Influence of Carbohydrate Ingestion on Blood Glucose and Performance in Runners

Randall L. Wilber and Robert J. Moffatt

Ten trained male runners performed a treadmill exercise test at 80% $\dot{V}O_2_{\text{max}}$ under two experimental conditions, carbohydrate (CHO, 7% carbohydrate) and placebo (P), to determine the effect of carbohydrate ingestion on endurance performance (treadmill run time), blood glucose concentration, respiratory exchange ratio (RER), and subjective ratings of perceived exertion (RPE). Treatment order was randomized and counterbalanced and test solutions were administered double-blind. Ingestion took place 5 min preexercise (250 ml) and at 15-min intervals during exercise (125 ml). Performance was enhanced by 29.4% ($p<0.05$) during CHO (115 ±25 min) compared to P (92 ±27 min). Blood glucose concentration was significantly greater during CHO (5.6 ±0.9 mM) relative to P (5.0 ±0.7 mM). There was a significant increase in mean RER following CHO ingestion (94 ±01) compared to P (90 ±01). Average RPE was significantly less during CHO (14.5 ±2.3) relative to P (15.4 ±2.4). These data suggest that time to exhaustion of high-intensity treadmill exercise is delayed as a result of carbohydrate ingestion and that this effect is mediated by favorable alterations in blood glucose concentration and substrate utilization.

In an effort to improve performance, endurance athletes often adhere to specific dietary regimens. One dietary modification commonly used by these athletes is ingestion of exogenous carbohydrate during exercise. In general, carbohydrate feeding during prolonged exercise has been shown to enhance performance (6, 11, 12, 21, 23, 24, 25, 28). Different mechanisms have been proposed regarding the ergogenic effect of carbohydrate ingestion. One possibility is that carbohydrate feeding during prolonged exercise acts to spare muscle glycogen, thereby delaying fatigue (19, 20, 22). Conversely, it has been suggested that exogenous carbohydrate does not affect muscle glycogen utilization (11, 15, 18) but instead may improve performance by maintaining blood glucose at a critical point in endurance exercise when liver and muscle glycogen levels are low and the uptake of glucose by skeletal muscle is increased (11).

The authors are with the Exercise Physiology Laboratory, Department of Nutrition, Food, and Movement Sciences, Florida State University, Tallahassee, FL 32306.
The influence of carbohydrate consumption during prolonged exercise is well documented. A majority of the studies investigating the effects of carbohydrate ingestion on exercise performance have utilized cycling protocols (4–6, 11, 12, 15, 21, 24, 25). To our knowledge, very few laboratory investigations have evaluated the influence of carbohydrate feeding on continuous running performance (23, 27–29), and among these investigations the results have been inconclusive. Accordingly, the purpose of this study was to determine the effects of carbohydrate ingestion on the performance of exhaustive treadmill exercise and on selected metabolic variables.

Methods

Subjects and Preliminary Testing

The subjects for this study were 10 male distance runners who were volunteers from a local track club. Mean (±SD) age, height, weight, and VO2max were 30 ±4 yrs, 176.9 ±8.0 cm, 65.3 ±6.0 kg, and 64.9 ±4.8 ml·kg⁻¹·min⁻¹, respectively. An informed consent statement approved by the institutional review board for human subjects research was obtained from each subject prior to the study.

Maximal aerobic capacity was determined during an incremental exercise test performed on a Quinton 18-60 treadmill using a modified Costill and Fox (9) protocol. Subjects breathed through a two-way Hans Rudolph valve, with expired gases directed to a mixing chamber for analysis of O2 (Applied Electrochemistry S3-A) and CO2 (Applied Electrochemistry CD-3A). Analog output from these instruments was directed to an Apple IIe microcomputer for calculation of VO2 and RER every 30 sec. Gas analyzers were calibrated prior to each test using a medical gas mixture (Air Products, Allentown, PA) of known O2 and CO2 concentrations. Heart rate was continuously monitored from the V1 position electrocardiographically. Within 48 hours of the maximal aerobic capacity test, subjects performed a 20-min preexperimental treadmill run for the purpose of defining more precisely the 80% VO2max running speed.

