The effects of substrate and fluid provision on thermoregulatory and metabolic responses to prolonged exercise in a hot environment

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A high ambient temperature reduces the capacity to perform prolonged exercise. Total carbohydrate oxidation is less, and thus glycogen depletion is not limiting. Fluid ingestion in the heat should, therefore, focus on maintenance of hydration status rather than on substrate provision. Six healthy males cycled to exhaustion at 60% of maximum oxygen consumption ($\dot{V}O_{2\text{max}}$) with no drink, ingestion of a 15% carbohydrate–electrolyte drink (1.45 ± 0.29 litres) or ingestion of a 2% carbohydrate–electrolyte drink (3.12 ± 0.47 litres). The ambient temperature was 30.2 ± 0.6°C (mean ± s), with a relative humidity of 71 ± 1% and an air speed of approximately 0.7 m·s$^{-1}$ on all trials. Weighted mean skin temperature, rectal temperature and heart rate were recorded and venous samples drawn for determination of plasma volume changes, blood metabolites, serum electrolytes and osmolality. Expired gas was collected to estimate rates of fuel oxidation. Exercise capacity was significantly ($P < 0.05$) different in all trials. The median (range) time to exhaustion was 70.9 min (39.4–97.4 min) in the no-drink trial, 84.0 min (62.7–145 min) in the 15% carbohydrate trial and 118 min (82.6–168 min) in the 2% carbohydrate trial. The 15% carbohydrate drink resulted in significantly ($P < 0.05$) elevated blood glucose and total carbohydrate oxidation compared with the no-drink trial. The 2% carbohydrate drink restored plasma volume to pre-exercise values by the end of exercise. No differences were observed in other thermoregulatory or cardiorespiratory responses between trials. These results suggest that fluid replacement with a large volume of a dilute carbohydrate drink is beneficial during exercise in the heat, but the precise mechanisms for the improved exercise capacity are unclear.

Keywords: exercise capacity, fluid replacement, heat stress, substrate oxidation, thermoregulation.

Introduction

Fatigue during prolonged cycle exercise of moderate intensity (70–75% of maximum oxygen consumption, $\dot{V}O_{2\text{max}}$) is generally associated with a depletion of muscle glycogen or the onset of hypoglycaemia (Ahlborg, 1967; Bergstrom et al., 1967; Bergstrom and Hultman, 1967). Furthermore, Fink et al. (1975) observed that the rate of muscle glycogen depletion was greater during exercise at 40°C than at the same power output at 9°C. These findings were supported by those of Febbraio et al. (1994), who observed a greater rate of muscle glycogen depletion during exercise at an ambient temperature of 40°C than at 20°C. In addition, we have previously shown that exercise capacity is reduced and that carbohydrate is not a limiting factor in a hot (30°C) environment compared with cooler (10°C and 20°C) environments (Galloway and Maughan, 1997). However, most studies of the effects of administering carbohydrate beverages during prolonged exercise have been conducted at around 20°C, in the absence of a large heat stress, and carbohydrate beverage composition is aimed at substrate provision rather than fluid replacement (for a review, see Coyle, 1992).

To date, the evidence suggests that carbohydrate supplementation or provision of water can delay the onset of fatigue during this type of exercise in neutral to warm environments (~20°C; Maughan et al., 1996), but neither the mechanism of action nor the optimum beverage formulation is known. In addition, few studies have looked at the effectiveness of carbohydrate
supplementation or fluid provision during exercise in the hot ambient temperatures that are often experienced by athletes in international athletic competitions (~30°C). Such temperatures are higher than those examined in most studies of carbohydrate provision and fluid replacement, but lower than the environmental temperatures that have been shown to result in altered utilization of muscle glycogen.

Studies have indicated that a solution with a carbohydrate content of 4% (40 g·l⁻¹) or more slows the rate of gastric emptying, thus limiting the rate of delivery of fluid to the intestine (Vist and Maughan, 1995). Thus, ingestion of a large volume of a solution with a low carbohydrate content may confer greater benefits than ingestion of a smaller volume of a high-carbohydrate solution during prolonged exercise, especially in the heat where dehydration may be more significant than carbohydrate depletion. Below et al. (1995) examined this hypothesis and whether water or carbohydrate alone, or in combination, would alter the cardiovascular and thermoregulatory responses to 50 min of exercise followed by a performance task in the heat (31.2°C, 54% relative humidity). Ingestion of either water or carbohydrate alone improved cycling performance in the heat and the effects were independent and additive. Below et al. also examined the effects of ingesting a large volume (1.3 litres in 50 min) or a small volume (0.2 litres in 50 min) of fluid on the exercise response. They showed that large volumes of fluid were more effective in improving performance regardless of carbohydrate content. The volumes of fluid administered by Below et al. (1995) replaced approximately 79% of fluid losses in the large fluid volume trial and approximately 13% of fluid losses in the small fluid volume trial.

