Differences in the Effects of Carbohydrate Food Form on Endurance Performance to Exhaustion

Scott D. Murdoch, Terry L. Bazzarre, Ian P. Snider, and Allan H. Goldfarb

This investigation examined the metabolic and performance effects of ingesting solid compared to slurried carbohydrate food (bananas) between two prolonged exhaustive exercise bouts. Eight highly trained male triathletes performed four exhaustive endurance tests (ET), each separated by at least 2 weeks. Each ET consisted of a 90-min run followed by 90 min of cycling, both at 70% VO$_{\text{max}}$. Workloads were then gradually increased on the cycle, and subjects continued to cycle until exhausted. They then rested for 20 min and ingested one of the following: an artificially sweetened placebo drink (P), slurried bananas (SL), or solid bananas (SO). Bananas were given in equal portions relative to each subject’s body weight. Subjects cycled to exhaustion a second time at 70% of their VO$_{\text{max}}$, at which point the mean blood glucose concentration for the combined carbohydrate treatments was significantly higher than that from the P treatment. The mean glucose concentration from the SL treatment did not differ significantly from the SO treatment. These data demonstrate that solid bananas are as effective as slurried bananas in maintaining plasma glucose and in enhancing endurance exercise performance.

Key Words: carbohydrate ingestion, exercise performance, blood glucose, bananas, fatigue

Many factors such as dehydration (11, 33) and the depletion of endogenous carbohydrate stores (1, 3, 4, 13, 17, 28) contribute to fatigue during prolonged exercise. Dehydration may be avoided by consuming fluids throughout exercise. Assuming adequate hydration, the depletion of endogenous carbohydrate stores (muscle and liver glycogen, and blood glucose) is a primary limiting factor in endurance events of moderate to high intensity (60–85% of VO$_{\text{max}}$) and prolonged duration (2 hours or more) (3, 13–17).

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A series of studies by Coggan and Coyle (13–15, 17) have demonstrated that plasma glucose is the predominant carbohydrate energy source during the latter stages of prolonged exercise, and that a decline in plasma glucose during prolonged exercise is associated with fatigue. Toward the latter stages of exhaustive cycling at 70% of VO2max, the blood glucose oxidation rate has been estimated to be at least 1.1 g/min (13) and may be as high as 2 g/min (14). Since endogenous carbohydrate stores may become depleted long before the conclusion of many prolonged training and racing events (i.e., lasting more than 3 hours), the need to ingest large amounts of carbohydrate during the exercise period is essential if the exercise intensity, or rate of energy output, is to be maintained.

Currently several commercial companies are manufacturing highly concentrated carbohydrate drinks (i.e., approximately 23% carbohydrate; weight per volume) that are targeted toward endurance athletes. Additionally, several studies have demonstrated favorable benefits from ingesting solutions of 50% carbohydrate during exhaustive exercise (13–15, 17, 18). Since fluid is ingested throughout endurance exercise, the ingestion of solid carbohydrate foods likely produces concentrated carbohydrate solutions in the stomach similar to the commercial drinks previously mentioned. Yet, to our knowledge, no studies have compared the effects of solid versus liquid carbohydrate intake during prolonged, exhaustive exercise on endurance performance.

The practice of ingesting solid carbohydrate foods (fresh and dried fruits, candy, cookies, energy bars, sandwiches, etc.) during prolonged training and racing is common among endurance athletes (8, 10, 21). The ingestion of solid carbohydrate foods may be of greater benefit as a fuel source (blood glucose) than liquid carbohydrate foods because of the following:

1. Solid food may stay in the GI tract longer, theoretically providing for a more continuous supply of carbohydrate being released into the circulation.
2. Solid food provides more carbohydrate per unit weight.
3. Solid food may have the advantage of greater availability/access to the athlete because it may be carried by the athlete during the event and costs less.
4. Solid food may be more psychologically and physiologically pleasing/satisfying.