Experimental Design

Each subject performed two randomly ordered experimental trials at 1-week intervals in a placebo double-blind investigation. During one trial subjects ingested an orange flavored 7% carbohydrate solution (85% glucose polymers, 15% sucrose; Exceed®, Ross Laboratories, Columbus, OH). During the other trial subjects ingested a water placebo that was artificially colored and flavored to make it indistinguishable from the carbohydrate drink. Ingestion took place 5 min prior to exercise (250 ml) and every 15 min during exercise (125 ml). Solutions were refrigerated at 5°C prior to ingestion.

Subjects reported to the laboratory at 8 a.m. following a 12-hr fast. To minimize thermal stress, the laboratory was maintained at 22°C. Subjects began each trial with a standardized warm-up run for 10 min at 60% VO2max. Immediately following the warm-up (which was included in the overall performance time), the treadmill speed was increased to the equivalent of 80% VO2max for each subject. At 15-min intervals the treadmill speed was reduced to 5 mph to allow subjects to step off for 45 to 60 sec, during which time they ingested 125
Influence of Carbohydrate Ingestion / 319

ml of test solution. Subjects were kept naive to the details of the experimental design and were told to simply exercise as long as possible during both trials. Each trial was terminated at exhaustion, which was defined as the point when the subject was unable to keep pace at the prescribed exercise intensity. Subjects were kept unaware of their performance and that of the other subjects until the end of the investigation.

In an effort to control for individual variation in liver and muscle glycogen stores, subjects were required to follow the same diet for 3 days prior to each trial and were not permitted to practice glycogen loading at any time during the investigation. Daily records were analyzed to ensure compliance with dietary restrictions. In addition, subjects were asked to maintain the same training schedule prior to each trial and were required to refrain from all exercise for 24 hrs prior to testing.

Sample Collection and Analysis

Single-drop capillary blood samples were obtained at -15 min, 0 min, every 15 min during exercise, and immediately postexercise for the determination of blood glucose concentration using an Accu-Chek II Blood Glucose Monitor (Boehringer Mannheim, Indianapolis), which is based on a modification of the glucose/peroxidase reaction demonstrated by Comer (7) and Free et al. (17). Whole-blood comparison studies of the Accu-Chek II with a glucose hexokinase reference method have supported its use as a valid \( r=.978 \) and reliable instrument (8). In addition, data collected in a preliminary study in our laboratory yielded an \( r \) value of .986 in the assessment of successive blood samples taken from the same individual \( (n=25) \).

Respiratory exchange ratio and \( \dot{V}O_2 \) were measured every 15 min during exercise and at exhaustion using the previously described system. Subjective ratings of perceived exertion (2) were obtained at these same time points. Performance, which was defined as total run time to fatigue, was recorded to the nearest second using a digital stopwatch (Seiko, Tokyo).

Data were analyzed using a two-factor (Treatment x Time) ANOVA with repeated measures. Significant differences revealed by the ANOVA were identified using Tukey (HSD) post hoc analysis. A paired \( t \) test was used to evaluate differences in mean running performance. For all statistical measures, significance was established at the 0.05 level of probability.

Results

Average performance was significantly greater \( (p<0.05) \) during the carbohydrate trial \( (115 \pm 25 \text{ min}) \) compared to the placebo trial \( (92 \pm 27 \text{ min}) \). This difference represented a mean improvement of \( 23 \pm 16 \text{ min} \) \( (p<0.05) \), or approximately 29\%. In addition, enhanced performance was observed during the carbohydrate trial for all 10 subjects. Performance results are listed in Table 1.

