Carbohydrate loading failed to improve 100-km cycling performance in a placebo-controlled trial

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Burke, Louise M., John A. Hawley, Elske J. Schabort, Alan St Clair Gibson, Inigo Mujika, and Timothy D. Noakes. Carbohydrate loading failed to improve 100-km cycling performance in a placebo-controlled trial. J Appl Physiol 88: 1284–1290, 2000.—We evaluated the effect of carbohydrate (CHO) loading on cycling performance that was designed to be similar to the demands of competitive road racing. Seven well-trained cyclists performed two 100-km time trials (TTs) on separate occasions, 3 days after either a CHO-loading (9 g CHO·kg body mass−1·day−1) or placebo-controlled moderate-CHO diet (6 g CHO·kg body mass−1·day−1). A CHO breakfast (2 g CHO/kg body mass) was consumed 2 h before each TT, and a CHO drink (1 g CHO·kg body mass−1·h−1) was consumed during the TTs to optimize CHO availability. The 100-km TT was interspersed with four 4-km and five 1-km sprints. CHO loading significantly increased muscle glycogen concentrations (572 ± 107 vs. 485 ± 128 mmol/kg dry wt for CHO loading and placebo, respectively; P < 0.05). Total muscle glycogen utilization did not differ between trials, nor did time to complete the TTs (147.5 ± 10.0 and 149.1 ± 11.0 min; P = 0.4) or the mean power output during the TTs (259 ± 40 and 253 ± 40 W, P = 0.4). This placebo-controlled study shows that CHO loading did not improve performance of a 100-km cycling TT during which CHO was consumed. By preventing any fall in blood glucose concentration, CHO ingestion during exercise may offset any detrimental effects on performance of lower preexercise muscle and liver glycogen concentrations. Alternatively, part of the reported benefit of CHO loading on subsequent athletic performance could have resulted from a placebo effect.

glycogen loading; road cycling; blood glucose

DURING PROLONGED (>90 min) continuous, moderate-intensity [70–80% of maximal oxygen uptake (V̇O2max)] cycling, the onset of fatigue is associated with very low (~100 mmol/kg dry wt) muscle glycogen concentrations (6, 8, 11) and hypoglycemia (6, 11). Muscle and liver glycogen stores can be increased above normal resting values by combining an exercise taper with the intake of large quantities of dietary carbohydrate (CHO) in the days before an endurance event (29). A recent review (18) concluded that such CHO loading improves endurance by ~20% during prolonged continuous exercise at a fixed submaximal work rate. Furthermore, performance of a fixed distance or workload of >90 min is also increased by ~2–3% after CHO loading.

The common assumptions from these studies are that 1) CHO loading acts exclusively by increasing muscle glycogen stores and 2) these studies establish the value of CHO loading for a wide variety of competitive sporting activities. However, the certainty of these conclusions is influenced by aspects of the experimental designs used in many of these studies. First, to our knowledge, only one CHO-loading study (17) has included a placebo control in the research design. Without placebo control, the influence on subsequent exercise performance of psychological factors, in particular the expectation of an effect by both researchers and subjects, cannot be excluded. Interestingly, that placebo-controlled study failed to show any benefit of CHO loading on performance, albeit in a 1-h cycling time trial (TT) in which any effect would seem unlikely.

Second, some studies have tested performance under conditions of an overnight fast and/or intake of water during the endurance test. These conditions are neither typical nor recommended for optimizing performance in an endurance event.

Importantly, little is known about the effects of CHO loading on performance when there are continual changes in work rate, an exercise pattern typical of many competitive sports. For example, road cycling races are characterized by periods of sustained steady-state exercise punctuated by bouts of high- and low-intensity work in accordance with the course profile, terrain, environmental conditions, and riding strategies of the cycling group (25). Exercise tasks that include such alternating work bouts frequently elicit physiological responses that are different from those in which work, power, or duration is held constant (26). Thus stochastic exercise might be expected to cause a
different pattern of fuel utilization compared with continuous, moderate-intensity work. It is only recently that laboratory studies have attempted to simulate actual race conditions in the laboratory (26, 28).