The purpose of this study was to examine the metabolic and performance effects of ingesting either solid or slurried carbohydrate food between two prolonged exhaustive exercise bouts. Bananas are commonly ingested by endurance athletes during prolonged events for a number of reasons, including high carbohydrate content, low cost, pleasing taste, accessibility, and handy carrying case. Additionally, bananas contain a great deal of water (approximately 75% by weight), making them easy to liquify. For these reasons, bananas were selected as the carbohydrate food for this investigation.

Methods

Subjects

Subjects between the ages of 18 to 35 were solicited from an advertisement in the Carolina Triathlon Club Newsletter. This study was approved by the University of North Carolina at Greensboro Human Subjects Review Board. Twelve male
biathletes/triathletes were chosen from a pool of 21 volunteers. All 21 volunteers gave written, informed consent to participate and were required to complete a medical history questionnaire to certify that they had no known medical problems and no history of heart disease, hypertension, hyperlipidemia, diabetes, or other known medical disorders that might compromise their full participation in this study.

Selection of the initial 12 subjects required normal blood levels of total cholesterol and HDL-cholesterol. Hemoglobin, hematocrit, and ferritin were analyzed in order to identify potential iron abnormalities in these athletes. Subjects were required to have averaged, during the previous month, a minimum of 30 miles/week running and 100 miles/week cycling. These requirements were verified from their training logs. A VO$_2$max of at least 55 ml·kg$^{-1}$·min$^{-1}$ on both the treadmill and the cycle was also required for participation in this study.

Additionally, all subjects completed a 3-hr trial performance test. This test was designed to help us select subjects who could finish the protocol, to assist in determining the workloads that elicited approximately 70% of their VO$_2$max, to familiarize each subject with the test protocol, and to identify any problems that might be associated with data collection. The protocol for the trial performance test included 90 minutes of running immediately followed by at least 90 minutes of cycling at 70% VO$_2$max until volitional fatigue. Subjects were encouraged to consume at least 8 oz of water every 15 minutes. Prior to each performance test, the subjects were instructed to approach these events as though they were long races, that is, be fully rested, consume a high carbohydrate diet, and drink plenty of fluid prior to the event.

**Anthropometric Measurements and VO$_2$max Testing**

Height (cm) and weight (kg) were measured using a Detecto™ beam scale. Percent body fat was determined using the sum of four skinfold measures (24) and hydrostatic weighing (37).

Cycling VO$_2$max values were determined using a graded maximal exercise test performed on a modified BodyGuard cycle ergometer (BodyGuard 990, Jonas Ogaend A.s, Sandnes, Norway) with racing toe-clips. The protocol began with a 5-min warm-up at a workload that elicited a heart rate of approximately 120 beats per minute. The workload, at 90 rpm, was increased every 2 minutes by 200 kpm. Subjects cycled until they reached volitional fatigue, with the VO$_2$max being identified as the highest VO$_2$ observed during any full minute of the test.

Running VO$_2$total was determined using a graded maximal treadmill exercise test (Quinton Q55, Quinton Instrument Co., Seattle). The protocol began with a 5-min warm-up at a workload that elicited a heart rate of approximately 120 bpm. Treadmill speed was increased every 2 minutes until a speed of 10 miles per hour was reached, after which the grade was increased 1% every 2 minutes (unless subjects indicated that an increase of 2% was tolerable) until volitional fatigue was reached. VO$_2$total was identified as the highest VO$_2$ recorded during any full minute of the test. Both a cycling and a running max test were performed during Weeks 0, 5, and 11, totaling six max tests/subject throughout
the 12-week study (see Figure 1). These tests were performed to ensure that there were no significant changes in aerobic fitness level throughout the 12-week study.

