Insufficient Dietary Carbohydrate During Training: Does it Impair Athletic Performance?

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It is well established that adequate bodily carbohydrate reserves are required for optimal endurance. Based on this fact, it has been hypothesized that consumption of a diet with a high percentage of carbohydrate energy will optimize training adaptations and athletic performance. Scrutiny of the literature, however, does not strongly support the hypothesis that short-term or long-term reductions in dietary carbohydrate energy impairs training or athletic performance. Additional studies with well devised training protocols and performance tests are necessary to prove or disprove the hypothesis that a high carbohydrate energy diet is necessary to optimize training adaptations and performance. Because dietary carbohydrate contributes directly to bodily carbohydrate reserves, and because a high carbohydrate energy diet does not impair athletic performance, it remains prudent to advise athletes to consume a diet with a high carbohydrate energy content.

Under normal circumstances, athletic performance improves as an athlete’s state of training improves. However, it is sometimes observed that athletic performance deteriorates even when indices of the state of training are improved or unchanged. On the other hand, training capacity sometimes deteriorates without explanation. There are many theories about the mechanisms underlying this deterioration in training and performance. One of these theories is that the decreased performance is caused by an acute depletion or chronic reduction in the bodily carbohydrate reserves.

It is well known that liver and muscle glycogen reserves are limited and that their depletion during intense, prolonged exercise reduces exercise capability. For these carbohydrate reserves to be replenished between exercise sessions, it is important that adequate dietary carbohydrate be consumed before the next exercise session. However, not all athletes consume adequate dietary carbohydrate to maintain bodily carbohydrate reserves.

Kuipers and Keizer (30) propose that training which causes an imbalance between the exercise-induced overload and recovery over the short term, and which results in fatigue, be called “overreaching.” Similarly, when the im-

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balance continues over the long term and results in persistent subjective and objective symptoms of fatigue, the athlete is suffering from the "overtraining syndrome," or "staleness" (30). Based on these viewpoints, depletion of bodily carbohydrate reserves resulting from inadequate dietary carbohydrate intake during training over the short or long term may cause both overreaching and staleness.

**Carbohydrate Reserves and Endurance Performance**

Relative to fat or protein stores, bodily carbohydrate stores are severely limited. Approximately 400 g and 70 g of glycogen are stored in muscle and liver, respectively. Assuming a resting muscle glycogen level of 130 mmol·kg\(^{-1}\) (42), an active muscle mass of 22 kg while running at 70% VO\(_{2}\)max (33), and a glycogenolysis rate of 4.5 mmol·kg\(^{-1}\)·km\(^{-1}\) (40), depletion of muscle glycogen would occur at about 28.9 km (17.9 miles). Because bodily carbohydrate stores are limited and carbohydrate is the preferred fuel for exercising muscle at exercise intensities between 65–85% VO\(_{2}\)max, exhaustion during prolonged exercise is related to depletion of these carbohydrate stores.

**Muscle Glycogen**

As exercise intensity increases linearly, muscle glycogen utilization increases exponentially. Saltin and Karlsson (40) demonstrated that the rate of glycogenolysis was 0.7, 1.4, and 3.4 mmol·kg\(^{-1}\)·min\(^{-1}\) when exercising at 50, 75, and 100% VO\(_{2}\)max, respectively. At exercise intensities less than 60% VO\(_{2}\)max, exercise can continue for hours without muscle glycogen depletion (40). At exercise intensities of 65–85% VO\(_{2}\)max, muscle glycogen decreases curvilinearly over time (19, 40) and exhaustion is related to depletion of muscle glycogen (2, 6, 19). Further, when subjects cycle intermittently at 77% VO\(_{2}\)max, muscle glycogen stores are depleted at exhaustion (19). However, at exercise intensities above 90% VO\(_{2}\)max, exhaustion occurs before muscle glycogen depletion. Therefore there is a strong relationship between muscle glycogen depletion during exercise at 65–75% VO\(_{2}\)max and exhaustion, but not at exercise intensities above or below this range.

**Blood Glucose**

During exercise, blood glucose levels reflect the balance between muscle glucose uptake and hepatic glucose production. During cycle ergometry, leg glucose uptake increases curvilinearly as the exercise intensity increases (26, 45). Katz et al. (26) reported that leg glucose uptake was 1.19 mmol·min\(^{-1}\) at 50% VO\(_{2}\)max and 3.82 mmol·min\(^{-1}\) at 100% VO\(_{2}\)max. Muscle glucose uptake also appears to increase as the duration of exercise increases (4, 25, 45). Ahlborg and Felig (4) reported that glucose uptake increased ~40% between 40 and 90 min of moderate intensity exercise. Because muscle glucose uptake is directly proportional to blood glucose concentration (32), glucose utilization declines during the later stages of prolonged exercise due to a decline in arterial glucose concentration (4, 5).

Blood glucose levels are maintained during the early stages of exercise at 30–40% VO\(_{2}\)max due to low muscle glucose uptake (3). As exercise continues,
however, blood glucose levels fall slowly, but rarely below 2.8 mmol\textsuperscript{-1} L\textsuperscript{-1}. On the other hand, at high exercise intensities the glucose uptake reaches almost 4 mmol\textsuperscript{-1} min\textsuperscript{-1} (26), but this is insufficient to meet energy demands. In this circumstance, muscle glycogenolysis is accelerated and muscle glycogen is the primary metabolic substrate.

