Muscle Glycogen Loading
With a Liquid Carbohydrate Supplement

David R. Lamb
The Ohio State University

Ann C. Snyder
University of Wisconsin–Milwaukee

Thomas S. Baur
Virginia Military Institute

This study compared two high carbohydrate (CHO) diets in 14 male runners for effects on muscle glycogen deposition, endurance, and sensations of gastrointestinal discomfort. Muscle glycogen was measured in the vastus lateralis at rest and run time to exhaustion at 75% VO₂max was measured following 3-1/2 days on a 50% CHO diet. After 14 days the subjects consumed a 20% CHO diet and continued training to reduce glycogen. During the next 3-1/2 days, subjects ran less and consumed a 90% CHO diet emphasizing pasta and rice (Pasta, n=7) or lesser amounts of pasta and rice supplemented by a maltodextrin beverage (Supplement, n=7). Glycogen was again measured, followed by a second run to exhaustion. Compared to the 50% CHO diet, Pasta increased muscle glycogen by 27.1±12.2 mmoles/kg muscle (M±SE; P<0.05) and run time by 15.7±5.9 min; Supplement increased glycogen by 43.2±13.5 mmoles/kg (P<0.05) and run time by 29.0±7.4 min (P<0.05). Total glycogen concentrations and run times were not significantly different for Pasta versus Supplement. Subjects reported less gastrointestinal discomfort and greater overall preference for Supplement than for Pasta. Thus, glycogen loading can be accomplished at least as effectively and more comfortably by substituting a maltodextrin drink for some of the pasta and rice in a glycogen loading diet.

Carbohydrate is a major source of fuel for physical activities that require more than 50% of maximal oxygen uptake (VO₂max) (12, 13). Depletion of carbohydrate in muscle, liver, and blood by prolonged exercise at >65% VO₂max or by consumption of low carbohydrate diets has been associated with the rapid onset of exhaustion, especially in activities of 30 min duration or longer (7, 8,

D.R. Lamb is with the School of HPER, Larkins Hall, The Ohio State University, Columbus, OH 43210. A.C. Snyder is with the Dept. of Human Kinetics at the University of Wisconsin–Milwaukee, Milwaukee, WI 53201. T.S. Baur is with the Dept. of Physical Education, Virginia Military Institute, Lexington, VA 24450.
Accordingly, nutritional regimens have been employed to improve the body's stores of muscle and liver glycogen in an attempt to improve performance (17, 18, 21).

One of the most commonly practiced dietary manipulations is the "glycogen loading" regimen, which typically involves a 5-6-day period before an important athletic competition. The regimen as first described includes a 2-3-day low carbohydrate diet combined with exhaustive exercise to deplete the glycogen stores, and culminates with 3 days of a high carbohydrate diet and little or no exercise (3, 21).

One difficulty in implementing the high carbohydrate phase of the diet is the gastrointestinal discomfort often associated with consuming the large quantities of pasta, rice, and bread required to assure the intake of 600-800 g of carbohydrate (70-90% of a 15-MJ diet). It seemed reasonable to hypothesize that gastrointestinal discomfort would be minimized if the volume of food in a high carbohydrate diet were reduced.

Therefore the purpose of this experiment was to determine whether a low residue, calorie rich, liquid carbohydrate dietary supplement could be useful for athletes who wish to increase storage of muscle glycogen. We substituted the carbohydrate drink for most of the pasta and rice traditionally used in glycogen loading diets to determine whether the drink-supplemented diet would be at least as effective as a pasta and rice diet in improving glycogen stores and running performance. We also compared the subjects' perceptions of gastrointestinal sensations and overall preference for the two diets.