Oxygen and CO₂ were monitored throughout each VO₂max test using an automated gas analysis system that employed a two-way nonrebreathing valve (Rudolph Valve, Hans Rudolph, Inc., Kansas City, MO). Expired air volumes were measured using a turbine flow meter (Ametek, Thermox Instruments Div., Pittsburgh). Expired gases were continuously sampled from a mixing chamber and analyzed for O₂ and CO₂ (Applied Electrochemistry S3-A and SD-3A, respectively). Software (Ametek’s Stress Program) and box interface (Ametek-71911KE) were programmed to calculate ventilation rate (L.min⁻¹ BTPS), VO₂ (ml·kg⁻¹·min⁻¹), VCO₂ (ml·kg⁻¹·min⁻¹), and the ventilatory exchange ratio (R) every 30 seconds. All values were corrected for STPD. Before each test, the O₂ and CO₂ were calibrated to a known gas (Air Products Industrial Gas) composed of 4.72 moles% carbon dioxide, 15.8 moles% oxygen.

**Endurance Performance Tests (EPT)**

Room temperature was maintained at approximately 23 °C by an individual air conditioning unit. After an overnight fast, subjects reported to the lab and their body weight was recorded (only shorts were worn). A catheter with a saline lock was inserted into a forearm vein to facilitate repeated blood samples. The catheter was kept patent with sterile physiological saline. Four ECG electrodes (three leads and one ground) were placed on the subject’s chest. Subjects warmed up on the treadmill before the run portion and on the cycle ergometer before the ride portion at their chosen workload for 5 minutes. After the warm-up, subjects ran on the treadmill for 90 minutes at 70% of their running VO₂max, followed by 90 minutes of cycling at 70% of their cycling VO₂max (Figure 2).

The percent VO₂max at which subjects were working was determined within the first 10 to 20 minutes of each mode of exercise. At the end of the
180 minutes, the workload on the cycle ergometer was increased every 5 minutes by 65 kpm, designed to elicit a workload corresponding to approximately 75%, 80%, and finally 85% of their cycling VO$_2$max, which was maintained until exhaustion (i.e., failure to maintain cycling cadence above 70 rpm). The first run-ride (of +180 min) was defined as Ride-1. Ride-1 was designed to bring each subject to a common, glycogen depleted state. Each subject was required to perform at least 180 minutes of Ride-1 in order for his data to be usable. The final increases in workload were designed to simulate biathlon/triathlon racing. Subjects were verbally encouraged toward the end of the ride. Although not recorded, subjects were encouraged to drink 3.4 ml-kg$^{-1}$ of body weight (i.e., 8 oz for a 70-kg subject) of cold water every 15 minutes during the tests in order to maintain hydration.

**Ingestion Period.** The banana was chosen as the carbohydrate food because it is essentially all carbohydrate, its carbohydrate concentration is relatively high (23% weight/volume), and because bananas are frequently consumed by biathletes/triathletes during training and races of more than 2 hours. The carbohydrate concentration of three bananas and 4.4 oz of water was approximately 16.4% (weight per volume).

Prior to this study, several triathletes were asked to quickly ingest as many bananas as possible within a 10-min period after a prolonged exhaustive training ride. From this experience we determined that a 70-kg male in a depleted state could “comfortably” consume approximately three medium sized bananas within the allotted time period.

At the end of Ride-1, subjects rested in a chair for 20 minutes and, after the first 5 minutes, they ingested one of the following (based on a 70-kg male): (a) a blended mixture of three bananas and 4.4 oz of water (totaling 16 oz), (b) three whole bananas and 4.4 oz of water (totaling 16 oz), or (c) 16 oz of an artificially sweetened, flavored, and colored placebo drink. The ingestion usually required at least 10 minutes to complete. Carbohydrate intake was 1.1 g/kg of body weight. The placebo was designed to mimic the taste of an orange flavored carbohydrate drink. The total volume for each of the three treatments (placebo, slurred, and solid) was 6.8 ml-kg$^{-1}$ of body weight. For a 70-kg subject this volume equaled 16 oz.
It should be noted that a fourth performance test was added to the design of this study for reasons relating to another ongoing investigation. Thus we proposed to use the data from 6 of the 12 subjects in Performance test 1 and from the other 6 subjects in Performance test 4 (Figure 1). All treatments were randomly assigned.