The aim of the present study was to examine further the effects of beverage volume and carbohydrate provision on exercise capacity, thermoregulatory and metabolic responses to exercise in a hot environment (30°C). Ingestion of either a dilute carbohydrate-electrolyte solution that replaced approximately 150% of fluid losses (predominantly to offset hypohydration) or a solution with a high carbohydrate content that replaced approximately 100% of fluid losses (predominantly to offset substrate depletion) was compared with no fluid ingestion.

**Materials and methods**

Six healthy male volunteers were enrolled. Their mean (± s) physical characteristics were: age 27 ± 6 years, body mass 70.6 ± 5.0 kg, height 178 ± 2 cm, body surface area 1.87 ± 0.06 m², \( \dot{V}O_{2\text{max}} \) 4.07 ± 0.37 l·min⁻¹. The participants’ \( \dot{V}O_{2\text{max}} \) was recorded during an initial test session and a \( \dot{V}O_{2\text{max}} \) verification was performed a few days later. The \( \dot{V}O_{2\text{max}} \) test followed a discontinuous incremental protocol on an electrically braked cycle ergometer.

All participants were physically active, but none was specifically trained for cycling or heat acclimatized (mean daily temperature, 5 ± 3°C) at the time of the study. They all received written information concerning the nature and purpose of the study before providing written informed consent. This study was approved by the Joint Ethical Committee of Aberdeen University and Grampian Health Board.

**Experimental protocol**

Each participant completed five rides to exhaustion on an electrically braked cycle ergometer (Sensormedics, UK) at a power output corresponding to approximately 60% of \( \dot{V}O_{2\text{max}} \). These trials were carried out at an ambient dry bulb temperature of 30°C (30.2 ± 0.6°C), with a relative humidity of 71 ± 1% and an air speed of approximately 0.7 m·s⁻¹ on all trials. The first two of these tests served to familiarize the participants with the experimental protocol and with the sensation of cycling to exhaustion. These familiarization trials also allowed us to evaluate power output to ensure that an intensity corresponding to approximately 60% \( \dot{V}O_{2\text{max}} \) was attained and that the participants were able to exercise for more than 1 h. During the familiarization trials, the participants ingested flavoured water every 10 min (mass-adjusted volume of 3.57 ml·kg⁻¹). The final three rides were the experimental trials and were performed 1 or 2 weeks apart and at the same time of day. On these trials, the participants ingested either a 2% glucose-electrolyte drink (2% carbohydrate), a 15% glucose polymer–sucrose–electrolyte drink (15% carbohydrate) or were allowed no drink as a control. The composition of these drinks is shown in Table 1. The experimental conditions were administered in a crossover randomization. The participants were instructed to record their dietary intake and physical activity for 2 days before the first experimental trial; their dietary intake and physical activity were then replicated before each of the subsequent experimental trials.

For each experimental trial, the participants attended the laboratory in the morning after an overnight fast and emptied their bladder before nude body mass was measured. They then inserted a rectal thermistor 10 cm beyond the anal sphincter and rested in a sitting position for 30 min in a standardized environment (26.8 ± 0.4°C). Thermistors (Comark, Kent, UK) were attached to the chest, arm, thigh and calf for measurement of skin temperature and calculation of weighted mean skin temperature (Ramanathan, 1964); a radiotelemetry system (Sport Tester, PE3000, Polar Electro,
Kempele, Finland) was used to record heart rate. For the last 10 min of this seated rest period, one of the participant’s hands was immersed in hot (42°C) water. A venous cannula was then inserted into a lower forearm vein and two resting blood samples (6.5 ml) were obtained 5 min apart. The cannula was kept patent by a slow (~0.5 ml·min⁻¹) saline infusion on all trials. Baseline recordings of rectal and skin temperatures were made and resting heart rate recorded.

