Dietary carbohydrate, muscle glycogen, and exercise performance during 7 d of training

William M Sherman, J Andrew Doyle, David R Lamb, and Richard H Strauss

ABSTRACT The effects of moderate- or high-carbohydrate diets on muscle glycogen and performance in runners and cyclists over 7 consecutive days of training were determined. Muscle biopsies were performed on 4 separate days before exercise for 1 h at 75% peak oxygen consumption (VO₂) followed by five, 1-min sprints. After the training session on day 7, subjects ran or cycled to exhaustion at 80% peak VO₂. Muscle glycogen for cyclists and runners was maintained with the high-carbohydrate diet but was reduced 30–36% (P < 0.05) with the moderate-carbohydrate diet. All subjects completed all training sessions, and there were no differences in times to exhaustion on day 7. For cyclists and runners, consuming a moderate-carbohydrate diet over 7 d of intense training reduces muscle glycogen but has no apparent deleterious effect on training capability or high-intensity exercise performance. A high-carbohydrate diet maintains muscle glycogen, but this has no apparent benefit on training capability or high-intensity exercise performance. Am J Clin Nutr 1993;57:27-31.

KEY WORDS Physical exertion, athletic training, exercise

Introduction

Endurance exercise at intensities ≈ 70–80% of maximal oxygen consumption (VO₂max) substantially lowers muscle glycogen concentrations (1). Associated with reduced muscle glycogen is the inability to maintain exercise intensity at 70–80% VO₂max (1). It is usually assumed that muscle glycogen must be restored between daily training sessions to facilitate optimal training capabilities (2, 3).

The carbohydrate content of athletes’ diets affects muscle glycogen concentration. Costill et al (4) reported that muscle glycogen progressively declined over 3 consecutive d of running training when subjects self selected a 43% carbohydrate diet. In spite of the 43% decline in muscle glycogen over those days, there was no consistent pattern of fatigue over the days of training. Nevertheless, it has been inferred that consumption of a diet containing moderate amounts of carbohydrate lowers muscle glycogen concentrations and thereby impairs both training capabilities and maximal exercise performance ability. This thesis, however, was not supported by Simonsen et al (5) for rowers who consumed a moderate-carbohydrate diet while undertaking twice-daily intense training. In this rowing study muscle glycogen was reduced but rowing ability was maintained. Thus, the association between dietary carbohydrate and muscle glycogen appears clear but the effects of reduced muscle glycogen concentration on training and exercise performance capabilities is uncertain (3).

This study was designed to compare the effects of moderate- (5 g carbohydrate·kg body wt⁻¹·d⁻¹) and high- (10 g carbohydrate·kg body wt⁻¹·d⁻¹) carbohydrate diets on muscle glycogen, training compliance, and maximal performance capabilities of runners and cyclists over 7 d of intense training.

Methods

Subjects

Thirty-six men volunteered to serve as subjects and provided informed consent according to institutional guidelines. Each subject was paid an honorarium for their participation in the study. This project was approved by the Biomedical Sciences, Human Subjects Review Committee of The Ohio State University. Subjects’ previous weekly training loads were similar to or exceeded those imposed by the experimental protocols. Each subject was also required to achieve a VO₂ peak ≥ 4 L/min for the applicable exercise mode.

The physical and physiological characteristics of the subjects are provided in Table 1. Hydrostatic weighing was used to determine lean body mass of the subjects on day 1 of the control phase. Vital capacity was used to estimate residual volume (6). Repeated measures of vital capacity and hydrostatic weighing were determined until the variability of the readings was ≤ 4%. The means for the three highest values were averaged, and the Siri equation (7) was used to calculate percent body fat.

Exercise mode–specific peak oxygen consumption (peak VO₂) was determined by using a progressive workload protocol that also allowed determination of the ventilatory threshold and maximal heart rate. VO₂ was determined with an automated open-circuit system that calculated VO₂ every 20 s. Inspiratory volumes were measured with a gasometer (RAM-9200; Rayfield Equipment, Wilton, VT) calibrated against a Tissot spirometer (Warren E Collins, Boston). Expired oxygen and carbon dioxide

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were measured with electric analyzers (S-3A/1; Ametek, Pittsburgh, and LB-2; Beckman, Fullerton, CA). The analyzers were calibrated with a National Bureau of Standards calibration gas, the concentrations of which were confirmed with chemical analyses.