The ANOVA revealed a significant treatment effect for blood glucose; mean blood glucose concentration was greater \( (p<0.05) \) during the carbohydrate run \( (5.6 \pm 0.9 \text{ mM}) \) relative to the placebo run \( (5.0 \pm 0.7 \text{ mM}) \). In addition, a significant treatment-time interaction was indicated; average blood glucose level was greater \( (p<0.05) \) during the carbohydrate-fed trial compared to the placebo
Table 1
Exercise Performance Under Carbohydrate and Placebo Conditions (Mean ± SD)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Duration of exercise (min)</th>
<th>Δ (min)</th>
<th>Δ (%)</th>
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<tr>
<td>Placebo</td>
<td>CHO</td>
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</tr>
<tr>
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<tr>
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<td>115*</td>
<td>+23**</td>
</tr>
<tr>
<td>±SD</td>
<td>27</td>
<td>25</td>
<td>16</td>
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</table>

*Significantly different compared to placebo, p < 0.05.
**Significantly different compared to zero, p < 0.05.

trial at 15, 45, and 60 min, and at exhaustion. During the carbohydrate trial, mean blood glucose concentration was elevated (p<0.05) above baseline values beginning at 15 min of exercise and increased by 2.0 ±0.5 mM from baseline to exhaustion. During the placebo trial, average blood glucose level was elevated (p<0.05) above baseline values beginning at 30 min of exercise and increased by 0.8 ±0.6 mM from baseline to exhaustion. Blood glucose response during exercise under carbohydrate and placebo conditions is illustrated in Figure 1.

A significant time effect was indicated by the ANOVA for RER, as the combined average of both trials was lower (p<0.05) at exhaustion compared to 30 min of exercise. A significant treatment effect was also revealed by the ANOVA, as mean RER during the carbohydrate run (.94 ±.01) was greater (p<0.05) relative to the placebo run (.90 ±.01). No treatment-time interaction was detected. Respiratory exchange ratio during exercise under the two experimental conditions is depicted in Figure 2.

As expected, a significant time effect was revealed by the ANOVA for RPE. Compared to 15 min, the combined average RPE in both trials increased (p<0.05) beginning at 30 min and continued to increase to exhaustion. In addition, a significant treatment effect was indicated by the ANOVA; mean RPE during the carbohydrate run (14.5 ±2.3) was less (p<0.05) compared to the placebo run (15.4 ±2.4). No treatment-time interaction was identified. Average values for RPE during the carbohydrate and placebo trials are illustrated in Figure 3.

Discussion
The purpose of the present study was to determine the effects of carbohydrate ingestion on continuous exhaustive treadmill exercise. In general, we found that consumption of carbohydrate during prolonged running resulted in (a) enhanced
Influence of Carbohydrate Ingestion

Figure 1 — Blood glucose during exercise under carbohydrate and placebo conditions, mean ± SE (* significantly different compared to placebo, *p*<0.05).

Figure 2 — Respiratory exchange ratio during exercise under carbohydrate and placebo conditions, mean ± SE.

physical performance, (b) elevated blood glucose concentration, (c) increased respiratory exchange ratio, and (d) less pronounced ratings of perceived effort.

The most important result of the present investigation was our finding regarding exercise performance. Performance (i.e., total run time to fatigue) averaged 115 ±25 min during the carbohydrate run and was significantly greater compared to the placebo run, which averaged 92 ±27 min. This represented a mean improvement of 23 min, or 29%. These results are comparable to studies involving cyclists. Coyle et al. (12) demonstrated a significant 23-min improvement in the performance of an exhaustive cycling bout (74% VO\textsubscript{2}max) when a 7% carbohydrate drink was ingested every 20 to 30 min during exercise. Similarly,
Coyle et al. (11) reported that time to fatigue of cycle ergometer exercise (71% VO$_2$max) was significantly longer by approximately 1 hour when trained subjects consumed a carbohydrate solution (2.0 g·kg$^{-1}$ at 20 min and 0.4 g·kg$^{-1}$ every 20 min thereafter).