All blood samples were collected using dry syringes. For each sample, 2.5 ml were immediately dispensed into a tube containing K₃-EDTA (1.5 mg·ml⁻¹); the remaining 4 ml were dispensed into a plain tube and allowed to clot. Duplicate aliquots (100 µl) were removed from the EDTA tube and were immediately deproteinized in 1 ml of ice-cold 0.3 mmol·l⁻¹ perchloric acid (PCA), which was then centrifuged and the supernatant used to measure glucose, lactate and glycerol concentrations. The remaining blood in the EDTA tube was used for determination of haemoglobin and microhaematocrit (in triplicate). The serum obtained by centrifugation of the clotted sample was divided into two aliquots. One aliquot was immediately stored at −20°C for subsequent determination of serum free fatty acids. The second aliquot was refrigerated and used for determination of serum electrolytes (Na⁺, K⁺, Cl⁻) and serum osmolality. Blood glucose and haemoglobin concentrations and microhaematocrit were all determined within 5 h of sampling, and serum osmolality and electrolytes within 2 days. The remaining plasma, serum and PCA supernatant were frozen and stored at −20°C until analysis. All analyses were performed in duplicate.

Immediately after collection of the second resting sample, the participants transferred to a climatic chamber where they ingested a bolus of 7.14 ml·kg⁻¹ of the assigned drink and then began exercising or, if on the no-drink trial, began exercising immediately. During exercise on the trials where a drink was assigned, the participants ingested either 3.57 ml·kg⁻¹ of the 2% carbohydrate drink or 1.79 ml·kg⁻¹ of the 15% carbohydrate drink every 10 min. Volumes of fluid and carbohydrate contents were chosen deliberately to maximize either fluid or substrate provision in the largest volume possible without inducing gastrointestinal discomfort. These volumes were estimated from previous work conducted with these same participants. Before ingestion, the drinks were kept in a water bath maintained at a temperature of 14°C. The participants were asked to maintain a cadence of 60–70 rev·min⁻¹ throughout the test; exhaustion was defined as the point at which they could no longer continue or could no longer maintain a cadence above 60 rev·min⁻¹.

Blood samples (6.5 ml) were drawn during exercise at 15-min intervals and at exhaustion (immediately after the participant stopped cycling). Expired gas was collected into Douglas bags for 2 min every 15 min and immediately analysed to determine minute ventilation (V̇E), oxygen uptake (V̇O₂) and the respiratory exchange ratio; these data were used to estimate rates of fuel oxidation (Consolazio et al., 1963). Where an expired gas collection coincided with the timing of a drink, the expired gas was collected early to allow drinks to be given on schedule (e.g. for the drink scheduled at 30 min, expired air was collected from 28 to 30 min). Ratings of perceived exertion for both overall perception of exertion and for perceived exertion of the legs were made every 10 min throughout the test using the Borg scale (Borg, 1982). Perceived ratings of exertion were recorded immediately before the participants received each drink. Heart rate, skin, rectal and ambient temperatures, and relative humidity were recorded every 5 min during exercise and at exhaustion. Time to exhaustion was noted on all trials; the participants were not informed of the elapsed time at any stage during the study.

After exercise, nude body mass was measured and weight loss, corrected for fluid volume consumed and
respiratory water loss and losses due to substrate exchange (Mitchell et al., 1972), was taken as representing sweat loss. A post-exercise urine sample was then obtained to determine urine volume and urinary electrolyte losses.

**Assay methods**

Blood glucose was measured manually by the glucose oxidase method (Boehringer Mannheim Biochemica, UK). Lactate was determined using the method of Maughan (1982). Glycerol was determined using the method of Boobis and Maughan (1983). Serum free fatty acids were measured by an enzymatic colorimetric method (Boehringer Mannheim Biochemica, UK). Serum and urine Na⁺ and K⁺ were determined by flame photometry (clinical flame photometer 410 C, Corning, Halstead, UK), serum and urine osmolality by freezing point depression (Gonotec Osmomat 030, YSI Ltd, Farnborough, UK), and serum and urine Cl⁻ by potentiometric titration (chloride meter, Jenway Ltd, Dunmow, UK). Microhaematocrit and haemoglobin (cyanmethaemoglobin method) were measured on all samples for calculation of percent changes in plasma volume (Dill and Costill, 1974). All coefficients of variation calculated for blood parameters were based on duplicate determinations of 50 samples; for analysis of urine, duplicate measurements on 30 samples were used. All coefficients of variation were below 2%.