**Experimental design**

After a 5-d exercise and dietary control period, cyclists and runners (n = 9 for each group) were randomly assigned in a double-blind design to either a moderate- or high-carbohydrate diet to assess the effects of dietary carbohydrate content on muscle glycogen and performance capabilities over 7 d of intense cycling or running training.

During the 5-d control period, both exercise and diet were supervised in the laboratory. Subjects exercised for 60, 40, 20, and 20 min at 75% peak VO2 for control days 1–5, respectively. Runners ran up a +6% incline on a motor-driven treadmill to favor concentric contractions and to minimize muscle damage before the start of the training phase (8). Cyclists exercised on Velodyne ergometers (Schwinn, Excelsior, IL) fitted with their own bicycles. During this control phase, subjects consumed a diet containing 8 g carbohydrate · kg−1 · d−1 (67% of energy from carbohydrates, 15% from protein, and 18% from fat; Table 2). An 18% carbohydrate beverage (GatorLode. The Quaker Oats Co, Chicago) was provided during the control period to familiarize the subjects with liquid dietary supplementation.

During the 7-d training period, exercise was supervised in the laboratory. Subjects exercised daily between 1600 and 1800 for 1 h at 75% peak VO2 followed by five 1-min sprints at 100% peak VO2 interrupted by 1-min rest intervals. For runners the treadmill grade remained at +6%. Heart rate and ratings of perceived exertion for the whole body and legs (9) were recorded after 15 and 45 min during the 1-h session and immediately before cessation of each sprint. The environmental conditions were 25 °C and 50% relative humidity. Subjects also consumed 250 mL cooled water every 20 min during exercise.

During the 7-d training period food was provided in the laboratory. Subjects consumed diets containing either 5 or 10 g carbohydrate · kg−1 · d−1 (Table 2). All diets were supplemented with a beverage containing 18% maltodextrins (GatorLode). During the training period, subjects consumed 660 mL (moderate) or 830 mL (high) of the liquid supplement with the evening meal between 1630 and 1730. Breakfast and lunch were consumed between 0600 and 0800 and 1200 and 1300, respectively. Raw vegetables (carrots and celery) were provided as snacks. Before breakfast and before the afternoon workout, body weight was recorded to the nearest 100 g. To minimize the potential influence of subject knowledge about dietary carbohydrate on performance, they were informed that the study was designed to determine the effects of two types of mineral supplements on muscle glycogen and performance.

**Blood analysis and muscle biopsies**

Blood samples and muscle biopsies were obtained at 1645 daily before the exercise session on days 1, 3, 5, and 7 of the training period. Biopsies were obtained from the vastus lateralis for the cyclists and from either the vastus lateralis or lateral head of the gastrocnemius for the runners. A subset of nine cyclists and nine runners also underwent a muscle biopsy on day 1 after the training session to assess muscle glycogen utilization from the training session. Muscle biopsies were obtained without suction from alternating legs at progressively proximal (> 3 cm) sites to the previous biopsy to eliminate the potential effects of previous biopsies on the glycogen content of a subsequent biopsy. Samples were quick frozen in liquid nitrogen and stored at −80 °C.

To determine muscle glycogen concentration, frozen muscle samples were first divided into three pieces (5–10 mg) under liquid nitrogen and weighed (to the nearest 0.01 mg at −20 °C). Each sample was then hydrolyzed in 2 mol HCl/L (2 h at 100 °C) and neutralized with NaOH. Finally, the glucose concentration of the hydrolyzate was determined enzymatically with fluorometry (10). The intraassay coefficient of variation (CV) was 2.2% for duplicates of the same muscle sample and 8.4% for triplicate samples of the same muscle. The interassay CV was 3.1%. Glycogen results were expressed per kg wet tissue.

Muscle citrate synthase activity (11) in the vastus lateralis and gastrocnemius muscles was analyzed in a subset of four runners and four cyclists in muscle obtained on day 1 of the training period. The CV for duplicate samples was 2.2%.

Blood samples were analyzed enzymatically for glucose by using a commercially available kit (Boehringer, Indianapolis). The duplicate sample and interassay CVs were 1.4% and 3.9%, respectively.