Accordingly, the aims of this study were to examine the reported ergogenic action of CHO loading on cycling performance tested on a reliable laboratory protocol (28) that simulates the demands of competitive road racing, and to exclude a possible placebo effect (28) that simulates the demands of competitive road performance tested on a reliable laboratory protocol (26, 28). Subjects were tested to simulate as fast as possible and were not given any feedback other than their elapsed distance.

Dietary intervention. Individual food plans were constructed for each subject on the basis of body mass (BM) and food preferences. Each subject was supplied with his food intake for the 72-h period before each trial. Menus were provided in written form, and the food assigned to each meal was individually prepared and packaged so that the need for further preparation by subjects was minimized. Subjects were required to record their actual food and fluid intake on dietary logs to account for any portion of meals left unconsumed or for any additional intake. Although some food items differed between subjects, each cyclist received identical breakfast, lunch, and dinner menus for both of his trials, with the CH0 intake from these meals designed to provide 6 g CH0·kgBM·day−1·day−1. Snacks were also provided for each day and provided the source of differentiation between trials. On the CHO loading diet, subjects received 1,200 ml of water each day and a number of sports bars (Gijima, Sasko, Paarl, South Africa) calculated to provide an additional 3 g CH0·kgBM·day−1·day−1. Each sports bar had a composition of 27 g CH0, 6.5 g fat, and 2.7 g protein. The sports bars were used to mimic what is used by competitive athletes during training and competitive events. On the placebo trial, daily snacks were provided in the form of 1,200 ml of an artificially sweetened low-calorie drink that was described to subjects as a “CH0-loading” drink.

Experimental trials. Each subject completed a random crossover design of two experimental trials separated by 7 days. Subjects performed their TTs at the same time of day under standard laboratory conditions (−20°C, 55% relative humidity). Subjects were requested to perform the same type of training for the duration of the trial and to refrain from training 3 h before the TT. Training diaries were kept to assess compliance to this condition. On the morning of an experiment subjects reported to the laboratory between 0700 and 0800, 12–14 h after an overnight fast. At this time the Kingcyle ergometer was calibrated, and then subjects consumed a standard breakfast providing 2 g CH0·kgBM. After the subjects rested quietly for 105 min, a preexercise muscle biopsy sample was taken from the vastus lateralis of the right leg according to the technique of Bergstrom (5) as modified by Evans et al. (12). After this procedure, the subjects mounted their cycle and began a 5-min self-paced warm-up.

Exactly 2 h after they had finished breakfast, subjects commenced the 100-km TT. To mimic the stochastic nature of cycle road races (24), the TT included a series of sprints: five 1-km sprints after 10, 32, 52, 72, and 99 km, as well as four 4-km sprints after 20, 40, 60, and 80 km. Subjects were instructed to complete the total distance in “the fastest time possible,” taking into consideration the sprints that were included. To ensure subjects participated at maximum capacity, a financial reward was offered to the subject who completed either the entire TT or sprints component in the fastest time for the group. Just before commencement of a sprint, an investigator gave a distance countdown and instructed the cyclist to complete the sprint in the fastest possible time as soon as he reached the specific distance at which the sprint

### Table 1. Subject characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>28 ± 4.5</td>
<td>22–37</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>72.1 ± 6.7</td>
<td>62–81</td>
</tr>
<tr>
<td>(\text{VO}_2\text{peak} ) ml·kg(^{-1})·min(^{-1})</td>
<td>63.9 ± 4.7</td>
<td>58.0–70.2</td>
</tr>
<tr>
<td>Power/weight, W/kg</td>
<td>5.7 ± 0.5</td>
<td>5.1–6.2</td>
</tr>
</tbody>
</table>

Values are means ± SD for 7 subjects. \(\text{VO}_2\text{peak} \), peak oxygen uptake.
started. Subjects viewed a diagram of the “course profile” that graphically illustrated where the 1- and 4-km sprints occurred, before and during each ride. Instantaneous power output was recorded at each 500-m split of both the 1- and 4-km sprints to provide an estimate of the average power output for the sprint. The only feedback given to subjects during the TT was their elapsed distance and heart rate (HR).