**Data analysis**

The data in the tables and text are presented as the mean ± standard deviation (s) or median (range), and in the figures as the mean ± standard error of the mean (sₓ) or median (range), as appropriate after a Shapiro-Wilks test for normality of distribution. A two-way analysis of variance for repeated measures was applied to determine any treatment or time effects during the first 60 min of the exercise protocol. After observation of a main effect, analyses of variance or Kruskal-Wallis tests were performed to determine at which times an effect was observed. Post-hoc analysis by paired t-tests or Wilcoxon tests was performed to determine which trials were significantly different. An analysis of variance was applied to identify any initial baseline differences in all variables. In all cases, significance was accepted at P < 0.05.

**Results**

The mean ambient temperature was 30.3 ± 0.2°C, 30.2 ± 0.4°C and 30.1 ± 0.3°C for the no-drink, 15% carbohydrate and 2% carbohydrate trials, respectively; no differences were observed between trials at any time. Exercise capacity (Fig. 1) was significantly (P = 0.01) affected by ingestion of the carbohydrate drinks, with a greater exercise capacity following ingestion of the carbohydrate drinks than no drink. The 2% carbohydrate drink conferred the greatest beneficial effect on exercise capacity. All trials were significantly different (P < 0.05) from each other. The 2% carbohydrate drink replaced 156 ± 49.5% and the 15% carbohydrate drink replaced 101 ± 36.8% of fluid losses incurred during exercise in the heat.

**Cardiorespiratory and fuel oxidation responses**

No differences were observed between trials in resting heart rate or in the heart rate response to exercise (Fig. 2). However, heart rate expressed as a mean value over the exercise as a whole was significantly higher (P < 0.01) during the 15% carbohydrate trial (155 ± 6 beats·min⁻¹) than the 2% carbohydrate trial (148 ± 6 beats·min⁻¹); mean heart rate was not different between the no-drink trial (152 ± 7 beats·min⁻¹) and the other two trials. No significant differences were observed between trials in the repeated measures analysis of variance. No differences were observed between trials in the V̇ₑ or V̇O₂ responses to exercise. Minute ventilation was 47.1 ± 3.8, 48.2 ± 3.2 and 47.2 ± 4.8 l·min⁻¹ at 15 min, and 53.6 ± 4.5, 52.8 ± 4.1 and 50.7 ± 4.7 l·min⁻¹ at 60 min, on the no-drink, 15% carbohydrate and 2% carbohydrate trials, respectively. Oxygen uptake was 2.36 ± 0.12, 2.40 ± 0.14 and 2.40 ± 0.16 l·min⁻¹ at 15 min, and 2.51 ± 0.19, 2.51 ± 0.16 and 2.49 ± 0.16...
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1·min⁻¹ at 60 min, on the no-drink, 15% carbohydrate and 2% carbohydrate trials, respectively.

The respiratory exchange ratio (Table 2) tended to fall throughout exercise but was not significantly different between trials. The estimated rate of carbohydrate oxidation (Table 2) fell significantly throughout exercise on the 2% carbohydrate trial, but on the 15% carbohydrate trial and no-drink trial it did not reach statistical significance. This probably reflects the shorter duration of exercise on these latter two trials, as the effect was not observed until 75 min in the 2% carbohydrate trial. No differences were observed between trials in the estimated rate of carbohydrate oxidation. The estimated rate of fat oxidation (Table 2) increased throughout exercise on all trials, but there were no significant differences between trials. However, there was a tendency for a lower rate of fat oxidation on the 15% carbohydrate compared with the no-drink trial. As a result of the differences in exercise duration between trials, significant differences were observed in total carbohydrate and total fat oxidation, with the highest total carbohydrate and fat oxidation on the 2% carbohydrate trial (Table 2). If only the first hour of exercise is considered, so as to exclude the effect of exercise time, total carbohydrate oxidation was highest on the 15% carbohydrate trial (109 ± 11 g), lowest on the no-drink trial (88 ± 15 g) and intermediate on the 2% carbohydrate trial (99 ± 12 g); all trials were significantly different from each other (P < 0.05). Fat oxidation in the first hour was lower (P < 0.01) on the 15% carbohydrate trial than on the other two trials (25 ± 6 g for the 15% carbohydrate trial; 31 ± 7 g for the no-drink trial; 32 ± 9 g for the 2% carbohydrate trial).