**TABLE 1**

Physical and physiological characteristics of the subjects*

<table>
<thead>
<tr>
<th>Age</th>
<th>Body fat</th>
<th>VO2 max</th>
<th>VO2 max body wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>yr</td>
<td>%</td>
<td>L/min</td>
<td>mL · kg−1 · min−1</td>
</tr>
<tr>
<td>Cyclists</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HI CHO</td>
<td>30 ± 3</td>
<td>11 ± 2</td>
<td>4.2 ± 0.2</td>
</tr>
<tr>
<td>MOD CHO</td>
<td>25 ± 3</td>
<td>9 ± 1</td>
<td>4.3 ± 0.2</td>
</tr>
<tr>
<td>Runners</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HI CHO</td>
<td>30 ± 3</td>
<td>11 ± 1</td>
<td>4.2 ± 0.2</td>
</tr>
<tr>
<td>MOD CHO</td>
<td>34 ± 3</td>
<td>10 ± 1</td>
<td>4.5 ± 0.1</td>
</tr>
</tbody>
</table>

* x ± SE; n – 9 for each treatment group. HI CHO, high-carbohydrate diet; MOD CHO, moderate-carbohydrate diet; VO2 max, maximal oxygen consumption.

**TABLE 2**

Characteristics of the control, moderate (MOD), and high (HI) carbohydrate (CHO) diets during the control and training phases for a typical subject

<table>
<thead>
<tr>
<th>Experimental phase and diet</th>
<th>Control/ control</th>
<th>Training/ MOD CHO</th>
<th>Training/ HIGH CHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy intake (J)</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
</tr>
<tr>
<td>CHO energy (% of total)</td>
<td>67</td>
<td>42</td>
<td>84</td>
</tr>
<tr>
<td>CHO from typical foods</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(g CHO/d)</td>
<td>539</td>
<td>234</td>
<td>565</td>
</tr>
<tr>
<td>(% total energy)</td>
<td>61</td>
<td>27</td>
<td>65</td>
</tr>
<tr>
<td>Liquid supplement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(g CHO/d)</td>
<td>46</td>
<td>132</td>
<td>166</td>
</tr>
<tr>
<td>(CHO as % total energy)</td>
<td>6</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>(mL/d)</td>
<td>230</td>
<td>660</td>
<td>830</td>
</tr>
</tbody>
</table>
DIETARY CARBOHYDRATE AND MUSCLE GLYCOGEN

To measure exercise performance, after the normal training session on day 7, each subject rested for 5 min before undertaking two maximal performance trials at 80% peak VO, until exhaustion. The two performance trials were separated by 5 min of rest. Exhaustion was identified as the time at which the subject was unable to maintain the prescribed rate of pedal revolutions on the cycle ergometer or to keep pace with the treadmill speed.

Statistical analysis

Two separate one-way analyses of variance (diet) with repeated measure (time) were used to assess the effects of the dietary treatments on the dependent variables for cycling and running. The least-significant-difference procedure was used to locate significant pair-wise differences among means. The probability of committing a Type I error was held to \( P < 0.05 \). Group data are reported as mean ± SE.

Results

All subjects completed the prescribed daily training on all 7 d of the training period. On average, exercise elicited 79% and 75% of maximal heart rate and peak VO\(_2\), respectively, throughout the daily 1-h training sessions. Similarly, exercise during the 5-min sprints elicited 90% of maximal heart rate on average. There were no significant effects of diet on heart-rate responses or on ratings of whole-body perceived exertion or leg perceived exertion for the daily training sessions (results not shown). There were also no differences in body weight over the 7-d training period for either the cyclists or runners consuming either diet (results not shown).

Interestingly, despite similar exercise and dietary controls during the 5-d control period, muscle glycogen was 65% higher in cyclists compared with runners \( (P < 0.05) \). This effect was consistent in runners for either the gastrocnemius or vastus lateralis muscles. For runners on day 1, muscle glycogen averaged 112.6 ± 8.9 and 104.0 ± 6.4 mmol/kg, respectively, for the gastrocnemius and vastus lateralis muscles. Muscle citrate synthase activity was similar \( (P > 0.05) \) in the vastus lateralis muscles for the cyclists and runners, averaging 30.7 ± 2.0 and 28.2 ± 3.2 \( \mu \)mol·min\(^{-1}·g\(^{-1}\) respectively.

A subset of runners and cyclists underwent muscle biopsies before and after exercise on day 1 of the training period. For cyclists, muscle glycogen concentrations before and after the training sessions were 186.7 ± 13.1 and 70.1 ± 10.9 mmol/kg, respectively. Corresponding values for runners were 106.7 ± 3.9 and 73.7 ± 4.2 mmol/kg. The Spearman correlation coefficients between the pre- and postexercise muscle glycogen concentrations were 0.18, 0.41, and 0.81 \( (P < 0.05) \) for all subjects, runners, and cyclists, respectively.