**Materials and Methods**

Fourteen well-trained males, ages 19-28 years, provided informed consent according to institutional guidelines prior to participation in the study. These subjects trained 4-6 days a week by running 3-24 km (typically on a hard day/easy day scheme) at approximately 65-75% \( \text{VO}_{2}\text{max} \). The characteristics of the subjects are shown in Table 1. Before any experimental treatment occurred, \( \text{VO}_{2}\text{max} \) was determined for each subject via a treadmill exercise test. Oxygen uptake was determined by standard open-circuit techniques using a Parkinson-Cowan CD-4 gas meter to measure inspired ventilation. Expired air was sampled from a mixing chamber and analyzed with electronic analyzers for \( \text{CO}_2 \) and \( \text{O}_2 \).

**Table 1**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Pasta (M ± SE)</th>
<th>Supplement (M ± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>71.6 ± 2.9</td>
<td>68.5 ± 2.7</td>
</tr>
<tr>
<td>( \text{VO}_{2}\text{max} ) (L/min)</td>
<td>4.7 ± 0.2</td>
<td>4.4 ± 0.2</td>
</tr>
<tr>
<td>( \text{VO}_{2}\text{max} ) (mL·kg(^{-1})·min(^{-1}))</td>
<td>65.9 ± 3.0</td>
<td>64.5 ± 2.4</td>
</tr>
<tr>
<td>Running pace (m/s)</td>
<td>3.26 ± 0.16</td>
<td>3.30 ± 0.14</td>
</tr>
</tbody>
</table>
The gas analyzers were calibrated prior to each exercise test with a standard gas previously verified by chemical analysis.

The subjects were matched into pairs according to body weight, \( VO_2_{\text{max}} \), and running pace at 75\% \( VO_2_{\text{max}} \). One member of each pair was then assigned to either the carbohydrate supplement group (Supplement, \( n = 7 \)) or the pasta and rice diet control group (Pasta, \( n = 7 \)). A crossover design was considered for this investigation but was rejected in order to minimize the adverse effects on motivation that may have resulted from requiring subjects to run three times to exhaustion at 75\% \( VO_2_{\text{max}} \), twice following carbohydrate loading regimens.

Subjects in both groups were given diet exchange lists and asked to consume, for 3-1/2 days, diets of 15 MJ/day containing 50\% of energy as carbohydrate, 20\% as protein, and 30\% as fat. Diet records and similarity of muscle glycogen concentrations for the two groups (see Results) suggest that the subjects complied with the diets. During the first 3 days the subjects ran 3.2-8.0 km/day at 65-75\% \( VO_2_{\text{max}} \). Late in the afternoon of the fourth day, a tissue sample was taken from each runner’s right vastus lateralis muscle by the needle biopsy technique (2). The vastus lateralis muscle was chosen as the biopsy site rather than the gastrocnemius to minimize exercise-induced damage to the more heavily used gastrocnemius (22). The biopsy tissue sample was frozen in liquid nitrogen and later analyzed for glycogen content as previously described (16).

Within 30 min after the biopsy, the subjects began a run to voluntary exhaustion on an indoor 220-m track at a pace equivalent to 75\% of \( VO_2_{\text{max}} \). The mean running paces for the two groups of athletes were nearly identical (Table 1). Running pace was monitored by stopwatch for each lap of the run. Subjects were kept unaware of how long they had been running. As an incentive for performance, subjects were paid $1 for every minute of exercise beyond 80 min and were promised a bonus of $50 if they ran longer than the average time of the other subjects in their group. The purpose of this phase of the experiment was to determine the preexercise muscle glycogen stores and to establish baseline endurance times for the subjects under normal dietary and exercise conditions.

**Protocol for Glycogen Depletion**

Two weeks after running to exhaustion under the 50\% carbohydrate diet condition, all subjects ate a 15-MJ low carbohydrate diet (20\% carbohydrate, 57\% fat, 23\% protein) for 3 days to reduce muscle glycogen stores. To further deplete glycogen, the subjects also ran 8-16 km on the first 2 days and 24 km on the third day. The classical glycogen loading protocol (3) was used rather than the modified protocol (21) in case some subjects in our sample would not have responded normally to the modified protocol.

