The effect of a high carbohydrate diet and glycogen depletion on graded maximal exercise

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Abstract.

The present investigation examined the influence of dietary carbohydrate (CHO) on the performance of graded maximal exercise on a bicycle ergometer. A group of highly trained college students [mean age 22.2 (SD 1.6) years] completed three trials of graded maximal exercise under three dietary conditions; normal diet (ND), glycogen depleted (CHD), and glycogen loaded (CHL) conditions with each trial separated by five days. Measurements of work done, maximal oxygen intake (\(V_{\text{O2max}}\)), serum lactate, glucose, and free fatty acids (FFA) concentrations were compared. The highest total work done was recorded by the CHL condition while the values obtained by the CHD and ND were similar. Although there was no significant difference in \(V_{\text{O2max}}\) among the three conditions, the value for the CHL was lower than those for the other two conditions. Observing blood lactate and FFA responses during the exercise, the increased reliance on elevated carbohydrate oxidation with preexercise carbohydrate loading was most likely related to the higher work output done because a higher concentration in blood lactate and a suppression of blood FFA during exercise were demonstrated.

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There is much evidence that muscle glycogen is the most important substrate for exercise of an intensity that requires 70–80% of maximum O₂ consumption (VO₂max). Endurance for such exercise can be increased by raising muscle glycogen stores and decreased by lowering muscle glycogen. The metabolic effects of carbohydrates prior to exercise have received considerable attention with respect to their effects on exercise performance. Since muscle glycogen and blood-borne glucose support a high rate of ATP resynthesis, particularly when oxygen availability at the muscle is challenged, sport physiologists and athletes alike have recognized the ergogenic potential of increasing the intake of dietary carbohydrate (CHO) prior to prolonged exercise. Most endurance athletes nowadays consume substantial amounts of CHO the days before and during competition to prevent glycogen depletion and to improve exercise performance.

The focus of these studies was the influence of dietary CHO loading on endurance capacity and on endurance performance during prolonged exercises. In a previous study, it was shown that endurance capacity during treadmill running can be improved by supplementing normal mixed diets with either complex or simple CHO. Another study on the influence of carbohydrate loading on endurance performance showed that running times, during a 30-km cross-country race, improved after CHO loading. Few studies investigated the effects of carbohydrate loading and glycogen depletion on work performance during a relatively short duration maximal exercise. Certainly, the performance of brief sprints would appear not to be significantly altered by CHO status. However, working with a small group of soccer players, Ekblom reported that high intensity intermittent exercise and the ability to delay the onset of fatigue are significantly dependent on muscle glycogen reserve.

The purpose of the present study was to examine the effects of high CHO diets on work performance during a relatively short duration maximal graded exercise using a cycle ergometer. To clarify the effects, two other diet conditions of glycogen depletion and normal diet were examined.
MATERIALS AND METHODS

Subjects.

The 7 subjects (22.2 ± 1.6 yr, 175.4 ± 5.6 cm, 66.4 ± 6.5 kg, mean ± SD) who volunteered to take part in this study were highly trained male college students.

Experimental design and procedure.

This study included three dietary treatments in the experimental procedure. One dietary condition (CHL) prescribed a diet high in carbohydrates and the other condition (CHD) prescribed a diet which was designed for glycogen depletion described by McLellan and Gass. The depletion procedure is shown in Fig. 1. For the condition of normal diet (ND), the subjects consumed a diet consisting of 50% carbohydrate, 32% fat, and 18% protein, for two days prior to the exercise test described by Sharman et al. Each subject performed three experimental trials during normal diet intake, after glycogen depletion and during carbohydrate loading. Each test was separated by 5 days.