For cyclists on the high-carbohydrate diet, muscle glycogen did not decline significantly over the 7-d training period (Fig 1). In contrast, for the moderate-carbohydrate diet, glycogen was significantly reduced on days 3, 5, and 7 compared with day 1. There was a significant difference in muscle glycogen for the high- and moderate-carbohydrate diets on days 5 and 7.

For runners on the high-carbohydrate diet, muscle glycogen did not change significantly over the 7-d training period (Fig 2). In contrast, for the moderate-carbohydrate diet, glycogen was significantly reduced on days 5 and 7. There was a significant difference in muscle glycogen for the high- and moderate-carbohydrate diets on days 5 and 7.

Exercise times were recorded for the first and second performance trials on day 7 of the training period. There was no effect of diet for either the first or second performances for either cyclists or runners (data not shown). Similarly, when performance times for the first and second trials were summed, there was no effect of diet for either the cyclists or runners. Mean (±SE) total performance times for the cyclists on the moderate- and high-carbohydrate diets were 550 ± 85 and 613 ± 45 s, respectively. Total performance times for the runners consuming the moderate- and high-carbohydrate diets averaged 613 ± 36 and 560 ± 106 s, respectively.

There were no significant effects of the dietary treatments for blood glucose (data not shown).

Discussion

Athletes are often advised to consume a high-carbohydrate diet during training to maintain muscle glycogen concentrations at optimal levels (2). The results of the present study clearly demonstrate that for cyclists and runners undertaking a constant daily training load, a moderate-carbohydrate diet (5 g·kg body

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FIG 1. Effects of consuming a moderate- or high-carbohydrate diet on muscle glycogen concentration over 7 d of cycling training. *\( P < 0.05 \) vs day 1; \# \( P < 0.05 \) vs comparison diet; \( n = 9 \) per treatment; values are \( \bar{x} \pm SE \).

FIG 2. Effects of consuming a moderate- or high-carbohydrate diet on muscle glycogen concentration over 7 d of running training. *\( P < 0.05 \) vs day 1; \# \( P < 0.05 \) vs comparison diet; \( n = 9 \) per treatment; values are \( \bar{x} \pm SE \).
wt.−1·d−1) significantly reduces muscle glycogen by 30–36% during days 5–7 of training. In contrast, consumption of a diet containing 10 g carbohydrate·kg body wt.−1·d−1 maintains muscle glycogen concentrations during days 5–7 of training. Two other studies have reported similar effects of a moderate-carbohydrate diet on muscle glycogen over several days when the training load was constant. Costill et al (4) observed a progressive decline (≈40%) in muscle glycogen when subjects self selected a diet containing 43% of energy from carbohydrate over 3 d of training. The daily training was running for 73 min at 80% VO2max followed by a VO2max test. Similarly, Pascoe et al (12) used both runners and cyclists in a 3-d study with a crossover design. Subjects consumed a diet containing 45% of energy as carbohydrate (5 g·kg body wt.−1·d−1) and exercised daily for 60 min at 75% VO2max. Muscle glycogen declined by ≈13% over the 3-d period and there were no differences in responses between runners and cyclists.

Other studies have examined the effects of dietary carbohydrate on muscle glycogen when the training load was suddenly increased. Costill et al (13) doubled daily swim training volume over 10 d when subjects consumed a self selected euenergetic diet containing 8.2 g carbohydrate·kg−1·d−1. During this time muscle glycogen declined from 130 to 110 mmol/kg. Similarly, Kirwan et al (14) had runners double their daily training distance for 5 d while consuming either 3.9 or 8.0 g carbohydrate·kg−1·d−1. Muscle glycogen averaged 82 and 121 mmol/kg for the moderate- and high-carbohydrate diets, respectively, before exercise on day 5 of the study.

The results of the present study and those of others (4, 12–14) demonstrate that dietary carbohydrate consumption influences muscle glycogen over 3–10 d of training when training volume is either constant or suddenly increased. Notably, a diet containing ≤5 g carbohydrate·kg−1·d−1 results in lower muscle glycogen than a diet containing ≥8 g carbohydrate·kg−1·d−1 (3, 4, 12–14). Importantly, the present study demonstrates the time course of the effects of consuming different amounts of dietary carbohydrate on muscle glycogen when daily training load is constant. Consuming 10 g carbohydrate·kg−1·d−1 maintains muscle glycogen, whereas consuming 5 g carbohydrate·kg−1·d−1 significantly reduces muscle glycogen from day 5 through day 7 of training.