**Protocol for Determining Glycogen Loading Effects**

After the glycogen depletion phase, all subjects consumed a 15-MJ glycogen loading diet consisting of 90\% CHO, 2.5\% fat, and 7.5\% protein for 3-1/2 days (Table 2). All food and supplements were prepared by laboratory personnel and consumed under supervision in three meals daily. The diet for the Pasta group emphasized pasta and rice whereas the Supplement group ate small amounts of these foods supplemented during each 24-hr period with 3.3 L of a low residue, carbohydrate beverage. In each 100 mL of the supplement there were
### Table 2

**Dietary Intake During 90% Carbohydrate Diet Phase**

<table>
<thead>
<tr>
<th>Food item</th>
<th>MJ</th>
<th>CHO (g)</th>
<th>PRO (g)</th>
<th>Fat (g)</th>
<th>MJ</th>
<th>CHO (g)</th>
<th>PRO (g)</th>
<th>Fat (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasta</td>
<td>17</td>
<td>8</td>
<td>5</td>
<td>11.01</td>
<td>654</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Supplement</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasta</td>
<td>15.10</td>
<td>72</td>
<td>11</td>
<td>14.97</td>
<td>800</td>
<td>69</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Corn flakes</td>
<td>1.84</td>
<td>102</td>
<td>8</td>
<td>0.92</td>
<td>51</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Table sugar</td>
<td>0.27</td>
<td>16</td>
<td>–</td>
<td>0.07</td>
<td>4</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skimmed milk</td>
<td>0.75</td>
<td>22</td>
<td>18</td>
<td>2</td>
<td>0.38</td>
<td>11</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Juice</td>
<td>1.67</td>
<td>100</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Rice product</td>
<td>3.35</td>
<td>178</td>
<td>15</td>
<td>5</td>
<td>0.67</td>
<td>35</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Dried apples</td>
<td>0.63</td>
<td>38</td>
<td>1</td>
<td>–</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Butter</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.15</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Lemonade</td>
<td>3.01</td>
<td>180</td>
<td>–</td>
<td>–</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Spaghetti</td>
<td>3.52</td>
<td>173</td>
<td>28</td>
<td>4</td>
<td>0.88</td>
<td>43</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Chicken broth</td>
<td>0.10</td>
<td>4</td>
<td>2</td>
<td>–</td>
<td>0.05</td>
<td>2</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>Tuna</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.84</td>
<td>–</td>
<td>45</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

17 g of maltodextrins (glucose polymers) from hydrolyzed corn starch and 3 g of sucrose. The subjects in the Supplement group obtained 82% of their dietary carbohydrate energy and 74% of all dietary energy from the supplement. For the glycogen loading diets, the subjects were required to consume all meals in the laboratory under direct supervision. Subjects were asked to refrain from consuming any food outside of the laboratory setting.

During the glycogen loading phase of the diet, the runners ran 3.2–8.0 km daily, that is, the same distances they ran during the control phase of the study. In the late afternoon of the fourth day on the high carbohydrate diet, each subject underwent a second muscle biopsy, this time from the left vastus lateralis, and again ran to exhaustion at 75% VO2max. The ambient temperature (22.3°C) and relative humidity (38%) were similar during both runs to exhaustion.

**Assessment of Diet Acceptability**

The morning after the second run to exhaustion, each subject responded on a Likert scale to two questions designed to evaluate perceived gastrointestinal sensations and diet quantity for the glycogen loading diets consumed for the previous 3-1/2 days (Figure 1). Open-ended responses concerning perceived adverse side effects of the diets were also solicited. For the next three meals the Pasta group crossed over to the Supplement diet while the Supplement group consumed the Pasta diet. The diet evaluation questionnaire was then administered a second time so that the subjects’ perceptions of both diets could be compared. A third question requesting the subjects to compare both diets for overall preference was added to the second questionnaire.
Circle the number that most accurately describes your response to each question:

- How would you rate your gastrointestinal sensations after eating your meals for the last 3-1/2 days?