**Ride-2.** At the end of the 20-min rest period, subjects began Ride-2. They warmed up for 3 minutes at a workload of their choice and then cycled at 70% \( VO_2 \text{max} \) (i.e., the workload used on the cycle ergometer during Ride-1) until exhaustion (Figure 2). A minimum of 10 minutes riding was required for the data to be considered usable. Water (3.4 ml·kg\(^{-1}\) of body weight) was provided at 15-min intervals. Assessment of the effectiveness of these supplements (i.e., solid or slurried bananas) on endurance performance was quantified by time to exhaustion for Ride-2.

**Incentives.** Subjects were paid in progressively increasing amounts after completing each EFT. In addition, monetary rewards were given to the top 3 subjects having the best performance (i.e., longest time) in both Ride-1 and Ride-2 for each performance test. Thus, the four performance tests resulted in a total of 24 monetary rewards being given. Subjects were kept unaware of the others’ performance times until all had completed the performance trial.

**Blood Analysis**
Plasma glucose, lactate, and free fatty acids (FFA) were measured from plasma samples obtained during the test (rest, 45- and 90-min run, 45- and 90-min bike, exhaustion-1, recovery, and exhaustion-2) (Figure 2). Blood hematocrit (microhematocrit method) and hemoglobin concentrations (cyanmethemoglobin method [23]) were immediately determined in duplicate. Whole blood was then centrifuged for 15 minutes at 3,000 rpm (at 10 °C), placed into storage containers, and stored at −70 °C.

Plasma glucose was determined using an enzymatic kit from Sigma Chemical Company (1988; 16-UV; St. Louis). Plasma long-chain FFA were determined using the colorimetric assay methods of Noma et al. (35). Plasma lactate was determined using an enzymatic kit by Sigma Chemical Company (1989; 826-UV) modified for use in plasma without deproteinization. Total blood cholesterol was determined using the method of Allain et al. (2). HDL cholesterol determination was based on the method described previously (2, 30). Serum ferritin was determined using a Ferrizyme kit from Abbott Laboratories (1985; 83-1156/R10). A Bausch & Lomb Spectronic 2000 spectrophotometer was used to measure absorbance changes for all chemical determinations. All samples were assayed in duplicate.

Each plasma substrate concentration was adjusted for plasma volume shifts, according to the methods of Dill and Costill (22). These adjustments were performed before any statistical analysis. Substrate preevent concentrations were considered the reference value (i.e., plasma volume of 100%); all other concentrations were adjusted to the preevent reference value.

**Statistical Analysis**
Statistical analyses were performed with the data collected pre- and post-Ride-2 (i.e., postrecovery and exhaustion-2 time periods), which occurred after the first exhaustion period. Eight subjects completed all experimental tests. The
two primary experimental interests compared the mean data from the combined carbohydrate treatments with that from the placebo treatment, as well as comparing the mean data from the two carbohydrate treatments with each other. Statistical comparisons were made using two one-way (separate analyses at each of the two time periods) analyses of variance in a randomized block (subjects) design, with orthogonal polynomial contrasts to further subdivide the three treatment conditions. Statistical significance for all comparisons was set at $p \leq 0.05$.

Results

Subjects

All of the volunteers had maintained the minimal mileage requirements for running and cycling. Of the 21 volunteers, 3 had total blood cholesterol concentrations equal to or greater than 240 mg%, which is the high risk level identified by the National Cholesterol Education Program (32). All but 1 subject had $\text{VO}_2\text{max}$ values greater than 55 ml·kg$^{-1}$·min$^{-1}$. Two subjects were unable to achieve the large time commitment. Three of the remaining 15 subjects were eliminated from the study due to low trial performance times (2 were barely able to perform for the required 3 hours, and another subject had knee problems associated with the protocol). Thus, 12 subjects (ID nos. 1 through 12) were chosen for this investigation.