Subjects were not informed of the elapsed total time or the times for the sprints until completion of the experiment. Throughout each trial, power output, speed, and elapsed time were monitored continuously and stored on computer. HR was recorded by using a SportTester HR monitor (Polar Electro, Kempele, Finland). We have previously reported that the between-test correlation for the time taken by eight well-trained cyclists and triathletes to complete this protocol was 0.93 [95% confidence interval (CI) 0.79–0.98], and the within-cyclist coefficient of variation (CV) was only 1.7% (95% CI 1.1–2.5%) (28).

During the 100-km ride, subjects ingested a 7 g/100 ml glucose polymer solution at a rate of 15 ml·kg BM⁻¹·h⁻¹. This drinking regimen was intended to replace ~80% of sweat loss (23) while providing CHO at ~1 g·kg BM⁻¹·min⁻¹, the maximum rate at which muscle can oxidize exogenous glucose (15). A fan was positioned to cool the subjects during their TT. The average sweat loss (liters) was estimated as the average fluid intake + weight change over the trial of all seven subjects. Immediately on completion of the TT, a second biopsy was taken from the same leg, a distance of 4 cm distal to the first incision. No metabolic measurements were taken during the trials because the TTs were performance trials, and it was believed that interfering with the athletes during the trials would impair their performance by spoiling their concentration.

Analytic techniques. Muscle samples were subsequently freeze-dried; dissected free of blood, connective tissue, and fat; and weighed. Muscle glycogen content was determined after acid hydrolysis by a hexokinase method (21). The CV for this assay in our laboratory is ~5% for duplicate glycogen assays of a single piece of muscle and <7% for assays of the glycogen content of separate pieces of the same muscle biopsy sample (17).

Statistical analyses. Differences in the sprint times and sprint power outputs and in the glycogen concentrations were examined by using repeated-measures ANOVA, whereas glycogen utilization, total 100-km time, and total power outputs were compared by using Student’s t-tests. A Sheffe’s post hoc test was used to assess differences revealed by the ANOVA. All data are reported as means ± SD, and all calculations were performed by using Statistica for Windows (version 6, Statsoft, Tulsa, OK).

RESULTS

Training diaries collected on the morning of each trial showed that all subjects complied with the pretrial training conditions: each subject undertook identical exercise sessions before each of his trials and achieved a training taper over this time. Reported dietary intake for the 72 h before each trial (Table 2) showed that subjects achieved the CHO intake goals predetermined for the study. Significantly greater CHO intake was consumed with the CHO-loading diet than with the placebo diet (9 vs. 5.8 g CHO·kg BM⁻¹·day⁻¹), with this additional CHO being provided exclusively by the sports bar. Muscle glycogen levels were significantly higher after CHO loading (Table 3). Total energy, protein, and fat intake were also significantly higher with CHO loading than in placebo (P < 0.05).

Table 2. Dietary intake during 72 h before trial commencement

<table>
<thead>
<tr>
<th>CHO loading</th>
<th>CHO, g</th>
<th>CHO, g·kg</th>
<th>Energy, kcal</th>
<th>Protein, g</th>
<th>Fat, g</th>
<th>Water, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHO loading</td>
<td>646 ± 54</td>
<td>9.0 ± 0.3</td>
<td>4,149 ± 315</td>
<td>110 ± 7</td>
<td>126 ± 9</td>
<td>2,997 ± 432</td>
</tr>
<tr>
<td>Placebo</td>
<td>419 ± 35*</td>
<td>5.8 ± 0.2*</td>
<td>2,726 ± 202*</td>
<td>88 ± 6*</td>
<td>79 ± 7*</td>
<td>3,059 ± 622</td>
</tr>
</tbody>
</table>

Values are means ± SD. CHO, carbohydrate. *CHO intake in CHO-loading diet was significantly greater than in placebo diet; energy, protein, and fat intake were significantly greater in CHO-loading diet than in placebo diet (P < 0.05).