During the initial stages of moderate intensity exercise, blood glucose levels are maintained or may even increase slightly (15, 21). However, as exercise continues beyond 90 min, blood glucose steadily decreases due to a decline in liver glucose output (4). If blood glucose declines to \(< 25\) mmol\textsuperscript{-1} L\textsuperscript{-1}, some individuals may exhibit symptoms related to hypoglycemia-induced neuroglycopenia (lightheadedness, lethargy, nausea). It is believed that less than 50% of individuals exercising at 60–70% \(\text{VO}_2\text{max}\) for 2.5–3.5 hours will show symptoms of hypoglycemia (4, 16). Of those individuals exhibiting such symptoms, only \(< 30\)% experience fatigue related to central nervous system factors, whereas fatigue in the remaining 70% appears to be due to peripheral factors. Coyle et al. (9, 16) have shown that a decline in blood glucose to 2.5–3.0 mmol\textsuperscript{-1} L\textsuperscript{-1} is accompanied by a decline in total carbohydrate oxidation and eventual exhaustion.

**Diet and Bodily Carbohydrate Reserves**

Because carbohydrate is the preferred fuel source for muscle during exercise at moderate intensities, and because of the direct relationship between the level of carbohydrate stores and time to exhaustion, it is reasonable to suggest that a high carbohydrate diet will elevate carbohydrate stores and thereby enhance endurance performance. Therefore it is important for endurance athletes to monitor their carbohydrate intake. Ideally, athletes should derive approximately 60–70% of dietary energy from carbohydrates to optimize bodily carbohydrate stores (13, 43).

**Muscle Glycogen**

The muscle glycogen content of an endurance trained athlete consuming a diet containing 50% of energy from carbohydrate is \(< 130\) mmol\textsuperscript{-1} kg\textsuperscript{-1} (14, 42). Bergstrom et al. (7) were the first to show that muscle glycogen levels could be elevated to supranormal levels (\(< 204\) mmol\textsuperscript{-1} kg\textsuperscript{-1}) using two exhaustive bouts of exercise separated by 3 days on a low carbohydrate diet followed by 3 days on a high carbohydrate diet and rest. Using various diet formulations to manipulate muscle glycogen levels, Bergstrom et al. (6) and Hermansen et al. (19) showed that preexercise muscle glycogen levels correlated well with time to exhaustion at 75% \(\text{VO}_2\text{max}\). These results were later confirmed by Ahlborg et al. (1).

**Liver Glycogen**

The liver glycogen stores in a normal man on a mixed diet are 270 mmol\textsuperscript{-1} kg\textsuperscript{-1} (20). With an average liver weight of 1.8 kg, this corresponds to 490 mmol of glycogen. Liver glycogen stores can be increased to as high as 900 mmol following a high carbohydrate diet (20). With a normal liver glycogen content and a resting rate of glycogenolysis of 32 mmol\textsuperscript{-1} h\textsuperscript{-1} (20), liver glycogen stores will decrease by \(< 78\%\) following a 12-hr fast. Further, the blood glucose concentra-
Dietary Carbohydrate and Training

Dietary Practices of Endurance Athletes

Based on recommendations from sports nutritionists and exercise physiologists (13, 41, 43), endurance athletes should ingest diets that derive 12-15% and 60-70% of energy from protein and carbohydrates, respectively, with the balance as energy from fat. Unfortunately, available evidence indicates that endurance athletes consume diets that are deficient in the percent of dietary energy that is carbohydrate (17, 18, 24). Grandjean (18) reported that elite male and female endurance athletes typically consume diets deriving only 49% of dietary energy from carbohydrate. Further, the average daily energy consumption of these athletes was significantly below that recommended for this active population. Theoretically, adequate ingestion of dietary carbohydrate on a daily basis will help maintain liver and muscle glycogen stores at optimal levels and enhance training capacity. Thus, adequate dietary carbohydrate may help prevent exercise-induced overreaching or staleness by maintaining bodily carbohydrate reserves.

Carbohydrate Consumption and Muscle Glycogen Synthesis After Exercise

Muscle glycogen is often depleted following prolonged, moderate intensity exercise. Further, liver and muscle glycogen can be repleted if a high carbohydrate diet is consumed. Many studies have been conducted to determine the best methods to optimize repletion of muscle glycogen after exhaustive exercise. These studies have investigated the effects of the amounts, timing, and types of carbohydrate feedings on muscle glycogen. Only one study (34) has examined methods to optimize repletion of liver glycogen following exhaustive exercise. This deficiency in the literature is due in large part to the invasive nature of obtaining liver biopsies in humans.