As the study progressed, Subject 7 withdrew due to a severe back injury. Subject 11 was forced to miss one of the treatment rides due to a cycling-running crash in a triathlon. Finally, Subjects 3 and 4 did not complete all of the four EPTs. These subjects were eliminated from all statistical analysis. Thus, 8 subjects completed all experimental tests. Mean descriptive and preliminary performance data on these 8 subjects are summarized in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>SEM</th>
<th>Min. value</th>
<th>Max. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
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<td>1.1</td>
<td>22.0</td>
<td>31.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.2</td>
<td>3.3</td>
<td>165.0</td>
<td>191.0</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>68.3</td>
<td>3.0</td>
<td>56.4</td>
<td>82.1</td>
</tr>
<tr>
<td>% Body fat (hydrostatic)</td>
<td>9.8</td>
<td>1.6</td>
<td>4.3</td>
<td>15.7</td>
</tr>
<tr>
<td>Total blood cholesterol (mg%)</td>
<td>170.0</td>
<td>7.6</td>
<td>140.4</td>
<td>204.9</td>
</tr>
<tr>
<td>HDL cholesterol (mg%)</td>
<td>55.5</td>
<td>4.8</td>
<td>40.0</td>
<td>84.2</td>
</tr>
<tr>
<td>Serum ferritin (ng/ml)</td>
<td>56.8</td>
<td>11.5</td>
<td>15.2</td>
<td>94.2</td>
</tr>
<tr>
<td>Bike $\text{VO}_2\text{max}$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>67.1</td>
<td>2.6</td>
<td>55.8</td>
<td>76.4</td>
</tr>
<tr>
<td>Run $\text{VO}_2\text{max}$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>68.1</td>
<td>5.4</td>
<td>60.4</td>
<td>74.2</td>
</tr>
</tbody>
</table>
**Time To Exhaustion-2**

Mean (±SEM) performance test times from Ride-2 were 28.2 ±4.3, 44.1 ±8.7, and 46.4 ±13.2 minutes for the placebo, slurried, and solid treatments, respectively (Figure 3). Since we hypothesized that carbohydrate ingestion in either form would delay fatigue, a one-tailed statistical analysis was performed. The two carbohydrate treatment times to exhaustion-2 were statistically longer (p=0.05) than the mean time from the placebo treatment. Individual performance times from Ride-2 ranged from 13.0 to 124.2 minutes. Total mean EPT time for Ride-1 was 217.3 ±7.1 minutes for all three treatment groups combined, and were not statistically different between trials.

**Plasma Glucose Concentrations**

At exhaustion-2 from Ride-2, the mean (±SEM) glucose concentration for the solid treatment (4.6 ±0.2 mmol·L⁻¹) was not statistically different from that of the slurried treatment (4.2 ±0.3 mmol·L⁻¹) (Table 2 and Figure 4). The mean glucose concentration for the combined carbohydrate treatments at exhaustion-2 (4.4 ±0.2 mmol·L⁻¹) was statistically higher (p=0.0094) than that of the placebo treatment (3.5 ±0.3 mmol·L⁻¹). Mean glucose concentrations postrecovery for the three treatment groups were not statistically different.

**Plasma FFA and Lactate Concentrations**

Mean FFA and lactate concentrations were not statistically different among treatments at both the postrecovery and exhaustion-2 time periods (Table 2). Mean plasma FFA concentrations for the postrecovery and exhaustion-2 time periods were:

- **Solid**: 0.3 ±0.1 mmol·L⁻¹
- **Slurried**: 0.3 ±0.1 mmol·L⁻¹
- **Placebo**: 0.3 ±0.1 mmol·L⁻¹

**Figure 3** — Mean cycling time (±SEM) to exhaustion-2 for each treatment. *Significantly shorter than the combined carbohydrate treatment (p=0.05).*
### Table 2

Plasma Glucose, FFA, Lactate Concentrations (mmol·L⁻¹), and Plasma Volume Shifts During Performance Tests for Each Treatment Group