The subjects performed a graded exercise test on a Monark cycle ergometer to establish maximum oxygen consumption (VO$_{2\text{max}}$),

![Glycogen depletion protocol](image)

**Fig. 1** Glycogen depletion protocol
using methods previously described by Podolin\textsuperscript{(21)}, after a warming up using 0 watt load and 60 rpm for 3 min, they cycled with a work load of 60 watts and pedaling speed of 60 rpm. The work load was increased by 60 watts every 3 minutes while pedaling speed remained of 60 rpm. The subjects were instructed to ride at 60 rpm, whereas exhaustion was defined as the time when they could no longer maintain 60 rpm. Metabolic measurements of expired gas were determined with Quinton gas analyzer a (Q-Plex 1, A. H. Robison) calibrated with standardized gases. Heart rate was monitored throughout the test using chest electrodes in the CM5 position using on electrocardiograph, ECG System (Quinton 5000).

\textit{Biochemical analysis.}

The subjects arrived at the laboratory in the morning after an overnight fast. They were weighed and had chest electrodes attached, for monitoring heart rate. Then, a catheter was inserted into a forearm vein for blood sampling and was kept with 0.9\% saline. Blood samples were obtained at rest and at 6 (60 watts), 9 (120 watts), 12 (180 watts), and 15 (240 watts) min of exercise. All samples were subsequently analyzed for glucose (Hitachi Autoanalyzer 736–20), lactate (Y. S. I. Auto blood lactate analyzer), and free fat acids (FFA) (Cecil spectrophotometer).

\textit{Statistical analysis.}

Statistical comparisons were made using an analysis of variance for repeated measures design, with the level of significance set at $P<0.05$. Post hoc comparisons were made using the Student-Newman-Keuls test.

\textbf{RESULTS}

A summary of CHO consumption for the three conditions during the study is provided in Table 1. The subjects in the CHL, ND and CHD conditions consumed CHO intakes averaging 79\%, 50\% and 12\%, respectively, of their daily energy intake. Dietary fat and
TABLE 1. Composition of caloric intake during dietary regimen

<table>
<thead>
<tr>
<th></th>
<th>Carbohydrate (Cal/day)</th>
<th>Fat (Cal/day)</th>
<th>Protein (Cal/day)</th>
<th>Total (Cal/diet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND</td>
<td>1456</td>
<td>930</td>
<td>524</td>
<td>2910</td>
</tr>
<tr>
<td></td>
<td>(50)</td>
<td>(32)</td>
<td>(18)</td>
<td>(100)</td>
</tr>
<tr>
<td>CHD</td>
<td>392</td>
<td>1460</td>
<td>1398</td>
<td>3250</td>
</tr>
<tr>
<td></td>
<td>(12)</td>
<td>(45)</td>
<td>(43)</td>
<td>(100)</td>
</tr>
<tr>
<td>CHL</td>
<td>2448</td>
<td>342</td>
<td>310</td>
<td>3100</td>
</tr>
<tr>
<td></td>
<td>(79)</td>
<td>(11)</td>
<td>(10)</td>
<td>(100)</td>
</tr>
</tbody>
</table>

Values are means (%); ND: Normal diet, CHD: Carbohydrate depletion; CHL: Carbohydrate loading

protein for the CHL, ND and CHD conditions were 11% and 10%; 32% and 18%; and 45% and 43%, respectively.

Cardiorespiratory exchange and work performance.

No significant differences were observed in VO_{2\text{max}} among the conditions. However, examination of the time to exhaustion (W_{\text{max}}) showed the work output in the CHL was significantly higher (P < 0.05) by about 14% than in the other two conditions averaging 12.5 min, 10.7 min and 10.5 min for the CHL, ND and CHD conditions, respectively (Table 2).

TABLE 2. Cardiorespiratory variables on maximal graded exercise in three dietary conditions

