week of training over 4 weeks, with one group consuming a moderate carbohydrate intake (\( \sim 5.3 \text{g/kg/day} \)), while a matched group consumed an iso-energetic diet higher in carbohydrate (8 g/kg/day) in which the additional carbohydrate was consumed as glucose during and after training sessions. Both groups improved their performance during a protocol lasting \( \sim 2 \text{h} \) equally (Cox et al. 2010; see Table 1). Clearly, the current literature barely scratches the surface of the work that needs to be carried out on this topic.

Are there other potential rewards and concerns with “train low” concepts?

The hypothesized benefits to “train low” strategies include enhanced metabolic adaptations to a given training stimulus, an increased ability to utilize fat as an exercise fuel and a reduced reliance on carbohydrate. While there is support for such benefits, there is currently no clear evidence that this translates into a performance benefit. In athletic circles, “train low” strategies are purported to enhance loss of body fat and reduce the need for carbohydrate intake during competition (reducing the potential for gastrointestinal side effects by reducing the amount of food or sports drinks an athlete might need to consume). These issues have not been studied, although the study from our own group (Cox et al., 2010) found that training with carbohydrate intake increases oxidation rates of exogenous carbohydrate with the adaptation presumably occurring at the level of gut uptake.

It is curious that the muscle and metabolic enhancements do not translate into performance benefits. Reasons for this apparent disconnect include the brevity of the study period, the possibility that performance is not reliant or quantitatively linked to the markers that have been measured, our failure to measure other counterproductive outcomes and our focus on the muscular contribution to performance while ignoring the brain and central nervous system. Most importantly, we may again be simply unable to measure performance well enough to detect changes that would be significant in the world of sport.

Meanwhile, it is important to consider the potential for side effects arising from “train low” strategies. There is already evidence that “training low” reduces the ability to train – increasing the perception of effort and reducing power outputs. Most athletes and coaches fiercely guard the ability to generate high power outputs and work rates in training as a preparation for competition. Indeed, in our extensive work on another dietary periodization strategy for athletes – adaptation to high-fat diets before carbohydrate loading for endurance and ultra-endurance events – we found evidence that the adaptations that we had considered glycogen “sparring” during exercise were, in fact, glycogen “impairing” (for review, see Burke & Kiens, 2006). These fat adaptation protocols enhanced the pathways for fat utilization, at the expense of the activity of pyruvate dehydrogenase, a rate-limiting enzyme in carbohydrate utilization (Stellingwerff et al., 2006). Here again, we could find no evidence of an expected improvement in exercise performance, but instead, a reduction in the ability to perform high-intensity exercise (Havermann et al., 2006). This is an important consideration because the outcome-defining activities in most sports are conducted at high intensity. Finally, the effect of repeated training with low carbohydrate status on the risk of illness (Gleeson et al., 2004), injury (Brouns et al., 1986) and over-training (Petibois et al., 2003) need to be considered.

Practical implications

1. Currently, we have insufficient evidence to provide guidelines to athletes for incorporating “train low” strategies into their training programs. While there may be a sound hypothesis that training in a low carbohydrate environment can amplify the training response, there is no clear proof that this leads to performance enhancements. Indeed, there are potential disadvantages to the health and performance of the athlete, including the not insignificant likelihood that “training low” may interfere with the volume or intensity of training.

2. In real life, most elite athletes practice an intricate periodization of both diet and exercise loads within their training program, which may change within a macrocycle or microcycle. Either by intent or for practicality, some training sessions are undertaken with low carbohydrate status (overnight fasting, several sessions in the day, little carbohydrate intake...
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During the workout, while others are undertaken using strategies that promote carbohydrate status (more recovery time, post-meal, carbohydrate intake during the session). It makes sense that sessions undertaken at lower intensity or at the beginning of a training cycle are most suited, or perhaps, least disadvantaged by “train low” strategies. Conversely, “quality” sessions done at higher intensities or in the transition to peaking for competition are likely to be the best undertaken with better fuel support. Athletes may, by accident or design, develop a mix-and-match of nutrition strategies that achieves their overall nutrition goals, suits their lifestyle and resources, and maximizes their training and competition performances. Finding this optimal balance is the art of coaching.

3. This art of coaching may not be fully understood by sports scientists and the complexity of the “ideal” approach to training nutrition may not easily be tested in conventional scientific studies. Nevertheless, the real challenge for sports scientists is to design studies with a multifactorial approach to nutrition support, combined with clever ways to measure performance outcomes that will mimic the demands of real-life sport and detect the small improvements that can differentiate the “podium placed” athletes from the rest of the field.

Key words: dietary periodization, carbohydrate intake, sports nutrition guidelines.

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