Muscle Glycogen Synthesis During the Hours After Exercise

Blom et al. (8) determined the amount of carbohydrate needed to maximize muscle glycogen synthesis following intermittent cycling at 75% VO_{2max} that reduced muscle glycogen to an average 23 mmol•kg^{-1}. Subjects were fed 0.35, 0.70, or 1.4 g glucose•kg^{-1} every 2 hrs for 6 hrs following exercise, and the subsequent rates of muscle glycogen synthesis were 2.1, 5.8, and 5.7 mmol•kg^{-1}•h^{-1}, respectively. Ivy et al. (23) depleted muscle glycogen with intermittent cycling exercise and then fed subjects either 0, 1.5, or 3.0 g glucose polymers•kg^{-1} immediately after and 2 hours after exercise. Muscle biopsies were obtained immediately after and 4 hrs after exercise. The rates of muscle glycogen synthesis during this 4-hr interval were 0.5, 4.6, and 5.2 mmol•kg^{-1}•h^{-1}, respectively. Therefore, based on these studies (8, 23), muscle
glycogen synthesis will be maximal when between 0.7 and 3.0 g carbohydrate kg\(^{-1}\) is consumed every 2 hrs after exercise.

To determine the optimal timing of postexercise carbohydrate feedings to maximize muscle glycogen synthesis, Ivy et al. (22) fed subjects either a placebo or 1.0 g glucose kg\(^{-1}\) immediately after exercise and 2 hrs later or only 2 hrs after exercise. Glucose feedings beginning immediately after exercise resulted in a muscle glycogen synthesis rate of 6.0 mmol kg\(^{-1}\) h\(^{-1}\), whereas the 2-hr postexercise feeding resulted in a glycogen synthesis rate that was only 4.1 mmol kg\(^{-1}\) h\(^{-1}\). When the placebo solution was consumed, the rate of glycogen synthesis was 3.2 mmol kg\(^{-1}\) h\(^{-1}\). Therefore, to maximize muscle glycogen synthesis following exercise, athletes should ingest high carbohydrate beverages or snacks as soon as possible following a strenuous workout or competition.

Several investigators have sought to determine the rate of muscle glycogen synthesis after ingesting different types of carbohydrates after exercise (8, 14). Costill et al. (14) examined the effect of ingesting a diet rich in simple or complex carbohydrates on muscle glycogen synthesis during the 48 hrs after a run that decreased muscle glycogen levels to 50 mmol kg\(^{-1}\). Rates of muscle glycogen synthesis were similar irrespective of diet for the first 24 hours, but during the second 24-hr period the diet containing complex carbohydrates resulted in significantly greater (20 mmol kg\(^{-1}\)) muscle glycogen storage. However, other studies have not supported the finding that a complex carbohydrate diet facilitates greater glycogen synthesis (27, 39). In fact, Keins et al. (27) reported that a simple carbohydrate diet induces greater glycogen synthesis during the first 6 hrs after exhaustive exercise; however, there was no difference in glycogen synthesis between complex and simple carbohydrate diets 20, 32, and 44 hrs after exhaustive exercise. Therefore a simple carbohydrate diet may be preferred during the early hours after exercise, whereas a complex or simple carbohydrate diet may be used to replenish muscle glycogen between daily training sessions.

Blom et al. (8) compared the rates of muscle glycogen synthesis when 0.70 g kg\(^{-1}\) of glucose, sucrose, or fructose was given every 2 hrs for 6 hrs following moderate intensity, intermittent exercise to exhaustion. Rates of muscle glycogen synthesis were 5.8, 6.2, and 3.2 mmol kg\(^{-1}\) h\(^{-1}\) when glucose, sucrose, and fructose were ingested, respectively. The lower rate of muscle glycogen synthesis following fructose ingestion is likely due to the fact that fructose metabolism takes place primarily in the liver (45) and therefore preferentially contributes to liver glycogen synthesis (34). This concept is consistent with the observation that liver glycogen synthesis is greater during fructose infusion than during glucose infusion (34). Therefore it is possible that consuming foods containing large amounts of fructose (fruits) will stimulate greater liver glycogen synthesis than consuming foods containing large amounts of glucose.

**Muscle Glycogen Content During the Days After Exercise**

Early work by Piehl (37) suggested that it takes up to 48 hrs to replete muscle glycogen stores following exhaustive exercise. Subjects were fed 8.6 g carbohydrate kg\(^{-1}\) 24 h\(^{-1}\) following 2 hrs of exhaustive cycling that depleted muscle glycogen. Muscle glycogen content reached 76% of preexercise levels at 24 and 34 hrs after exercise but did not return to baseline until 46 hrs following exercise. Piehl et al. (38) later confirmed this finding. On the other hand, much of the
literature suggests that muscle glycogen can be repleted in 24 hrs, provided that adequate carbohydrate is ingested during the postexercise period (2, 7, 29). Bergstrom et al. (7) had subjects perform one-legged cycling to exhaustion. Subjects consumed 9.3 g carbohydrate·kg⁻¹·24 h⁻¹, and muscle glycogen stores had returned to preexercise levels within 24 hrs after exercise. Similarly, Kochan et al. (29) fed subjects 11.3 g carbohydrate·kg⁻¹·24 h⁻¹ following 60 min of one-legged cycling at 75% VO₂max and found normal muscle glycogen stores 24 hrs postexercise.