<table>
<thead>
<tr>
<th></th>
<th>Resting Mean</th>
<th>Resting SEM</th>
<th>Exhaustion-1 Mean</th>
<th>Exhaustion-1 SEM</th>
<th>Treatment</th>
<th>Postrecovery Mean</th>
<th>Postrecovery SEM</th>
<th>Exhaustion-2 Mean</th>
<th>Exhaustion-2 SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Glucose</strong></td>
<td>4.9</td>
<td>0.1</td>
<td>3.9</td>
<td>0.3</td>
<td>Placebo</td>
<td>4.3</td>
<td>0.3</td>
<td>3.5</td>
<td>0.3*</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>0.2</td>
<td>4.5</td>
<td>0.4</td>
<td>Slurried</td>
<td>5.0</td>
<td>0.3</td>
<td>4.2</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>0.1</td>
<td>3.6</td>
<td>0.3</td>
<td>Solid</td>
<td>4.7</td>
<td>0.3</td>
<td>4.6</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>FFA</strong></td>
<td>.27</td>
<td>.05</td>
<td>.90</td>
<td>.09</td>
<td>Placebo</td>
<td>.85</td>
<td>.08</td>
<td>.92</td>
<td>.06</td>
</tr>
<tr>
<td></td>
<td>.25</td>
<td>.03</td>
<td>.88</td>
<td>.13</td>
<td>Slurried</td>
<td>.96</td>
<td>.15</td>
<td>.88</td>
<td>.13</td>
</tr>
<tr>
<td></td>
<td>.25</td>
<td>.04</td>
<td>.92</td>
<td>.05</td>
<td>Solid</td>
<td>.80</td>
<td>.10</td>
<td>.83</td>
<td>.09</td>
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<tr>
<td><strong>Lactate</strong></td>
<td>1.6</td>
<td>0.2</td>
<td>1.9</td>
<td>0.3</td>
<td>Placebo</td>
<td>1.5</td>
<td>0.3</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>0.2</td>
<td>2.2</td>
<td>0.3</td>
<td>Slurried</td>
<td>2.0</td>
<td>0.5</td>
<td>1.4</td>
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<td></td>
<td>2.0</td>
<td>0.2</td>
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<td>0.6</td>
<td>Solid</td>
<td>2.7</td>
<td>0.2</td>
<td>1.9</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Plasma volume shifts</strong></td>
<td>0</td>
<td>0</td>
<td>-14</td>
<td>2</td>
<td>Placebo</td>
<td>-6</td>
<td>5</td>
<td>-12</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>-6</td>
<td>2</td>
<td>Slurried</td>
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<td>2</td>
<td>-5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>-12</td>
<td>3</td>
<td>Solid</td>
<td>-9</td>
<td>3</td>
<td>-10</td>
<td>3</td>
</tr>
</tbody>
</table>

*Significantly lower than the combined carbohydrate treatments, \( p < 0.01 \).

![Figure 4](image_url)  
Mean plasma glucose concentrations at exhaustion-1, postrecovery, and exhaustion-2. *Significantly lower than the combined carbohydrate treatments (\( p < 0.01 \)).
periods were .85 ±0.08 and .92 ±0.06, .96 ±0.15 and .88 ±0.13, and .80 ±0.10 and .83 ±0.09 mmol·L⁻¹ as a result of the placebo, slurried, and solid treatments, respectively. The mean plasma lactate concentrations for the postrecovery and exhaustion-2 time periods were 1.5 ±.3 and 1.7 ±.3, 2.0 ±.5 and 1.4 ±.2, and 2.7 ±.2 and 1.9 ±.2 mmol·L⁻¹ as a result of the placebo, slurried, and solid treatments, respectively. Plasma volume deficits were smaller at exhaustion-1 and 2 for the placebo treatment group than for either the slurried or solid treatment groups (Table 2). For each treatments group, the plasma volume deficit was smaller at postrecovery than at either of the exhaustion time periods.