Laboratory investigations evaluating the effects of carbohydrate ingestion on running performance have produced inconclusive results (23, 27–29). Our findings are in agreement with McMurray et al. (23), who assessed trained females who ran at 80% VO$_2$max to exhaustion. Consumption of a 30% glucose solution 45 min preexercise resulted in a significantly longer treadmill run time relative to a placebo (CHO = 63.9 ±8.5; P = 52.2 ±5.5 min). Likewise, Sasaki et al. (28) tested adolescent male distance runners who ran at 80% VO$_2$max to fatigue and reported that mean treadmill run time following ingestion of 45 g of carbohydrate immediately preexercise was significantly longer compared to a placebo trial (CHO = 58 ±15; P = 39 ±11 min). In contrast to our results, Riley et al. (27) failed to detect a difference in time to exhaustion in male runners who exercised at 70% VO$_2$max while consuming either a 7% carbohydrate or placebo solution every 20 min during exercise (CHO = 106 ±8; P = 102 ±8 min). Similarly, Williams et al. (29) evaluated male distance runners and reported that mean treadmill run time was not significantly different in a carbohydrate trial (124 ±14.9 min) relative to a placebo trial (129 ±17.7 min).

The discrepancy between our findings and those of Riley et al. (27) is somewhat difficult to explain, considering that both studies were similar with respect to subject fitness level, feeding schedule, and concentration of carbohydrate solution consumed during exercise. Although the subjects in Riley et al. (27) exercised at a lower intensity (70% VO$_2$max) compared to subjects in the current study (80% VO$_2$max), we do not believe this was the cause of the inconsistent results, since prior investigations involving cyclists who exercised at 70% VO$_2$max demonstrated improvements in exercise performance in response to carbohydrate feeding (6, 24). One notable difference between Riley et al. (27)
and the present study, however, was the duration of the preexercise fast; subjects in Riley et al. (27) fasted for 21 hrs compared to 12 hrs in the current investigation. Dohm et al. (14) demonstrated that a 23-hr fast actually produced an increase in blood glucose during exercise; this effect was attributed to a decrease in blood glucose utilization secondary to increased gluconeogenesis and FFA utilization. Similar blood glucose increments were observed in the 21-hr fasted subjects in Riley et al. (27). In contrast, Coyle et al. (12) reported that a 12-hr fast resulted in a decrease in exercise blood glucose concentration. Thus it is possible that the 21-hr preexercise fast employed by Riley et al. (27) may have altered glucose metabolism to the extent that exogenous carbohydrate had no effect on exercise performance.

Although Williams et al. (29) reported that overall treadmill performance time for a simulated 30-km run was approximately 5 min slower in a placebo trial compared to a carbohydrate trial, the difference was not statistically significant. It is interesting to note, however, that during the placebo trial the self-selected running speed at 30 km (3.76 ±0.83 m·s⁻¹) was significantly slower than at 10 km (4.08 ±0.50 m·s⁻¹), 15 km (4.10 ±0.51 m·s⁻¹), and 20 km (4.10 ±0.51 m·s⁻¹). In contrast, self-selected running speed in the carbohydrate trial remained relatively constant from 10 km (4.13 ±0.52 m·s⁻¹) to 30 km (4.12 ±0.50 m·s⁻¹). Moreover, mean running speed at 30 km in the placebo trial (3.76 ±0.83 m·s⁻¹) was significantly slower compared to the carbohydrate trial (4.12 ±0.50 m·s⁻¹). Thus, when viewed in the context of self-selected running speed, it appears that overall performance was enhanced as a result of carbohydrate consumption.