Costill et al. (14) examined the effects of feeding subjects meals containing 188, 325, 525, or 648 g carbohydrate·24 h⁻¹ on muscle glycogen synthesis during the 24 hrs following exercise. Subjects ran 16 km at ~80% VO₂max followed by five 1-min sprints at an estimated 130% VO₂max. This exercise decreased muscle glycogen levels to 50 mmol·kg⁻¹. It is not possible to accurately assess whether muscle glycogen was repleted 24 hrs following exercise because preexercise muscle glycogen levels were not measured. However, a significant correlation was found between the carbohydrate content of the diet and muscle glycogen storage over the 24-hr period; this suggests the importance of ingesting adequate carbohydrate on a daily basis to maintain optimal muscle glycogen. Further, glycogen content during the 24-hr period after exercise was similar when 525–648 g carbohydrate was consumed per day.

**Effects of Changes in Carbohydrate Intake on Muscle Glycogen and Performance**

Because of the direct relationship between muscle glycogen and endurance capacity, and because of the direct relationship between dietary carbohydrate intake and muscle glycogen content, exercise physiologists have sought to determine the short- and long-term consequences of varying carbohydrate intakes on exercise performance. These studies, summarized in Table 1, have utilized different exercise modes and different dietary manipulations, and some have examined the consequences of the dietary manipulations on performance.

**Studies Lasting Less Than 7 Days**

It is well recognized that endurance athletes should consume a high carbohydrate diet daily to maintain muscle glycogen during training. It has long been proposed that if inadequate carbohydrate is consumed between training sessions, muscle glycogen will gradually decline and endurance performance will be compromised (13). This has led to several short-term studies in which dietary carbohydrate intake was manipulated during daily training in order to directly assess the effects on muscle glycogen and in some cases on performance.

Costill et al. (10) concluded that consuming a moderate carbohydrate diet resulted in progressive glycogen depletion during successive days of training. The subjects ran 16.1 km at 80% VO₂max on three successive days while consuming a diet containing an estimated 45% of daily energy consumption as carbohydrate. Preexercise muscle glycogen levels were approximately 110, 88, and 66 mmol·kg⁻¹ on each of the 3 days. The daily declines in muscle glycogen were accompanied by a reduction in the estimated percent of energy derived from carbohydrate, that is, 87, 66, and 57% for the three successive days, respec-
Table 1
Summary of Studies That Have Manipulated Diet
to Assess Effects on Muscle Glycogen, Performance Capabilities, and/or Training Capabilities

<table>
<thead>
<tr>
<th>Authors (ref)</th>
<th>Exercise mode</th>
<th>Carbohydrate consumption (g·kg⁻¹·d⁻¹)</th>
<th>Days of study</th>
<th>Daily exercise</th>
<th>Performance task</th>
<th>Glycogen content (mmol·kg⁻¹)</th>
<th>% Change in glycogen</th>
<th>% Change in performance</th>
<th>Evidence of overreaching or overtraining</th>
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<tbody>
<tr>
<td><strong>Studies ≤7 Days</strong></td>
<td></td>
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<tr>
<td>Costill et al. (10)</td>
<td>Running</td>
<td>4.7 ¹</td>
<td>3</td>
<td></td>
<td></td>
<td>73 min @ 80% (\text{VO}_2\text{max}) &amp; (\text{VO}_2\text{max}) test</td>
<td>None</td>
<td>~110</td>
<td>~88</td>
</tr>
<tr>
<td>Pascoe et al. (35)</td>
<td>Running</td>
<td>5.0</td>
<td>3</td>
<td></td>
<td></td>
<td>60 min @ 75% (\text{VO}_2\text{max})</td>
<td>None</td>
<td>~115</td>
<td>~110</td>
</tr>
<tr>
<td>Cycling</td>
<td></td>
<td>5.0</td>
<td>3</td>
<td></td>
<td></td>
<td>60 min @ 75% (\text{VO}_2\text{max})</td>
<td>None</td>
<td>~127</td>
<td>~120</td>
</tr>
<tr>
<td>Costill et al. (13)</td>
<td>Swimming</td>
<td>8.2</td>
<td>10</td>
<td></td>
<td></td>
<td>Increased training vol. from 4266 to 8990 m·d⁻¹</td>
<td>Training</td>
<td>130</td>
<td>110</td>
</tr>
<tr>
<td>Swimming²</td>
<td></td>
<td>5.3</td>
<td>10</td>
<td></td>
<td></td>
<td>from 4266 to 8990 m·d⁻¹</td>
<td>Training</td>
<td>100</td>
<td>80</td>
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<tr>
<td>Study Group</td>
<td>Sport</td>
<td>Days</td>
<td>Training Description</td>
<td>Muscle Glycogen Changes</td>
<td>Notes</td>
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<tr>
<td>Kirwan et al.</td>
<td>Running</td>
<td>3.9</td>
<td>1.5-fold @ 80% VO₂max Training distance</td>
<td>91</td>
<td>66 - 27</td>
<td>Not affected</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Maint. of intensity of 82</td>
<td>-32</td>
<td>Not affected</td>
<td>No</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>interval training</td>
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<td></td>
<td></td>
<td></td>
<td>between 5 to 3000 m</td>
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<tr>
<td>Lamb et al.</td>
<td>Swimming</td>
<td>6.5</td>
<td>80% VO₂max</td>
<td>121</td>
<td>65% Vol.</td>
<td>Maint. of Training</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Swimming</td>
<td></td>
<td>Training</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>No</td>
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<td></td>
<td></td>
<td></td>
<td>Not assessed</td>
<td>Not affected</td>
<td>No</td>
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</table>