<table>
<thead>
<tr>
<th></th>
<th>HR_{\text{max}} (bpm)</th>
<th>VO_{2\text{max}} (l/min)</th>
<th>VCO_{2\text{max}} (l/min)</th>
<th>VE_{\text{max}} (l/min)</th>
<th>RER</th>
<th>Work_{\text{max}} (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND</td>
<td>190.2</td>
<td>3.52</td>
<td>3.91</td>
<td>109.8</td>
<td>1.17</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>(7.2)</td>
<td>(0.36)</td>
<td>(0.84)</td>
<td>(29.1)</td>
<td>(0.05)</td>
<td>(1.6)</td>
</tr>
<tr>
<td>CHD</td>
<td>187.8</td>
<td>3.44</td>
<td>3.82</td>
<td>118.3</td>
<td>1.15</td>
<td>10.52</td>
</tr>
<tr>
<td></td>
<td>(12.5)</td>
<td>(0.63)</td>
<td>(0.83)</td>
<td>(10.1)</td>
<td>(0.07)</td>
<td>(1.5)</td>
</tr>
<tr>
<td>CHL</td>
<td>186.3</td>
<td>3.22</td>
<td>4.10</td>
<td>107.5</td>
<td>1.19</td>
<td>12.5*</td>
</tr>
<tr>
<td></td>
<td>(10.1)</td>
<td>(0.66)</td>
<td>(0.30)</td>
<td>(13.1)</td>
<td>(0.09)</td>
<td>(1.6)</td>
</tr>
</tbody>
</table>

Values are means (SD) *denotes P < 0.05
ND: Normal diet, CHD: Carbohydrate depletion, CHL: Carbohydrate loading
Furthermore, no significant differences were observed in the respiratory exchange ratio (RER), nor maximal heart rate (HR\textsubscript{max}).

*Serum glucose and lactate.*

Resting value of blood glucose concentration was lower in the CHL than in both the ND and in the CHD. However, no significant differences were observed between any of the conditions. With the onset of exercise, blood glucose was elevated proportionally to work intensity. From the baseline values (resting level), however, significant differences were found at 240–w load in the ND and in the CHL (Table 3 and Fig. 2). The resting blood lactate concentration for subjects following the ND and CHD were 25.7 (4.7SD) and 25.4 (6.3SD), respectively. The resting blood lactate concentration was higher following the CHL. With the onset of exercise, blood lactate concentrations also increased similarly in all three trials (Table 3 and Fig. 3). The CHL had the highest blood lactate concentrations during

<table>
<thead>
<tr>
<th>TABLE 3. <em>Blood glucose and lactate concentrations (mg/dl)</em> at rest and during graded exercise in three conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Rest</td>
</tr>
<tr>
<td>60w</td>
</tr>
<tr>
<td>120w</td>
</tr>
<tr>
<td>180w</td>
</tr>
<tr>
<td>240w</td>
</tr>
</tbody>
</table>

Lactate

<table>
<thead>
<tr>
<th>Rest</th>
<th>25.7 (4.7)</th>
<th>25.4 (6.3)</th>
<th>35.5 (6.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60w</td>
<td>28.9 (5.5)</td>
<td>29.3 (5.8)</td>
<td>41.7 (10.5)</td>
</tr>
<tr>
<td>120w</td>
<td>36.0* (6.1)</td>
<td>33.1 (11.2)</td>
<td>48.6* (7.2)</td>
</tr>
<tr>
<td>180w</td>
<td>52.0** (6.7)</td>
<td>48.1* (21.2)</td>
<td>69.6** (16.8)</td>
</tr>
<tr>
<td>240w</td>
<td>83.9** (12.9)</td>
<td>56.8* (15.3)</td>
<td>99.1** (28.0)</td>
</tr>
</tbody>
</table>

Values are means (SD)

* and ** denote $P<0.05$ and $P<0.01$, respectively from resting level.
Fig. 2 Mean blood glucose concentrations during graded exercise in three dietary conditions (—○—ND; —△—CHD; —□—CHL)

Fig. 3. Mean blood lactate concentrations during graded exercise in three dietary conditions (—○—ND; —△—CHD; —□—CHL)

*P < 0.05    **P < 0.01
Fig. 4. Statistical comparisons of blood lactate concentrations in reference to work intensities in three dietary conditions

* $P<0.05$  ** $P<0.01$

the exercise. Fig. 4 shows statistical comparisons of lactate concentrations as a function of work intensity in three conditions. Except for 180-w load, the concentrations in the CHL were significantly higher than in the ND and in the CHD ($P<0.01$).