Thermoregulatory responses

Rectal temperature increased progressively throughout all trials, but there was no difference (P = 0.95) in rectal temperature between trials at any time during the first hour of exercise or at exhaustion (Fig. 3). The median (range) rectal temperature at exhaustion was the same on all trials in spite of differences in exercise time: 39.4°C (38.9–39.7°C) on the no-drink trial, 39.5°C (38.8–40.0°C) on the 15% carbohydrate trial, and 39.5°C (38.9–39.9°C) on the 2% carbohydrate trial. Between 60 min and exhaustion, rectal temperature rose 0.3°C in approximately 10 min on the no-drink trial, 0.2°C in approximately 24 min on the 15% carbohydrate trial, and 0.3°C in approximately 58 min on the 2% carbohydrate trial. This equates to a rate of rise in core temperature of 1.8, 0.5 and 0.3°C·h⁻¹ on the no-drink, 15% carbohydrate and 2% carbohydrate trials, respectively.

There was no difference in the weighted mean skin temperature (P = 0.26) between trials (Fig. 3). The
Table 2. Respiratory exchange ratio (RER) and estimated rates of fat and carbohydrate oxidation at 15-min intervals during the trials with no drink (ND), a 15% carbohydrate drink and a 2% carbohydrate drink (mean ± s)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Exercise time (min)</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
<th>90</th>
<th>105</th>
<th>Total oxidation (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RER</td>
<td>ND</td>
<td>0.88 ± 0.03</td>
<td>0.86 ± 0.03*</td>
<td>0.86 ± 0.02</td>
<td>0.85 ± 0.02*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(V'CO₂/V'O₂)</td>
<td>15%</td>
<td>0.90 ± 0.02</td>
<td>0.89 ± 0.02*</td>
<td>0.88 ± 0.02*</td>
<td>0.89 ± 0.03</td>
<td>0.88 ± 0.01</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2%</td>
<td>0.88 ± 0.02</td>
<td>0.88 ± 0.02*</td>
<td>0.88 ± 0.02*</td>
<td>0.87 ± 0.03</td>
<td>0.86 ± 0.02*</td>
<td>0.85 ± 0.04</td>
<td>0.85 ± 0.03*</td>
<td></td>
</tr>
<tr>
<td>Fat oxidation</td>
<td>ND</td>
<td>0.46 ± 0.14</td>
<td>0.57 ± 0.18*</td>
<td>0.56 ± 0.12*</td>
<td>0.64 ± 0.13*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>34.9 ± 12.9*</td>
</tr>
<tr>
<td>(g·min⁻¹)</td>
<td>15%</td>
<td>0.39 ± 0.10</td>
<td>0.45 ± 0.11*</td>
<td>0.49 ± 0.10*</td>
<td>0.45 ± 0.13*</td>
<td>0.51 ± 0.03</td>
<td>-</td>
<td>-</td>
<td>38.3 ± 14.4*</td>
</tr>
<tr>
<td></td>
<td>2%</td>
<td>0.45 ± 0.11</td>
<td>0.46 ± 0.12*</td>
<td>0.50 ± 0.12*</td>
<td>0.53 ± 0.16</td>
<td>0.58 ± 0.12*</td>
<td>0.64 ± 0.18</td>
<td>0.66 ± 0.14*</td>
<td>64.8 ± 22.3*</td>
</tr>
<tr>
<td>Carbohydrate oxidation</td>
<td>ND</td>
<td>1.75 ± 0.25</td>
<td>1.61 ± 0.32</td>
<td>1.68 ± 0.11</td>
<td>1.51 ± 0.19</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>102 ± 39.7*</td>
</tr>
<tr>
<td>(g·min⁻¹)</td>
<td>15%</td>
<td>1.97 ± 0.17</td>
<td>1.91 ± 0.17</td>
<td>1.83 ± 0.21</td>
<td>1.96 ± 0.23</td>
<td>1.90 ± 0.20</td>
<td>-</td>
<td>-</td>
<td>163 ± 53.3*</td>
</tr>
<tr>
<td></td>
<td>2%</td>
<td>1.82 ± 0.18</td>
<td>1.84 ± 0.19</td>
<td>1.81 ± 0.15</td>
<td>1.74 ± 0.31</td>
<td>1.65 ± 0.23*</td>
<td>1.58 ± 0.31</td>
<td>1.51 ± 0.25*</td>
<td>200 ± 60.2*</td>
</tr>
</tbody>
</table>

* Significant difference (P < 0.05) from 15-min values. **/** Significant difference (P < 0.05) from corresponding values with no drink, 15% carbohydrate and 2% carbohydrate drinks, respectively.
results appear to indicate a tendency for a lower weighted mean skin temperature response in the 2% carbohydrate trial. A significant increase in weighted mean skin temperature from resting values was observed during exercise on all trials.