  1  2  3  4  5  6  7  8  9  10  
  Very overstuff & uncomfortable  Satisfied & comfortable  Very hungry & uncomfortable

- To what extent was your diet for the last 3-1/2 days adequate in quantity?

  1  2  3  4  5  6  7  8  9  10  
  Far too much  About right  Far too little

(The following question was asked only on the second administration of the questionnaire.)

- If both the Pasta diet and the Supplement diet improved running performance to the same extent, which would you be more likely to use?

  1  2  3  4  5  6  7  8  9  10  
  Pasta always  Both diets to same extent  Supplement always

Figure 1 — Diet acceptability questionnaire.

Statistical Analysis

Group data are expressed as $M \pm SEM$. Significant group differences in glycogen concentration and run time were detected with Student two-tailed dependent and independent $t$ tests as appropriate. Comparisons between diets for perceptions of gastrointestinal sensations and diet quantity were tested with the Wilcoxon paired sample test, and the sign test was used to test the significance of overall diet preference results.

Results

The initial muscle glycogen levels were similar for the two groups (Pasta = 103.0±13.0, Supplement = 107.1±8.6 mmoles/kg wet muscle weight). The mean run times to exhaustion for the two groups after the 50% carbohydrate diet (Pasta = 153.1±13.0 min; Supplement = 138.7±7.0 min) were not significantly different.

Compared to the 50% carbohydrate diet condition, both 90% carbohydrate diets resulted in markedly greater ($P<0.05$) concentrations of muscle glycogen (Pasta = 130.2±12.7 mmoles/kg; Supplement = 150.2±11.8; Figure 2). Although the differences in total glycogen concentration after the two 90% carbohydrate diets did not achieve statistical significance, the mean absolute increase for Supplement runners (43.2±13.5 mmoles/kg) was much greater than that for the Pasta group (27.1±12.2 mmoles/kg) ($P<0.05$). Similarly, the mean percentage increase in muscle glycogen was greater for the Supplement runners (44.9±12.2%, $P<0.05$) than for the Pasta runners (33.9±15.2%).

The mean run time to exhaustion of the Supplement group increased by 29.0±7.4 min (20.4±5.0%, $P<0.05$) compared to the 50% carbohydrate diet
Figure 2 — Effect of glycogen loading diets on muscle glycogen content (M±SE). *P<0.05 vs. 50% carbohydrate diet.

Figure 3 — Effect of glycogen loading diets on run time to exhaustion at 75% VO₂max (M±SE). *P<0.05 vs. 50% carbohydrate diet.

condition, whereas the Pasta subjects improved by 15.7±5.9 min (10.6±3.8%) (Figure 3). Total endurance times for the two groups after the 90% carbohydrate diets were essentially identical (Pasta = 168.8±8.1 min; Supplement = 167.7±7.2 min).
Ten of the 14 runners reported less extreme sensations of gastrointestinal fullness and discomfort when consuming the Supplement diet (4.1 ± 0.5) compared to the Pasta diet (2.6 ± 0.4) (P < 0.005). (See Figure 1 for rating scales.) Similarly, 11 subjects rated the Pasta diet as greater in perceived quantity than the Supplement diet (2.4 ± 0.3 vs. 4.7 ± 0.4; P < 0.001). Also, 12 of the 14 subjects responded that they would be more likely to use the Supplement diet for glycogen loading (8.0 ± 0.4; P < 0.001), whereas two stated that they would be equally likely to use the two diets. No difference was apparent between the two diets in other perceived side effects. Two runners in each group reported slight diarrhea during the glycogen loading diets. Two subjects in the Pasta group and one subject in the Supplement group reported a feeling of hyperactivity and an eagerness to run during carbohydrate loading.