**Serum FFA.**

Serum FFA at rest in the ND was significantly higher than in the CHD and CHL ($P<0.01$). With the onset of exercise, FFA of the CHD abruptly increased at 60-w load, but not significantly. Thereafter, FFA in the ND and CHD tended to decrease as the work load became higher while the change of FFA during exercise in the CHL was stable. These values and trends are shown in Table 4 and Fig. 5.
TABLE 4. Serum FFA concentration at rest and during graded exercise in three conditions

<table>
<thead>
<tr>
<th></th>
<th>ND</th>
<th>CHD</th>
<th>CHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>764.5 (267.4)</td>
<td>488.3 (138.8)</td>
<td>432.0 (177.9)</td>
</tr>
<tr>
<td>60w</td>
<td>795.7 (258.5)</td>
<td>690.0 (246.9)</td>
<td>450.7 (291.5)</td>
</tr>
<tr>
<td>120w</td>
<td>746.3 (235.1)</td>
<td>658.4 (246.5)</td>
<td>421.6 (267.8)</td>
</tr>
<tr>
<td>180w</td>
<td>684.7 (223.1)</td>
<td>551.9 (225.1)</td>
<td>398.6 (197.2)</td>
</tr>
<tr>
<td>240w</td>
<td>665.6 (202.6)</td>
<td>512.3 (101.4)</td>
<td>403.0 (134.7)</td>
</tr>
</tbody>
</table>

Values are means (SD)

![Graph showing serum FFA concentrations during graded exercise](image)

**Fig. 5.** Mean serum FFA concentrations during graded exercise in three dietary conditions (●—ND; ▲—CHD; ○—CHL)

* P<0.05; ** P<0.01

**DISCUSSION**

An improvement in endurance capacity or performance associated with CHO supplementation have primary been observed during long-term (2–4 hr), moderate-intensity exercise (45–50%
The results of present study showed that under the condition of a relatively short-term exercise, the subjects' capacity for the performance of graded exercise was affected by the pattern of dietary modifications imposed upon them (Table 2). For the subjects on the ND and CHD the time to exhaustion was 10.7 min and 10.5 min, respectively. Following a high CHO diet it resulted in an increase to 12.5 min. This finding is in agreement with the results of many investigators\(^{(6, 15, 22, 24)}\) showing that carbohydrate loading prior to exercise or glucose administration during prolonged moderately severe exercise improves endurance or performance. Research in recent years has established the importance of muscle glycogen in supporting maximal and supramaximal exercise\(^{(14, 17)}\). A low value of \(\text{VO}_{2\text{ max}}\) in the CHL relative to the two conditions, therefore, was somewhat unexpected. The ability to maintain performance during high intensity exhaustive exercise is, in part, dependent on the availability of glycogen within the working muscle\(^{(1, 8)}\). The study\(^{(17)}\) by Maughan and Poole investigating the effects of glycogen depletion on anaerobic exercise performance revealed that the time to exhaustion was significantly reduced following a low CHO diet. At relatively low exercise intensities, up to roughly 65% of \(\text{VO}_{2\text{ max}}\), fat is the primary fuel, and heat stress, dehydration, and possibly glycemia contribute to exhaustion. However, between 65% and 85% of \(\text{VO}_{2\text{ max}}\), exhaustion often occurs upon depletion of muscle glycogen; thus muscle glycogen is a limiting factor for exercise at these intensities. That there was no effect on maximal cycling time for the CHD in our study was difficult to understand.

Chasiotis et al.\(^{(5)}\) reported that the mean value of blood lactate concentration during exercise and its highest values were seen proportionally to the rate of CHO loading. Our data support these findings; that is, blood lactate concentrations for CHL was significantly higher than those for the other two conditions. Such higher concentrations of blood lactate during exercise following CHO diet may reflect that the exercising muscles utilize more of the energy produced through the glycolysis of the increased muscle glycogen. This is because the lipolysis is reduced so that the rate of synthesis
from fatty acids to fat is increased\(^{(2)}\). This increased reliance on carbohydrate ingestion is most likely related to alterations in substrate availability. Maughan and Poole\(^{(17)}\) observed a lower blood lactate concentration at the end of anaerobic work in subjects following a low glycogen diet. This result is also in agreement with that obtained in the present study.