Early studies established the relationship between low muscle glycogen concentrations and fatigue during endurance performance (1, 15). This has led to the presumption that reduced muscle glycogen that resulted from consuming a moderate- or low-carbohydrate diet over days or weeks of training would decrease training compliance and maximal performance capabilities. As indicated from the results for a subset of nine subjects, training on day 1 of the experimental period reduced muscle glycogen by 117 and 33 mmol/kg for the cyclists and runners, respectively. Presumably, this amount of muscle glycogen or less was degraded on a daily basis during each training session. Interestingly, in spite of significantly reduced muscle glycogen concentrations by days 5 and 7 for both cyclists and runners, the subjects completed all daily training sessions. Similarly, on day 7 after the daily training session there was no difference in the time to fatigue during the maximal performance tests between the high- and moderate-carbohydrate diets. Subjects neither reported increased perception of effort nor exhibited increased cardiovascular strain (eg, heart rate) on day 7 during either the daily training or the maximal performance tests.

The lack of a systematic effect of lowered muscle glycogen concentrations resulting from a moderate- or low-carbohydrate diet on daily training compliance and on maximal performance capabilities is not unusual. Costill et al (4) reported that “no consistent pattern was observed with regard to increased levels of fatigue with successive days of exertion” when muscle glycogen decreased by 40% from day 1 to day 3 of training. On the other hand, Pascoe et al (12) did not systematically study the effects of the 13% reduction in muscle glycogen on training capabilities. However, even in studies in which training volume was suddenly doubled and muscle glycogen declined by 15% (13) or differed by 1.47-fold (14), there was still no systematic effect of the reduced muscle glycogen concentration on training compliance when energy intake matched energy expenditure. Although subjects reported local muscular fatigue and difficulty completing the performance sessions (13) or increased ratings of perceived exertion and slightly higher oxygen consumption when muscle glycogen was reduced (14), subjects completed the required training sessions. When inadequate energy intake decreased muscle glycogen by 20%, training compliance significantly declined (13). However, in this case (13) it is uncertain if the reduced training capability resulted from the energy deficit or from the reduced muscle glycogen.

It is possible that the performance tasks used in the present and other studies (4, 13, 14) were not appropriate to detect the effects of differing muscle glycogen concentrations on maximal performance. Early studies reported a close association between the preexercise glycogen concentration and time to fatigue during constant power exercise (1, 15). On the other hand, most competitive endurance events require athletes to traverse fixed distances as fast as possible with a period of higher intensity exercise during the final stages of the event. The training bout followed by the performance trials undertaken on day 7 of the present experiment were selected to more or less simulate these phases of an endurance event. Under these conditions, a high-carbohydrate diet and resultant higher muscle glycogen concentrations did not enhance maximal endurance performance. Perhaps the high-carbohydrate dietary regimen was too brief to influence athletic performance or perhaps short-term diet-induced reductions in muscle glycogen do not impair athletic performance. Nevertheless, high-carbohydrate diets are recommended as part of a healthy lifestyle (16), and because there have been no reported detrimental effects of high carbohydrate consumption on athletic performance, it remains prudent to advise athletes to consume a high-carbohydrate diet.

The reasons for the different muscle glycogen concentrations between runners and cyclists on the first day of the experimental period are not readily apparent. During the control period the same diet was consumed, and the relative exercise intensity was 75% of the mode-specific peak VO2. Also, the runners ran uphill to concentrically bias the exercise to minimize the potential influence of muscle damage on muscle glycogen (17–19). Trained muscle has a higher glycogen content than untrained muscle. It might be argued that the cyclists’ quadriceps muscles were more trained than those of the runners. However, this is not consistent with the observed similarities in citrate synthase activities in the quadriceps muscles of the runners and cyclists; thus, differences in training status do not appear to explain the differences in muscle glycogen concentration between runners and cyclists. It is possible that the control conditions did not equate muscle glycogen for the two exercise modes or that carbohydrate is
somehow stored differently between cyclists and runners (20). Nevertheless, because comparisons were not made between cyclists and runners, this initially different muscle glycogen concentration does not negate the observations of the effects of dietary carbohydrate intake on muscle glycogen and the resultant lack of effect on training compliance and maximal performance capabilities.

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References