**Studies ≥7 Days**

<table>
<thead>
<tr>
<th>Study Group</th>
<th>Sport</th>
<th>Training Description</th>
<th>Muscle Glycogen Changes</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>Phinney</td>
<td>Cycling</td>
<td>&lt;0.3</td>
<td>143</td>
<td>76 - 47</td>
</tr>
<tr>
<td>et al.</td>
<td></td>
<td>Normal training</td>
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<td></td>
<td></td>
<td>intensity &amp; vol.</td>
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<td></td>
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<td>To exhaustion @ 65%</td>
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<td></td>
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<td>VO₂max</td>
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<td></td>
<td>3 x 2500 m</td>
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<td>training ~ 90 min/d</td>
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<td></td>
<td></td>
<td>@ &gt;70% VO₂max</td>
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<td></td>
<td>Time trials</td>
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<td></td>
<td></td>
<td>115</td>
<td></td>
<td></td>
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<tr>
<td>Simonsen</td>
<td>Rowing</td>
<td>5</td>
<td>124</td>
<td>+11</td>
</tr>
<tr>
<td>et al.</td>
<td></td>
<td>Twice daily</td>
<td>124</td>
<td>+11</td>
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<tr>
<td></td>
<td></td>
<td>training ~ 90</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>min/d @ &gt;70% VO₂max</td>
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<tr>
<td></td>
<td></td>
<td>94</td>
<td></td>
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</table>

*Estimated based on a diet containing 43% of energy as carbohydrate, a caloric consumption of 12.6 MJ•d⁻¹ (3,000 kcal•d⁻¹), and an average body mass of 69 kg.

*Subgroup of swimmers who did not increase daily caloric intake to match energy expenditure of training. Approximately 4.18 MJ•d⁻¹ (1,000 kcal•d⁻¹) deficit.

Time _F_ represents the muscle glycogen content at the beginning of the experiment whereas Time _L_ represents the glycogen content on the final day of the experiment. If a glycogen concentration is reported between these two times, the muscle glycogen content was measured at an intermediate time.
tively. Unexpectedly, Costill et al. reported that "no consistent pattern was observed with regard to increased levels of fatigue with successive days of exertion" (p. 835) despite a 40% decline in the preexercise muscle glycogen concentration from the first to the third day.

Later these results were hypothetically combined in a schematic drawing to indicate the muscle glycogen levels over three successive days of 2 hrs of running when subjects consumed either a moderate or a high carbohydrate diet (13). This schematic demonstrated that the high carbohydrate diet maintained muscle glycogen levels daily, and it has been interpreted to indicate that daily training capabilities were maintained by the "normal" glycogen concentrations. Although this schematic is often used to illustrate the effects of high and moderate carbohydrate diets on muscle glycogen, the results for the high carbohydrate diet were not experimentally determined (13).

Pascoe et al. (35) fed subjects a diet containing 45% of the daily energy consumption as carbohydrate (5 g carbohydrate·kg⁻¹·d⁻¹) over 3 days using a crossover design for cycling and running. Subjects exercised for 60 min at 75% VO₂max, and the treadmill grade was a 4% incline. Preexercise muscle glycogen declined from approximately 120 mmol·kg⁻¹ on the first day to approximately 105 mmol·kg⁻¹ on the third day. Unfortunately, Pascoe et al. did not determine whether a decline in endurance performance over the 3 days occurred coincident to the roughly 13% reduction in muscle glycogen. However, because there was a gradual decline in preexercise muscle glycogen over the 3 days of training, and because of the apparent lack of a systematic approach to assess performance in these two studies (10, 35), they do not rule out the possibility that it may be important for athletes to consume a diet containing adequate calories from carbohydrate to maintain normal muscle glycogen levels, and thus eliminate bodily carbohydrate depletion as a potential cause of exercise-induced overreaching.

Several studies have attempted to determine whether dietary carbohydrate intake influences the athlete's ability to train when the daily training volume is suddenly increased. Costill et al. (11) studied the effects of 10 days of increased training volume on muscle glycogen and swimming performance. Before the study, the swimmers trained 1.5 h·d⁻¹, 5 d·wk⁻¹, averaging 4,266 m·d⁻¹ at 94% VO₂max. During the 10 days of the study, the training distance was increased to two 1.5-hr training sessions per day, 5 d·wk⁻¹, averaging 8,970 m·d⁻¹ while swimming intensity was maintained at 94% VO₂max. The increased training volume resulted in an estimated total daily energy expenditure of 19.5 MJ. The subjects ate ad libitum during the experiment, and dietary recall records were used to estimate the characteristics of the diets. The subjects consumed a diet containing an estimated 8.2 g carbohydrate·kg⁻¹·d⁻¹. Muscle glycogen was 130 mmol·kg⁻¹ before the study and had declined to 110 mmol·kg⁻¹ on Day 10. The swimmers reported local muscular fatigue and difficulty completing the training sessions, but swimming power, sprinting, and endurance performance were unchanged as a result of the 10-day training overload and the 15% decline in muscle glycogen.