Table 3. Muscle glycogen concentrations after the dietary treatments and 100-km TT

<table>
<thead>
<tr>
<th>CHO loading (9 g CHO·kg body mass⁻¹·day⁻¹)</th>
<th>Preexercise</th>
<th>Postexercise</th>
<th>Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>572 ± 107</td>
<td>96 ± 63</td>
<td>476 ± 66.5</td>
<td></td>
</tr>
<tr>
<td>Placebo (6 g CHO·kg body mass⁻¹·day⁻¹)</td>
<td>485 ± 128*</td>
<td>55 ± 28</td>
<td>431 ± 116</td>
</tr>
</tbody>
</table>

Values are means ± SD given in mmol/kg dry wt. TT, time trial. *Preexercise muscle glycogen content was significantly lower compared with CHO-loaded trial, P = 0.05.
DISCUSSION

The major finding of this study is that, when tested against placebo, CHO loading did not improve performance during a prolonged (~2.5-h) self-paced TT that included high-intensity work bouts and CHO ingestion before and during the trial. This finding contrasts with the majority of studies that show that CHO loading enhances performance during prolonged exercise under a wide variety of laboratory and field conditions (18). A number of characteristics, unique to this trial, could explain this unexpected finding.

First was the use of a double-blind placebo-controlled design. This is an essential characteristic of any intervention study measuring an effect that might be influenced by psychological factors and is an accepted requirement in studies of CHO feeding during exercise. The failure of the majority of CHO-loading studies to include a placebo control group reduces the certainty of the conclusions inferred from their findings. Because endurance athletes are now well educated about the principles of CHO loading (9) and the reported benefits of this popular practice, it is likely that many subjects participating in current studies of CHO loading would expect to perform better after that intervention, thus introducing a psychological bias.

To date, only one other study of CHO loading has attempted to include a full placebo control, by providing subjects with their food intake during the pretrial period and disguising the true CHO-enriched menu by matching the other diet with a low-energy placebo supplement (17). That study also failed to find an improvement in performance associated with elevated preexercise glycogen stores, although their exercise protocol involved only ~60 min of cycling. Although in this trial a third nonplacebo group was not included, this does not alter the results of our present trial because subjects were blinded to the nature of the CHO or placebo ingestion.

Our present study therefore invites the possibility that the subjects’ knowledge that they were CHO loading could be an important determinant of the measured ergogenic effect of CHO-loading studies that are not placebo controlled. Future studies of CHO loading must be appropriately controlled either to refute or support this unexpected interpretation.

Table 4. Time and power data for individual sprints and 100-km TT

<table>
<thead>
<tr>
<th></th>
<th>CHO Loading</th>
<th>Placebo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time, mins</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–11 km sprint</td>
<td>1:11.7 ± 0.35</td>
<td>1:12.8 ± 0.45</td>
</tr>
<tr>
<td>99–100 km sprint</td>
<td>1:20.7 ± 0.66</td>
<td>1:22.2 ± 0.74</td>
</tr>
<tr>
<td>Δ 1-km sprint</td>
<td>0.8 ± 0.86</td>
<td>0.9 ± 0.57</td>
</tr>
<tr>
<td>20–24 km sprint</td>
<td>5:24.1 ± 0.206</td>
<td>5:19.2 ± 0.199</td>
</tr>
<tr>
<td>80–84 km sprint</td>
<td>5:35.3 ± 0.191</td>
<td>5:44.7 ± 0.229</td>
</tr>
<tr>
<td>Δ 4-km sprint</td>
<td>0:11.2 ± 0.142</td>
<td>0:25.5 ± 0.172</td>
</tr>
<tr>
<td>Total 100-km TT</td>
<td>147:30 ± 10:0</td>
<td>149:07 ± 11:0</td>
</tr>
<tr>
<td><strong>Power, W</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10–11 km sprint</td>
<td>377.8 ± 54.1</td>
<td>380.2 ± 54.8</td>
</tr>
<tr>
<td>99–100 km sprint</td>
<td>313.2 ± 57.6*</td>
<td>287.1 ± 70.6</td>
</tr>
<tr>
<td>Δ 1-km sprint</td>
<td>64.6 ± 65.9</td>
<td>93.1 ± 62</td>
</tr>
<tr>
<td>20–24 km sprint</td>
<td>313.7 ± 51.5</td>
<td>325.1 ± 47.1</td>
</tr>
<tr>
<td>80–84 km sprint</td>
<td>286.6 ± 37.5</td>
<td>269.7 ± 41.5</td>
</tr>
<tr>
<td>Δ 4-km sprint</td>
<td>27.1 ± 37.1</td>
<td>55.4 ± 39.5</td>
</tr>
<tr>
<td>Total 100-km TT</td>
<td>258.7 ± 40.1</td>
<td>253 ± 40.1</td>
</tr>
</tbody>
</table>