**Run and Bike VO₂max Values**

Mean run and bike VO₂max values at Weeks 0, 5, and 11 were 68.1 ±1.9, 68.0 ±2.3, and 69.5 ±2.1 ml·kg⁻¹·min⁻¹ for the run; and 67.1 ±2.6, 67.7 ±2.5, and 66.9 ±2.0 ml·kg⁻¹·min⁻¹ for the bike, respectively. These means were not significantly different either between modalities or across time. Individual VO₂max values ranged from 55.8 to 78.2 ml·kg⁻¹·min⁻¹ on the cycle ergometer and treadmill.

**Discussion**

Since prior nutrient status of the athlete can significantly influence his/her ability to endure prolonged exercise, we chose a study design (13) that would bring our subjects to a similar physiological endpoint (i.e., endogenous glycogen depleted state) before the carbohydrate treatments were ingested. With this design we have greater confidence in attributing any metabolic and performance results to the treatments themselves. Additionally, endurance athletes periodically find themselves exhausted before the end of a training session or even a race. The design of this study simulates this scenario and thus provides some insight into the athletes’ ability to reverse fatigue by ingesting carbohydrate in either a solid or slurried form.

After several hours of prolonged, moderately intense exercise, when muscle glycogen concentration becomes low, the primary source of carbohydrate oxidation is circulating blood glucose (16). Increased blood glucose during exercise of this duration is strongly associated with increased performance time to exhaustion. In the present study, differences between the mean performance times to exhaustion of the placebo treatment (28 minutes) and both carbohydrate treatments (44 and 46 minutes for the slurried and solid, respectively) are consistent with previous findings (16).

Several studies have demonstrated increased blood glucose levels as a result of ingesting liquid (7, 13–15, 17, 18, 20) or solid (7, 25, 27) carbohydrates during endurance exercise, when compared to water alone. Yet, during exercise the glycemic response from ingesting an identical carbohydrate food in either a solid or slurried form has not been investigated. The results of this study demonstrate that the ingestion of either solid or slurried bananas was equally effective in maintaining higher plasma glucose concentrations throughout the second exhaustive exercise bout as compared to water. Thus, in the glycogen depleted state it appears that the glycemic response from ingesting bananas was not significantly affected by the form in which it was ingested.

In resting subjects, the rate of gastric emptying for solid or liquid foods
influences the rate of absorption. At rest, solid food empties from the stomach more slowly than liquid foods (31). Ingesting solid bananas results in lumps of fruit being presented to the stomach. These lumps of banana are eventually reduced in size and ultimately introduced to the small intestine. The digestive enzymes required to further break down the banana into its simplest absorptive components have limited access to all the nutritive constituents in these banana lumps, suggesting that the digestion of solid carbohydrate food is slower than that of liquid carbohydrate food (6). However, no differences were observed in the rate at which blood glucose concentration peaked from the ingestion of solid or pureed carbohydrate (6), indicating that the delay in gastric emptying that accompanies the ingestion of solid carbohydrate food occurs only after significant absorption has taken place (i.e., after 60 min in resting subjects).

In a recent study (36), the rate of delivery and storage of ingested solid carbohydrate food (banana/rice cakes) did not differ from that of an isocaloric CHO drink (3 g carbohydrate/kg of body weight) immediately after 2 hours of moderately intense cycling, suggesting similar gastric emptying rates. With so little known about the rate of gastric emptying of solid foods ingested during exercise, as well as the effect of exercise on the digestion/absorption of solid foods, further investigations are warranted.

The question as to how much carbohydrate should be ingested in order to maintain euglycemia (or to avoid hypoglycemia) is in part dependent upon the rate of absorption for that carbohydrate. In order to maintain blood glucose within a normal range, glucose infusion during exhaustive cycling at 70% VO_{2max} required an infusion rate of 1.1 g glucose/min (13). In the latter stages of exhaustive cycling at a similar intensity, the carbohydrate oxidation rate was estimated to be 2 to 2.6 g/min (9, 17). Whether the ingestion of a particular amount of solid carbohydrate food can supply 1.1 g glucose/min to the circulation over a prolonged period of time, and without compromising hydration, remains to be determined.