Importantly, consumption of a high carbohydrate preexercise meal also resulted in a significant suppression of the blood FFA concentration at rest and during exercise (Fig. 5). The lower circulating FFA levels may indicate a greater cellular uptake of fats or a lower FFA metabolism due to the elevated glucose, causing reesterification. With onset of exercise, blood FFA increased in all three conditions. Such changes of blood FFA are similar to those of an animal study by Harada et al.\(^{(16)}\) in which blood concentration of FFA during exercise was similar to the resting value if the work load is high.

The level of muscle glycogen at the beginning of intense exercise can limit an athlete’s endurance\(^{(9,16)}\). Preexercise glycogen concentration is clearly related to endurance at an exercise intensity between 65% and 85% \(\text{VO}_{2\text{max}}\)\(^{(12)}\). Since we used a graded exercise protocol in this study, a relation such as the above might be less affected during early stages of low intensities. Even though, it is somewhat difficult to observe blood glucose concentration for CHL, it was not significantly increased over those for CHD and ND. Furthermore, no substantial reduction in blood glucose concentration at rest and during exercise for the CHD was seen. These data raise the question as to whether or not glycogen can be stored through the carbohydrate loading program and whether glycogen can be significantly depleted by the protocol used in the present study. Since we did not directly measure the muscle glycogen, there is some uncertainty when discussing the levels in the loaded and depleted conditions.

However, the facts that blood glucose levels for the CHD remained depressed throughout the exercise (Table 4 and Fig. 2); and the aforementioned responses of blood lactate and FFA
concentrations during the exercise may support the effects of high and low carbohydrate diets on the levels of the muscle glycogen.

In summary, present investigation has shown that when compared to a low CHO diet, high consumption of dietary CHO could increase work performance of graded maximal exercise with a relatively short duration. Although this increase was associated with a greater utilization of CHO loaded prior to exercise, further study is needed to clarify further mechanism of CHO loading effects on graded maximal exercise. Investigation of hormonal responses such as catecholamines on the work may be necessary.

REFERENCES


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持久性運動に対する糖質摂取の重要性について，これまで多くの先行研究が炭水化物（CHO）ローティング（糖質貯蔵）が持久性運動の成績改善に有意に機能するとの報告をしている。それらの研究の多くが主に長時間（2〜4時間）運動でその運動強度として最大酸素摂取量の45〜65％を対象にしたものであって，比較的短時間の最大負荷運動に対するCHOローティングの効果を検討するものは多くない。本研究は異なる三つの体内糖質貯蔵（糖質貯蔵，糖質枯渇，通常状態）と増強負荷最大運動の成績について検討を試みた。

7名の身体的よく鍛錬された男子学生（年齢22.2 ± 1.6歳，身長175.4 ± 5.6 cm，体重66.4 ± 6.5 kg）がそれぞれの体内糖質状態で自転車エルゴメーターによる漸増負荷最大運動（ゼロワット60回転/分での3分間ウォームアップの後，運動負荷は3分毎に60ワット増加させ，60回転が遂行不可能になるまで継続させた）を行った。最大酸素摂取量の測定のほかに安静時と負荷が増加するごとに採血がなされ血中グルコース，乳酸，遊離脂酸（FFA）濃度を測定した。

最大運動時間は糖質貯蔵（CHL）状態において最も長く，通常食（ND）と糖質枯渇（CHD）状態では類似した値を示した。しかし，最大酸素摂取量においては三条件間に有意差は見られなかった。安静時血中グルコース濃度に対するCHLとCHDの影響は見られなかったが，運動時の血中FFAの利用がCHDに比べてCHL状態では有意に低く抑えられたこと，及び最大負荷に近いところでCHLの血中乳酸濃度が有意に上昇したことから，CHLの最大運動時間の延長は体内の糖質貯蔵レヴェルに関係したものと考えられる。糖質貯蔵は運動のエネルギー源を無酸素過程と有酸素過程に求める最大負荷運動においても，その成績の改善に影響を持つものと思われる。