Values are means ± SD. Δ, Change. *Power output of final 1-km sprint significantly lower compared with first 1-km sprint in CHO-loaded trial, \( P < 0.05 \).
A second characteristic that may have influenced the outcome of this trial was the exercise protocol used to evaluate cycling performance. The exercise task was designed to mimic the requirements of a 100-km road race (25) rather than to have subjects exercise at fixed submaximal workloads to exhaustion as in previous studies of cycling (1, 6, 8, 20) or running (7, 14, 22). In other studies, CHO loading has been shown to reduce the time taken to complete a prolonged running or cycling task (21, 31, 32). Under these conditions, enhanced performance after CHO loading was achieved by the maintenance of greater average speeds because the rate of decline in power output during the latter stages of the task was reduced.

Although these protocols involved self-paced efforts and the possibility of a changing workload, it is unlikely that the typical pacing strategies used in these trials involved the random injection of extremely high-intensity efforts, as are characteristic of mass start road cycling events (25). Thus it is possible that elevated pretrial glycogen concentrations might increase performance in those forms of exercise in which the intensity is relatively more constant but not in the stochastic form of exercise evaluated in this trial, in which there are bouts of exercise of very high intensity. Indeed the inclusion of repeated high-intensity sprints in our TT protocol produced postexercise muscle glycogen concentrations as low as have been reported in any previous study (6, 8, 11).

Third, although preexercise glycogen concentrations were significantly elevated by ~20% at the beginning of the CHO-loaded TT compared with the placebo TT, this increase may not have been sufficient to ensure a physiological benefit to the performance of the repeated high-intensity sprints and therefore the overall time to complete the TT. However, the 20% increase in muscle glycogen concentrations induced by CHO loading is in agreement with values previously reported by other investigators (17, 22, 27) and was sufficient to enhance performance in these studies (22, 27). It should, however, be remembered that the original CHO-loading studies compared the performance of subjects with very large (~100%) differences in initial muscle (and liver) glycogen concentrations (6, 21) because the comparison was usually between high- and low-CHO diets rather than between high- and normal-CHO diets as in this study.

A fourth feature of our study design was the inclusion of several dietary strategies to optimize CHO availability during performance. CHO was consumed in a preevent meal and during the TT in accordance with current sports nutrition guidelines (3, 4) and the typical practices of competitive cyclists.

Several studies have partially or systematically studied the interaction of CHO loading and CHO ingestion during exercise on exercise performance. Flynn and co-workers (13) reported that CHO intake during cycling did not improve performance in CHO-loaded subjects during 2 h of self-paced cycling at ~80% VO2max. In contrast, the study of Kang et al. (20) showed that CHO feeding in CHO-loaded subjects enhanced performance during ~3 h of exercise at 70% VO2max. The study of Widrick et al. (31) evaluated performance during a self-paced 70-km TT when preexercise glycogen content was manipulated by CHO loading and CHO or placebo was ingested during the ride (31). CHO ingestion during the TT prevented a decline in blood glucose concentrations regardless of the starting muscle glycogen content. Performance was best in subjects who were CHO loaded and who ingested CHO during exercise and was worst in those who neither CHO loaded nor ingested CHO during exercise. However, performance differences were relatively small, especially between the CHO-loaded group who ingested placebo during exercise and the CHO-depleted group who ingested CHO during exercise. This occurred despite the fact that the CHO-depleted group had exercised for 45 min 24 h before the performance trial, whereas they rested for 48 h before the CHO-loaded trial. Thus, whereas CHO ingestion during exercise did not influence performance in CHO-loaded subjects, CHO ingestion enhanced the performance of CHO-depleted subjects, perhaps by preventing the development of hypoglycemia (mean blood glucose concentrations of ~3.2 mmol/l) and a synchronous fall in power output in subjects who did not CHO load before exercise.