Fatigue from prolonged, moderately intense exercise appears to result from an inadequate delivery rate of carbohydrate to the exercising muscle (17) rather than to an inadequate delivery of carbohydrate to the central nervous system (12). In this study, exhaustion did not always coincide with a low blood glucose concentration. Boje (5) reasoned that an improvement in blood glucose regulation results from physical training, enhancing our capacity to prevent exercise induced decreases in blood glucose. Second, sensitivity to changes in blood glucose are quite variable among individual athletes; some respond to small blood glucose changes while others show no symptoms of hypoglycemia even though they have extremely low blood glucose levels (34).

In this study, mean pre-event plasma glucose was 4.8 mmol·L⁻¹ (range: 4.1–5.6) and the mean glucose at exhaustion-1 was 4.0 mmol·L⁻¹ (range: 2.5–5.8). Fourteen of 23 glucose values at exhaustion-1 were less than 4.0 mmol·L⁻¹, and 6 of the 14 values were less than 3.0 mmol·L⁻¹. This decrease in blood glucose is consistent with data from other investigations (13–15, 17, 18). Yet, 9 out of 23 glucose concentrations at exhaustion-1 were above 4.0 mmol·L⁻¹, suggesting that carbohydrate availability was only one of several factors (such as hydration, core temperature, motivation, etc.) that influence the onset of volitional fatigue.

Plasma volume decreased significantly (up to 12%) throughout exercise. Davis et al. (20) demonstrated a similar pattern of plasma volume loss with
cyclists during a 2-hr ride at 70% of their VO2max. The mean plasma volume shifts for each treatment were variable at both the postrecovery and exhaustion-2 time periods; however, no significant differences were detected between treatments. This plasma volume loss represents either a shift of the fluid into other areas of the body or an inability to completely replace all of the fluid lost during exercise. The subjects were encouraged to drink at least 8 oz of cool water every 15 minutes in order to minimize the effects of dehydration during their performance. Nevertheless, the mean weight loss at exhaustion-2, when compared to mean pre-event weight, was 2 kg. This weight-fluid loss may have contributed to the volitional fatigue in some subjects.

Jenkins et al. (29) determined the glycemic response from ingesting two solid bananas (50 g carbohydrate), as compared to 50 g glucose (reference value equal to 100%). They found a moderate glycemic response equal to 62% of the reference glucose value. The primary assumption of this study was that the glycemic response of ingesting solid bananas would be lower than when bananas were consumed in slurried form. This assumption appears reasonable since the literature clearly demonstrates that the disruption of food form (via mixing, cooking, blending, pureed, etc.) increases the glycemic response to that food in healthy resting subjects (6, 19, 26). Yet, statistical differences in plasma glucose were not observed at either postrecovery or exhaustion-2 between the solid and slurried banana treatments. These results suggest that the glycemic effect produced from ingesting bananas may either be altered by exercise or requires a longer exercise time before it takes effect.

The banana was selected as the experimental solid food because its caloric composition is almost exclusively carbohydrate and because it is a food of choice consumed during exhaustive endurance events. Bananas provide carbohydrate in both simple and complex forms. However, because of their moisture content (approximately 75% water), bananas are more semisolid than solid. This semisolid carbohydrate food may not have been structurally different enough from the slurried form to elicit the metabolic and performance responses of other solid carbohydrate foods. Future research using carbohydrate foods with less moisture content (such as cookies, figs, energy bars, etc.) could increase the magnitude of any metabolic and performance differences between solid and slurried carbohydrate foods when ingested during prolonged, moderately intense exercise.

There is a large gap in the research pertaining to the ingestion of solid carbohydrate food during prolonged exercise. Further study will enhance and support the efforts of competitive endurance athletes to overcome performance variables associated with fuel depletion, and thereby expand the boundaries of human performance.

References


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