Costill et al. (11) reported that four of the eight subjects consumed 4.18 MJ less per day than required according to the estimated energy expenditure of the daily training. These four subjects self-selected diets that contained only 5.3 g carbohydrate·kg⁻¹·d⁻¹, and their muscle glycogen decreased from 100 mmol·kg⁻¹ to 80 mmol·kg⁻¹ over the 10 days of training. These four sub-
jects were “unable to tolerate the heavier training demands and were forced to swim at significantly slower speeds during the training sessions” (p. 249), presumably as a result of the 20% decline in muscle glycogen over the 10 days of training. Apparently some athletes may not increase their energy intake when the training load is suddenly increased and may suffer impaired performance because of insufficient dietary carbohydrate and/or energy. Overall, it appears that most athletes will voluntarily increase their energy intake when the training load is suddenly increased, and this increased dietary energy prevents the impairment of performance.

In a similar study, Kirwan et al. (28) had 10 runners increase their daily training load for 5 days while consuming a diet whose carbohydrate composition was 50 or 100% of the runners’ estimated daily energy expenditure. This resulted in the runners consuming either 3.9 or 8.0 g carbohydrate•kg\(^{-1}•d\(^{-1}\). Over the 5 days of intensified running, subjects completed 1.5 times the average preexperiment daily training distance at 80% \(VO_2\text{max}\). Compared to the high carbohydrate diet, the low carbohydrate diet resulted in significantly lower muscle glycogen levels before the training session on the fifth day. Overall, muscle glycogen averaged 121 and 82 mmol•kg\(^{-1}\) for the two diets, respectively. The low carbohydrate diet resulted in significantly higher ratings of perceived exertion and higher oxygen consumption at a fixed running speed compared to the high carbohydrate diet. However, both groups were able to complete the training sessions despite the significantly different preexercise muscle glycogen concentrations.

Based on the recommendation that athletes consume a diet containing 60–70% of energy as carbohydrate (14, 41, 43), Lamb et al. (31) examined the effects of 9 days of a high (80% of energy) or a moderate (43% of energy) carbohydrate diet on the ability of swimmers to maintain swimming intensity during interval workouts on the final 5 days of the diets. The swimmers consumed an average 19.56 MJ daily. Average daily carbohydrate consumption was 502 (6.5 g•kg\(^{-1}•d\(^{-1}\)) and 935 (12.1 g•kg\(^{-1}•d\(^{-1}\)) grams for the moderate and high carbohydrate diets, respectively. The three morning workouts totaled 3,800 m.

The afternoon interval workouts for 3 days totaled 7,300 m for an average 74 min at an estimated 88% \(VO_2\text{max}\). The afternoon interval workouts for 2 days totaled 6,300 m for an average 62 min at an estimated 88% \(VO_2\text{max}\). Each swimmer attempted to maintain a preselected pace for the afternoon workouts that included interval sets of swims ranging from 50 to 3,000 m. There were no diet effects on mean swim velocities (1.37 m•s\(^{-1}\)) for the interval workouts. Because Costill et al. (12) observed significant glycogen degradation in the posterior deltoid muscle at swim velocities and distances similar to those in the Lamb et al. study (31), it can be safely inferred that the interval training sessions resulted in glycogen depletion. Recall that the moderate carbohydrate diet was based on the percentage of calories and that the daily carbohydrate consumption was \(\geq 502 \text{ g•d}^{-1}\). Costill et al. (14) have previously suggested that 24-hr glyco- gen synthesis reaches a plateau when between 525–648 g carbohydrate are consumed per day. Therefore it is possible that the moderate carbohydrate diet provided the necessary carbohydrate to fully restore muscle glycogen daily and facilitate the maintenance of daily interval swimming intensity.

Based on the results of the study by Lamb et al. (31), it is possible that the amount of carbohydrate consumed by athletes should not be based on a percentage of the energy consumed as carbohydrate. If carbohydrate consumption is
fixed as 70% of daily energy consumption and the athlete’s energy intake increases, the amount of carbohydrate consumed per day increases. In fact, if the athlete is consuming 20.9 MJ·d⁻¹ (5,000 kcal·d⁻¹) and the percentage is fixed at 43% as carbohydrate, the average athlete (70 kg) will consume 537 g carbohydrate·d⁻¹. This amount exceeds the amount required to fully restore muscle glycogen in 24 hrs (14). Therefore it appears that the recommended carbohydrate consumption by athletes should be based either on total daily carbohydrate consumption (g·d⁻¹) or, because of differing sizes of athletes, on the amount of carbohydrate consumed relative to body weight (g·kg⁻¹·d⁻¹). However, for more practical purposes, the amount of carbohydrate that an athlete in training should consume per day may also be represented as the amount of daily energy that should be derived from carbohydrate to maintain carbohydrate consumption at 10 g·kg⁻¹·d⁻¹ (Table 2).