The estimated mean sweat rate, assessed from body mass change and corrected for fluid volume consumed and respiratory and metabolic losses, was not significantly different between trials. The estimated mean sweat rate on the no-drink, 15% carbohydrate and 2% carbohydrate trials was $1.2 \pm 0.4$, $1.1 \pm 0.4$ and $1.1 \pm 0.31 \cdot h^{-1}$, respectively.

**Plasma volume responses**

A significant reduction in plasma volume (Fig. 4) was observed on all trials between rest and the 15-min exercise sampling time. Plasma volume then remained below resting values at all times on the no-drink and 15% carbohydrate trials. In the 2% carbohydrate trial, plasma volume was gradually restored during exercise. The reduction in plasma volume was significantly less on the 2% carbohydrate trial at all times during exercise and at exhaustion than on the no-drink and 15% carbohydrate trials.

**Serum and urine electrolyte and osmolality responses**

No differences were observed in the serum Na$^+$, K$^+$ and Cl$^-$ responses to exercise (Table 3) between the three trials. Serum Na$^+$ and Cl$^-$ concentrations remained constant at all times throughout exercise and did not change from resting values on any trial except at the last sampling time on the no-drink trial, when a significant elevation in Cl$^-$ was observed. Serum K$^+$ concentration rose significantly from resting values during exercise on all trials and remained elevated throughout. Serum osmolality (Table 3) was significantly elevated above resting values on the no-drink and 15% carbohydrate trials at all times throughout exercise. On the 2% carbohydrate trial, serum osmolality was elevated above resting values at the 15-min sampling time only, and at all subsequent sampling times was not significantly different from resting values. No difference in serum osmolality between trials was observed at any time.

Post-exercise urine Na$^+$, K$^+$ and Cl$^-$ content and urine osmolality (Table 4) were not significantly different between trials. Post-exercise urine volume was significantly ($P < 0.05$) higher after ingestion of the 2% carbohydrate drink than after the no-drink and 15% carbohydrate trials (Table 4).

**Metabolite responses**

The blood glucose concentration was significantly different ($P < 0.05$) between trials (Fig. 5). On the no-drink trial, blood glucose fell during the first 15 min of exercise and then gradually increased throughout the remainder of the test. On the 2% carbohydrate trial, an initial increase in blood glucose above rest was observed; however, this was followed by a gradual decline in concentration over the remainder of the test. On the 15% carbohydrate trial, blood glucose was significantly elevated above resting values throughout. Because of the different response patterns, blood glucose concentration was significantly lower during the no-drink trial than during the other two trials. At exhaustion, the blood glucose concentration was significantly higher on the 15% carbohydrate trial than on the other two trials. The blood lactate concentration (Fig. 5) was not different ($P = 0.53$) between trials but was significantly elevated above resting values at all sampling times during exercise on all trials.