The mechanism by which carbohydrate ingestion improves the performance of prolonged exercise was initially believed to be related to the sparing of muscle glycogen (19, 20, 22). However, more recent evidence has suggested that carbohydrate consumption may not affect muscle glycogen utilization (11, 15, 18) but may instead enhance exercise performance by maintaining blood glucose when liver and muscle glycogen stores are low and, concomitantly, the uptake of glucose by skeletal muscle is accelerated (11). In an investigation of trained cyclists who exercised to fatigue at 71% \( \dot{V}O_{2\text{max}} \), Coyle et al. (11) reported that subjects in a carbohydrate-fed trial exercised for an additional hour compared to a placebo trial. Biopsy samples of the vastus lateralis revealed that the pattern of muscle glycogen utilization did not differ during the first 3 hours of exercise in the two trials. Moreover, muscle glycogen utilization during the extra hour of cycling in the carbohydrate trial was negligible. Plasma glucose concentration and carbohydrate oxidation, however, were maintained in the carbohydrate-fed trial but not in the placebo trial. Thus, Coyle et al. (11) concluded that exogenous carbohydrate did not spare muscle glycogen; rather, it served to maintain plasma glucose, which in turn provided the substrate utilized in the additional hour of exercise during the carbohydrate trial.

Mean blood glucose concentration in the present investigation was significantly greater during the carbohydrate trial (5.6 ±0.9 mM) compared to the placebo trial (5.0 ±0.7 mM). These results compare favorably with studies of continuous exhaustive cycling exercise (6, 12, 24). Likewise, our findings are similar to a majority of the investigations of prolonged running (27–29). In contrast to our study, however, are the results of McMurray et al. (23), who reported that blood glucose during treadmill exercise (80% \( \dot{V}O_{2\text{max}} \)) was lower following glucose ingestion compared to a placebo. The discrepancy between the
present investigation and that of McMurray et al. (23) may be related to differences in timing of the preexercise carbohydrate feeding. The subjects of McMurray et al. (23) consumed a glucose drink 45 min before running whereas subjects in the current study were fed a glucose polymer solution 5 min preexercise. It has been shown that if glucose is consumed from 15 to 45 min before exercise, blood glucose levels during strenuous exercise are usually lower than if no glucose is given (1, 16). On the other hand, when glucose solutions are ingested approximately 5 min before prolonged exercise, blood glucose is maintained or elevated (3); this effect may be due to the release of catecholamines during exercise, which in turn act to suppress insulin output and thus allow blood glucose to accumulate (3).

Another factor affecting blood glucose levels during exercise is the gastric emptying rate of the exogenous carbohydrate source. Gastric emptying is regulated by several determinants, the primary one being the caloric content of the fluid. At rest, the gastric emptying rate of a carbohydrate solution is less rapid than that of water, due to the greater caloric content of the carbohydrate drink (10). During moderate and high intensity exercise, however, a carbohydrate solution containing up to 10% glucose has a gastric emptying rate similar to that of plain water (26). In addition, the net absorption of water through the small intestine epithelial cells is significantly accelerated by the active transport of glucose and sodium (13), both of which were constituents of the carbohydrate drink used in the current investigation. Considering these factors, it is not surprising that blood glucose concentration was significantly greater during the carbohydrate trial compared to the placebo trial. It would appear that elevations in blood glucose evident during the carbohydrate run contributed to the improvement in physical performance. However, the specific mechanism by which blood glucose affected running performance could not be identified from the data of the present investigation.

Average RER during the carbohydrate run (.94 ± 0.01) was significantly greater relative to the placebo run (.90 ± 0.01) and essentially paralleled the corresponding changes in blood glucose concentration. Our results regarding RER suggested, but did not conclusively establish, that the additional blood-borne glucose provided by carbohydrate ingestion was subsequently metabolized as an energy substrate by the exercising musculature, thereby enabling subjects to run approximately 23 min longer. This finding is consistent with investigations of trained cyclists. Coggan and Coyle (6) and Mitchell et al. (24) demonstrated elevated RER values and enhanced performance in response to carbohydrate ingestion during cycle ergometer exercise performed at 70% VO₂max to exhaustion. Likewise, our results are comparable to laboratory studies of prolonged treadmill running. McMurray et al. (23) and Sasaki et al. (28) reported that total run time was significantly longer and RER was significantly greater during a carbohydrate-fed trial compared to a placebo trial, which suggested a greater reliance on carbohydrate and a reduced dependence on fat as an energy source. This finding was further supported by the fact that plasma concentrations of FFA and glycerol were significantly depressed during the carbohydrate run compared to the placebo run (23, 28).