Sherman et al.¹ fed runners and cyclists 5 or 10 g carbohydrate·kg⁻¹·d⁻¹ in 12.6 MJ for 7 days. The moderate carbohydrate diet contained a total of 42% of energy from carbohydrate, with 15% of that energy supplied from a liquid carbohydrate beverage. The high carbohydrate diet contained a total of 84% of energy from carbohydrate, and 19% of that energy was supplied from a liquid carbohydrate beverage. During the week before the experiment, subjects tapered their daily exercise and consumed a diet containing 8 g carbohydrate·kg⁻¹·d⁻¹ (67% energy as carbohydrate). The subjects exercised each day using their respective exercise modes for 60 min at 75% VO₂max followed by five 1-min sprints at 130% VO₂max. After completing this exercise session on Day 7, the subjects undertook exhaustive exercise at 80% VO₂max during two exercise bouts that were separated by 5 min of rest. Muscle glycogen was measured before exercise on Days 1, 3, 5, and 7 of the experiment. Figure 1 is a schematic

### Table 2

**Recommended Daily Carbohydrate Consumption for Various Sized Athletes Undertaking Heavy Training, Based on 65% of Daily Energy Intake as Carbohydrate and Maintaining Carbohydrate Ingestion at 10 g·kg⁻¹·d⁻¹**

<table>
<thead>
<tr>
<th>Body mass (kg)</th>
<th>Daily energy intake* (kcal)</th>
<th>As carbohydrate (kcal)</th>
<th>Daily carbohydrate intake (g·d⁻¹)</th>
<th>(g·kg⁻¹·d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>2800</td>
<td>1800</td>
<td>450</td>
<td>10</td>
</tr>
<tr>
<td>57</td>
<td>3500</td>
<td>2300</td>
<td>575</td>
<td>10</td>
</tr>
<tr>
<td>68</td>
<td>4200</td>
<td>2700</td>
<td>675</td>
<td>10</td>
</tr>
<tr>
<td>79</td>
<td>4900</td>
<td>3200</td>
<td>800</td>
<td>10</td>
</tr>
<tr>
<td>91</td>
<td>5600</td>
<td>3650</td>
<td>912</td>
<td>10</td>
</tr>
<tr>
<td>102</td>
<td>6300</td>
<td>4100</td>
<td>1025</td>
<td>10</td>
</tr>
<tr>
<td>113</td>
<td>6900</td>
<td>4500</td>
<td>1125</td>
<td>10</td>
</tr>
</tbody>
</table>

*Provided as kcal because these units are understood by most practitioners; to convert to appropriate scientific units (MJ), divide the kcal units by 238.92.
representation of the experimental results for muscle glycogen for the runners and cyclists. It is apparent that the high carbohydrate diet maintained muscle glycogen compared to the moderate carbohydrate diet over 7 days of intense training. Interestingly, the exercise times to exhaustion for the separate or combined sessions were similar among the treatments.

Collectively, these studies demonstrate that diets containing between 3–5 g carbohydrate·kg\(^{-1} \cdot d\)^{-1} will result in a progressive decline in muscle glycogen over 7 days of intense daily training. Conversely, a diet containing 8 g carbohydrate·kg\(^{-1} \cdot d\)^{-1} results in less glycogen depletion whereas a diet containing 10 g carbohydrate·kg\(^{-1} \cdot d\)^{-1} prevents glycogen depletion. If the athlete is in an energy deficit that results in decreased muscle glycogen levels, training capabilities may be impaired. However, it is not known whether this is due to the energy deficit or the reduced carbohydrate intake. Interestingly, none of these studies conclusively demonstrate that a moderate carbohydrate diet impairs the subjects' ability to complete the required exercise tasks. Further, the high carbohydrate diet apparently does not enhance the subjects' ability to complete the required exercise tasks. Either the dietary effects are too acute to influence ath-

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1Sherman, Doyle, and Lamb. Training, carbohydrate and muscle glycogen, American College of Sports Medicine, abstract submission, 1991.
letic performance, or short-term reductions in muscle glycogen by diet do not significantly impair athletic performance.

It is also possible that the performance tasks used in previous studies were inappropriate to adequately reflect the effects of different initial muscle glycogen levels on performance. For example, the studies demonstrating the highest associations between preexercise muscle glycogen content and endurance performance have commonly used cycling exercise at 70–75% VO₂max. Additionally, some aspects of the recovery of muscle function may be independent of the muscle glycogen content and related to other factors (46). It is evident that more research is required to clarify the significance of short-term reductions in muscle glycogen on performance.

Studies Lasting More Than 7 Days

Although short-term (<7 days) changes in dietary carbohydrate consumption affect muscle glycogen, the long-term effects of changes in dietary carbohydrate consumption on muscle glycogen are relatively unknown. Further, because the acute changes in muscle glycogen have not been directly shown to affect performance, it is possible that more chronic changes in muscle glycogen will have more detectable effects on performance. Theoretically, over the long term a diet containing a 5 g·kg⁻¹·d⁻¹ should result in chronically lower muscle glycogen levels, and this should result in staleness—a deterioration of the athlete's ability to train or perform optimally. On the other hand, a diet containing 10 g·kg⁻¹·d⁻¹ should result in higher muscle glycogen levels; this should optimize training and performance and prevent staleness. Unfortunately, only two studies have examined the long-term effects of different levels of carbohydrate intake on endurance and training performance.