![Fig. 4. Mean change in plasma volume during the first 60 min of exercise and at exhaustion (END) in the no-drink (ND), 15% carbohydrate (CHO) and 2% carbohydrate trials. Group mean errors are shown to indicate the variance at each sampling time. Significance levels are as indicated in Fig. 1. * Significant difference ($P < 0.05$) from resting values.](image-url)
Table 3. Serum osmolality, sodium (Na⁺), potassium (K⁺) and chloride (Cl⁻) responses at rest, during exercise and at exhaustion (End) in the trials with no drink (ND), a 15% carbohydrate drink and a 2% carbohydrate drink (mean ± s)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Rest 1</th>
<th>Rest 2</th>
<th>Exercise time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Osmolality (mosmol·kg⁻¹)</td>
<td>ND 282 ± 3</td>
<td>281 ± 4</td>
<td>288 ± 6*</td>
</tr>
<tr>
<td></td>
<td>15% 284 ± 4</td>
<td>284 ± 5</td>
<td>292 ± 5*</td>
</tr>
<tr>
<td></td>
<td>2% 285 ± 5</td>
<td>285 ± 3</td>
<td>292 ± 6*</td>
</tr>
<tr>
<td>Na⁺ (mmol·l⁻¹)</td>
<td>ND 135 ± 2</td>
<td>135 ± 1</td>
<td>137 ± 2</td>
</tr>
<tr>
<td></td>
<td>15% 136 ± 1</td>
<td>136 ± 2</td>
<td>138 ± 1</td>
</tr>
<tr>
<td></td>
<td>2% 136 ± 3</td>
<td>137 ± 3</td>
<td>138 ± 3</td>
</tr>
<tr>
<td>K⁺ (mmol·l⁻¹)</td>
<td>ND 4.6 ± 0.2</td>
<td>4.6 ± 0.2</td>
<td>5.5 ± 0.3*</td>
</tr>
<tr>
<td></td>
<td>15% 4.8 ± 0.3</td>
<td>4.8 ± 0.2</td>
<td>5.5 ± 0.3*</td>
</tr>
<tr>
<td></td>
<td>2% 4.7 ± 0.4</td>
<td>4.8 ± 0.4</td>
<td>5.3 ± 0.3*</td>
</tr>
<tr>
<td>Cl⁻ (mmol·l⁻¹)</td>
<td>ND 100 ± 2</td>
<td>99 ± 2</td>
<td>101 ± 3</td>
</tr>
<tr>
<td></td>
<td>15% 100 ± 1</td>
<td>100 ± 1</td>
<td>101 ± 1</td>
</tr>
<tr>
<td></td>
<td>2% 100 ± 2</td>
<td>99 ± 2</td>
<td>100 ± 1</td>
</tr>
</tbody>
</table>

* Significant difference (P < 0.5) from resting values.
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Table 4. Post-exercise urine osmolality, sodium (Na⁺), potassium (K⁺) and chloride (Cl⁻) content, and urine volume following the trials with no drink, a 15% carbohydrate drink and a 2% carbohydrate drink (median (range))

<table>
<thead>
<tr>
<th></th>
<th>No drink (n = 4)</th>
<th>15% CHO (n = 5)</th>
<th>2% CHO (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osmolality (mosmol·kg⁻¹)</td>
<td>801 (218–1005)</td>
<td>547 (283–836)</td>
<td>605 (127–956)</td>
</tr>
<tr>
<td>Na⁺ (mmol)</td>
<td>84 (17–141)</td>
<td>78 (34–119)</td>
<td>61 (12–113)</td>
</tr>
<tr>
<td>K⁺ (mmol)</td>
<td>57 (37–94)</td>
<td>59 (41–129)</td>
<td>79 (22–155)</td>
</tr>
<tr>
<td>Cl⁻ (mmol)</td>
<td>83 (35–186)</td>
<td>91 (61–129)</td>
<td>94 (27–216)</td>
</tr>
<tr>
<td>Volume (ml)</td>
<td>30 (0–122)c</td>
<td>52 (0–108)c</td>
<td>103 (53–174)a,b</td>
</tr>
</tbody>
</table>

Note: No urine was passed post-exercise in some trials and n-values are indicated in parentheses. a,b,c Significant difference (P < 0.05) from corresponding values with no drink, 15% carbohydrate and 2% carbohydrate drinks, respectively.

Exhaustion on the 2% carbohydrate trial, when they were not significantly different from resting values. On the no-drink trial, no significant change from resting values was observed. The blood glycerol concentration was significantly different between the no-drink and 15% carbohydrate trials at 15 and 30 min and at exhaustion. Glycerol concentration increased above resting values by 15 min on all trials and a gradual rise in concentration was observed throughout exercise on all trials. The blood glycerol concentration was significantly higher during the no-drink trial than the 15% carbohydrate trial.

Subjective responses

Overall and leg ratings of perceived exertion (RPE) increased during exercise on all trials but no significant differences were observed between trials at any time for either of these variables. The median values throughout exercise ranged from 10 to 18 for overall RPE and from 11 to 19 for leg RPE.

Discussion

The results of the present study indicate that ingestion of a large volume of a dilute glucose-electrolyte drink (2% carbohydrate), aimed primarily at rapid fluid replacement, delays the onset of fatigue when exercising at a moderate intensity in a hot (30°C) environment. A significant, but less marked, delay in the onset of fatigue was also observed when ingesting a smaller volume of a more concentrated (15% carbohydrate) drink compared with the no-drink trial.