In contrast, the results of the present study are in disagreement with Williams et al. (29), who noted that RER values during a carbohydrate-fed trial and a placebo trial were not significantly different. In addition, no differences were
observed between the two experimental conditions in terms of plasma FFA, plasma glycerol, and running performance (29). These findings are difficult to explain, considering that Williams et al. (29) noted a significant elevation in blood glucose during the carbohydrate run compared to the placebo run. Consequently, it would be expected that elevated blood glucose levels would promote greater carbohydrate utilization and lead to an improvement in physical performance.

This effect was demonstrated by Coyle et al. (11), who reported that elevated RER values evident during the latter stages of a prolonged carbohydrate-fed cycling bout reflected the metabolism of carbohydrate in the form of plasma glucose, not muscle glycogen. Glycogen utilization during the first 3 hours of exercise did not differ for the carbohydrate and placebo trials. However, during the carbohydrate trial the subjects exercised an additional hour before exhaustion and maintained their initial RER throughout exercise. Muscle glycogen utilization during the extra hour of exercise in the carbohydrate trial was negligible. Plasma glucose, however, was maintained during the additional hour, which led Coyle et al. (11) to conclude that plasma glucose, not muscle glycogen, was responsible for the favorable effects on RER, carbohydrate utilization, and physical performance. It is possible that the mechanism proposed by Coyle et al. (11) explains the elevated RER values and enhanced treadmill performance demonstrated in the present study. However, since we were unable to assess muscle glycogen utilization, this conclusion cannot be made unequivocally.

Subjective ratings of perceived effort averaged 14.5 ±2.3 during the carbohydrate run and were significantly less compared to the placebo run, which averaged 15.4 ±2.4. Investigations that have assessed RPE in response to carbohydrate feeding among trained cyclists have yielded equivocal results (4–6, 11). Likewise, studies of RPE response during continuous running have been limited and inconclusive (23, 27, 29). The findings of the present investigation are in agreement with McMurray et al. (23) and Riley et al. (27), each of whom demonstrated significantly lower RPE values during a carbohydrate-fed run compared to a placebo run. In contrast to our results, Williams et al. (29) reported that RPE during carbohydrate and placebo trials was not significantly different.

The discrepancy between our findings and those of Williams et al. (29) may be related to differences in experimental design. Subjects in the current investigation were required to run at a constant speed equivalent to 80% of their individual VO2max, whereas the subjects in Williams et al. (29) were permitted to reduce the treadmill speed during a simulated 30-km performance run. Because running speed was self-regulated in the study by Williams et al. (29), it is possible that subjects were better able to control exercise related physiological and psychological stresses, which may account for the similar RPE values in the two experimental trials. Subjective ratings of perceived exertion are reflective of CNS function (2), which in turn is affected by alterations in substrate availability. It has been demonstrated that low blood glucose concentration during prolonged exercise induces CNS distress (30). However, this mechanism does not explain the RPE response evident in the current investigation, since blood glucose concentration in both the placebo and carbohydrate trials did not fall to hypoglycemic levels. Thus, some factor other than substrate availability appears to have been responsible for the significantly higher RPE values observed during the placebo run relative to the carbohydrate run.

In conclusion, the data of the present investigation suggest that the perfor-
mance of prolonged exhaustive treadmill exercise is significantly enhanced as a result of carbohydrate ingestion. This ergogenic effect appears to be mediated by elevations in blood glucose concentration. In addition, our study demonstrated that favorable blood glucose increments were paralleled by an increase in RER, which suggests that the additional blood-borne glucose provided by carbohydrate ingestion was subsequently metabolized as an energy substrate. Finally, the current investigation found that subjects perceived the effort of exhaustive treadmill exercise to be less strenuous following carbohydrate consumption.

References


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