Phinney et al. (36) used five well-trained cyclists and for 7 days fed them a eucaloric balanced diet containing “35–50 kcal·kg⁻¹·d⁻¹, 1.75 g protein·kg⁻¹·d⁻¹ and the remainder of kilocalories as two-thirds carbohydrate and one-third fat” (p. 769) for 7 days. Thereafter the subjects consumed a eucaloric ketogenic diet contained <20 g carbohydrate·d⁻¹ for 28 days. During the study the subjects maintained their normal training distance (apparently ≥162 km·wk⁻¹). Based on several variables, the investigators reported that "there was excellent compliance with the rigid dietary restrictions imposed by the study" (p. 769). An endurance test to exhaustion at 65% VO₂max and pre- and posttest biopsies were conducted before and after the 28-day eucaloric diet. Preexercise muscle glycogen was significantly reduced from 143 to 76 mmol·kg⁻¹ by the eucaloric ketogenic diet. Interestingly, the lower preexercise muscle glycogen concentrations did not significantly reduce the time to exhaustion (147 vs. 151 min for the eucaloric balanced and ketogenic diets, respectively). Unfortunately, the subjects' responses were quite variable: two had improved performance while three had decreased performance after the ketogenic diet.

This study suggests that a long-term adaptation to chronically low dietary carbohydrate intake may occur that provides for a greater oxidation of fat and conservation of glycogen stores during exercise. However, this study may not be applicable to most athletes because the exercise intensity is much lower than that which would be undertaken by competitive athletes during training and per-
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Furthermore, the results of this study indicate that there may be a limit to the intensity of exercise that can be performed following a ketogenic diet because, as stated by the investigators, "there was a marked attenuation of the RQ values at VO_2_{max}, suggesting a severe restriction on the ability of subjects to do anaerobic work" (p. 772).

Simonsen et al. (44) fed rowers undertaking 4 wks of twice-daily intense rowing training a diet containing either 5 or 10 g carbohydrate·kg^{-1}·d^{-1}. Protein intake was constant at 2 g protein·kg^{-1}·d^{-1}, and energy intake was adjusted with fats to maintain body weight during training. The high carbohydrate diet included a liquid carbohydrate beverage that supplied approximately 29 and 41% of the daily dietary energy and carbohydrate, respectively. The moderate carbohydrate diet group also consumed an artificially colored, flavored, and textured placebo solution. Six mornings each week the subjects undertook cycling and/or rowing exercise for 45 min at 70–80% VO_2_{max}. On three afternoons each week the rowers completed training equaling 107 min of rowing at ≥70% VO_2_{max}. On the other three afternoons the rowers completed training equaling 100 min of rowing at ≥70% VO_2_{max}, including three 2,500-m time trials. One morning each week the rowers completed training equaling 35 min of rowing at ≥70% VO_2_{max}.

Power output for the three 2,500-m time trials was used to assess the effects of the diet on changes in training/performance capabilities during the 4-wk training period. The vastus lateralis was biopsied once each week before a set of time trials. Over the 4 weeks, muscle glycogen increased from 94 to 155 mmol·kg^{-1} for the high carbohydrate group whereas it averaged 119 mmol·kg^{-1} for the moderate carbohydrate group. Average power output for the three 2,500-m time trials increased significantly more for the high carbohydrate group (10.7%) than for the moderate carbohydrate group (1.6%) on the last day of the 4 wks of training. Interestingly, the moderate carbohydrate group experienced neither a progressive glycogen depletion nor a significant reduction in average power output during the 4 wks of training. Based on the literature (19, 40, 42) it can be safely inferred that the daily rowing sessions significantly metabolized muscle glycogen. Furthermore, pilot studies demonstrated that three 2,500-m time trials can reduce muscle glycogen by 84 mmol·kg^{-1}. Therefore, while the high carbohydrate diet facilitated an improvement in average power output over 4 wks of rowing training, the moderate carbohydrate diet did not result in glycogen depletion that had a detrimental effect on performance of the time trials.

Although far from conclusive, these studies suggest that long-term consumption of a high carbohydrate diet may improve both training and performance capabilities. On the other hand, they do not support the hypothesis that long-term consumption of a moderate carbohydrate diet leads to progressive glycogen depletion and impaired training or performance capabilities or staleness. Perhaps the body adapts to a "nonoptimal" carbohydrate intake by enhancing carbohydrate storage or by increasing the metabolism of fats.

A limited number of studies have examined the effects of consuming varying amounts of dietary carbohydrate on training and performance for longer than 10 days. This is obviously due to the cost and labor of conducting long-term training and diet studies. Until a suitable collection of well-controlled long-term studies exists, we can only extrapolate from the short-term studies and the one
long-term study that was summarized (44). Until the effectiveness of a high carbohydrate diet on athletic training and performance is disproved, it appears prudent to advocate a high carbohydrate diet for athletes.

Summary

The hypothesis that insufficient dietary carbohydrate during heavy training causes low muscle glycogen concentrations that in turn cause diminished training or performance capabilities and overreaching or staleness is not strongly supported by the literature. However, it is well established that low blood glucose, muscle, and/or liver glycogen concentrations can contribute to fatigue during certain types of exercise. Because dietary carbohydrate contributes directly to maintenance of these bodily carbohydrate reserves, it remains prudent to advise athletes to consume a high carbohydrate diet. Because it is difficult to induce voluntary overreaching and staleness in subjects in laboratory studies, it is necessary to identify the indices of overwork and/or staleness by observing athletes in the field or those whose dietary habits make them more susceptible to exercise-induced overreaching or staleness.

References