Higher blood glucose concentrations with CHO ingestion than with placebo were also associated with superior exercise performance in the CHO-loading studies of Kang et al. (20). Similarly, superior performance in a 30-km run after CHO loading was associated with higher blood glucose concentrations during exercise than when only water was consumed (33). As in the study of Widrick et al. (31), reductions in running speed fell synchronously with the blood glucose concentrations in both CHO-loaded and control groups. In contrast, performance was not enhanced by CHO ingestion in the trial of Williams et al. (32), even though blood glucose concentrations were higher with ingestion of CHO than placebo during exercise. The opposite result was reported by Tsintzas et al. (30), where performance was enhanced by CHO ingestion during exercise even though blood glucose concentrations were essentially unaffected.

Accordingly, performance in this trial may have been the same in CHO-loaded and placebo groups because blood glucose concentrations may have been similar in both trials due to the ingestion of CHO during the ride. Hence the optimization of CHO ingestion before and during exercise in this trial may have negated any additional beneficial ergogenic effect of CHO loading alone.

Finally, although CHO loading did not produce a significant ergogenic effect in this trial, the results should be examined in light of what might be meaningful in a competitive sports event. In this study, CHO loading was associated with a 1.1% improvement in TT performance, with true differences in the performance of a similar population likely to range from a 1.6% decrement to a 3.6% improvement. At best, this improvement would not greatly change the outcome of the
performances of the “back of the pack” cyclists; even a 4% improvement would not move these athletes to the front of the field. However, such an improvement, if real, is meaningful to the top cyclists in a race in that it would enhance the likelihood of an improvement in finishing order (19).

Hopkins and colleagues (19) have calculated that the smallest intervention likely to enhance the performance of a top-finishing athlete is 0.4–0.7% of the typical within-athlete CV in performance between events. The typical within-athlete CV for cyclists competing in such road events is currently not known. However, in other sports such as road running and track cycling, this CV is ~1–2% for good competitors and often <1% for the best international competitors (W. G. Hopkins, personal communication). Thus a 1.1% improvement in performance is likely to be worthwhile to an elite road cyclist. Should performance in mass-start road cycling races be less reliable than for other sports (e.g., CV >4%), then the impact of our effect would need to be recalculated. Power analysis shows that a sample size of ~30 subjects would be needed in a similar study to reduce the confidence intervals of the true performance change to approximately ±1%, that is ~0–2%, and therefore discount the likelihood of a meaningful effect.

In summary, this study shows that a CHO-loading protocol that increased preexercise muscle glycogen concentrations resulted in a minimal effect on the performance of a 100-km TT involving high-intensity sprints when CHO was ingested before and during the event according to contemporary sports nutrition guidelines. Although we cannot completely discount the possibility that CHO loading has a worthwhile effect on the performance of competitive cyclists under conditions similar to our trial, our data suggest that this effect is small and, at best, only likely to rearrange the finishing order of the top cyclists in the field. Furthermore, this study raises the possibility that part or all of the ergogenic effect of CHO loading reported in previous studies could result either from a placebo effect or from higher preexercise liver glycogen stores that could delay the onset of hypoglycemia during prolonged exercise. If this is the case, CHO ingestion during exercise, as included in this study, would minimize any ergogenic effect of CHO loading by preventing the development of hypoglycemia in persons beginning exercise with lower liver (and muscle) glycogen concentrations.

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