Discussion

To our knowledge this is the first investigation in which a maltodextrin supplement has been used in a glycogen loading regimen. However, at least two studies of the chronic use of maltodextrins during routine exercise training have been published. Millard-Stafford et al. (18) used maltodextrins to supplement the diets of athletes undergoing 7 days of normal training. They found that the supplement increased the contribution of carbohydrate to the diet and improved treadmill run time to exhaustion at 90% VO2 max by 23%. On the other hand, Lamb et al. (17) supplemented swimmers’ diets with maltodextrins for 9 days and did not detect any effect of the high carbohydrate diet on daily interval swim training performance, perhaps because the swimmers were not adequately motivated to provide maximal performance on all swims.

The increase in muscle glycogen observed in the present study after the carbohydrate loading regimen was greater than that observed in some studies of runners (10) and less than that shown in other experiments, particularly those in which cycling was used to first deplete glycogen stores (4, 13, 16). Possibly the more intensive use of the vastus lateralis muscle during cycling than running stimulates the glycogen supercompensation mechanism more effectively, or the trauma associated with running 24 km somewhat reduces the optimal glycogen supercompensation (20, 22). Also, whereas subjects in some previous studies did not exercise during the carbohydrate loading phase of the diet (3, 16), our subjects ran from 3.2 to 8.0 km daily—moderate exercise that may have somewhat reduced muscle glycogen stores (5).

The greater loading of glycogen in the muscle of the runners who consumed the liquid CHO supplement may have been caused by a more rapid assimilation of the carbohydrate calories in liquid form. Although Keizer et al. (15) did not find any difference in postexercise glycogen resynthesis rates 22 hours after consumption of a liquid or solid meal, the solid meal consisted of a greater percentage of carbohydrates (77.5 vs. 71.4%, respectively). Also, 22 hours after eating, muscle glycogen stores in the report by Keizer et al. (15) were only 90–100% of the preexercise values. A more rapid assimilation of the carbohydrate calories in the liquid form in the present investigation may have stimulated a greater insulin response to increase the rate and extent of glycogen synthesis throughout the 3-day high carbohydrate period (6, 16, 19).

It is also possible that the maltodextrin drink was more completely absorbed
from the gut than was the pasta; it has been estimated that 10–20% of pasta is normally not absorbed in many subjects (1). Finally, as a possible explanation of the greater improvement in running endurance for the Supplement group, it is conceivable that the subjects who consumed the maltodextrin supplement obtained a psychological benefit of this dietary manipulation that was not available to the Pasta group.

Few athletes would be likely to use a carbohydrate supplement for glycogen loading in the manner required of our subjects, that is, by consuming all of the liquid at mealtimes. We used this protocol in our experiment so that we could carefully control energy intake, but some subjects objected to having to consume so much beverage at one sitting; they would have preferred to drink smaller portions throughout the day. However, it was apparent that the runners could have consumed even larger quantities of the drink if they could have spread that consumption over the entire day. Even under the strict mealt ime conditions we imposed, all but two of the runners favored the diet that emphasized the liquid carbohydrate supplement over the pasta and rice diet, primarily because they felt less full while consuming meals.

However, it must be acknowledged that even though the design was counterbalanced, conditions preceding the acceptability rating of the second diets differed markedly from conditions before the rating of the first diets. Accordingly, one or more of these conditions may have influenced the acceptability ratings in some unknown manner. Nevertheless, as a whole the results suggest that to optimize glycogen loading, a carbohydrate supplement drink should be consumed with normal high carbohydrate meals and as a snack between meals to the extent that the athlete feels comfortable. In most cases it should be practical while maintaining a normal energy intake to consume approximately 2 L of such a drink in a day, providing 400 g of carbohydrate energy in place of fat and as a supplement to other dietary carbohydrates.

In conclusion, our results suggest that when compared to a pasta and rice diet alone, glycogen loading in runners can be accomplished more comfortably and muscle glycogen concentrations and running endurance can be increased at least as effectively if the pasta and rice are supplemented with a maltodextrin-rich drink. It remains to be determined whether such supplements are effective in other sport activities.

References


**Acknowledgments**

The authors express their appreciation to Gary L. Prah, M.D., for performing the muscle biopsies, and to Stokely Van Camp, Inc., Indianapolis, for financial support of this research.