Cardiovascular, thermoregulatory and fluid balance responses to exercise

Fluid (water) replacement has been shown to attenuate the rise in body core temperature and prevent declines in stroke volume and cardiac output during prolonged
exercise (2 h) at an ambient temperature of 20–22°C (Hamilton et al., 1991; Montain and Coyle, 1992). In addition, the provision of fluids in sufficient volume to replace mass losses attenuated the utilization of muscle glycogen over 2 h exercise at 20–22°C (Hargreaves et al., 1996). The cardiovascular and thermoregulatory benefits of water provision during exercise are thought to be the main factors resulting in a delayed onset of fatigue in hot environments (Coyle and Hamilton, 1990). Below et al. (1995) exercised participants for 50 min in a hot environment (31°C) during which they ingested either a small volume of fluid (placebo or a 200 ml drink with carbohydrate) or a large volume of fluid (fluid alone or fluid plus carbohydrate, to try and match body mass loss of 1.3 litres). Below et al. observed no difference in heart rate or core temperature response to either of the two trials in which carbohydrate was ingested compared with those in which no carbohydrate was ingested, but core temperature was 0.33 ± 0.04°C lower and heart rate 4 ± 1 beats·min⁻¹ lower on the large fluid ingestion trial than on the small fluid ingestion trial. These results clearly indicate that fluid volume rather than carbohydrate content is more important for the reduction in the core temperature and heart rate responses to exercise when carbohydrate-electrolyte drinks are ingested.

In the present study, we found no significant effect on thermoregulatory or cardiovascular variables when comparing a large fluid volume trial (2% carbohydrate, 3.1 litres) that replaced approximately 155% of fluid losses, or a relatively small fluid volume trial (15% carbohydrate, 1.5 litres) that replaced approximately 100% of fluid losses, with no fluid ingestion. However, we did observe a tendency for a lower heart rate response during exercise after ingestion of the 2% carbohydrate drink than on the 15% carbohydrate and no-drink trials, suggesting that stroke volume may have been higher in the 2% carbohydrate trial. Indeed, from the plasma volume results, it is clear that intravascular volume was maintained better when the 2% carbohydrate drink was ingested; it appears that there was an attenuation of cardiovascular drift in the 2% carbohydrate trial. The maintenance of plasma volume on the 2% carbohydrate trial may have resulted in better perfusion of active muscle tissues during exercise and may have resulted in a better maintenance of cellular hydration (Fortney et al., 1981, 1984). The similar response in blood lactate concentration between trials suggests no difference in the anaerobic contribution to exercise in the three conditions; however, this does not indicate whether there was a difference in muscle blood flow between trials. The results of Savard et al. (1988) indicate that blood flow to the working muscle is not reduced during moderate-intensity exercise under heat stress, whereas those of Gonzalez-Alonso et al. (1998) show that exercising limb perfusion may be reduced during prolonged exercise combined with heat stress and dehydration. The crucial factor when comparing these studies is that a decline in cardiac output is associated with a decline in limb blood flow. In the present study, the large fluid volume (2% carbohydrate trial) ensured better cardiovascular stability, as evidenced by the tendency for reduced cardiovascular drift, and thus cardiac output would probably be unchanged and muscle perfusion would not decline.

A reduction in weighted mean skin temperature, although not statistically significant, could indicate reduced perfusion of cutaneous circulation, but might also indicate improved evaporative cooling. Estimated mean sweat rate was not different between trials and, in the absence of a difference in environmental conditions, it is unlikely that evaporative cooling could have been greater in one trial than another. Thus, the skin temperature results indicate reduced perfusion of the cutaneous circulation, which may reflect a lower core temperature stimulus to thermoregulatory driven circulatory adjustments. This would then place less demand on the cardiovascular system to maintain cardiac output and mean arterial pressure, and skeletal muscle perfusion would be unlikely to be compromised.

It is clear from the studies cited above and the results of the present study that the absence of any significant cardiovascular or thermoregulatory benefit (lower heart rate or rectal temperature response to exercise) from fluid and carbohydrate ingestion during exercise is unusual when compared with water or no fluid. Others (e.g. Murray et al., 1989) have failed to observe a reduction in core temperature or heart rate response to exercise with fluid ingestion in a hot (33.4°C) environment. Factors other than cardiovascular, thermoregulatory or metabolic changes must, therefore, affect the capacity to perform exercise of this duration in a hot environment. Other factors are probably involved, which relate largely to improved perfusion of many areas, including exercising muscle and skin, but also non-exercising muscle, splanchnic and renal vascular beds, thus maintaining substrate supply, metabolic end-product removal and heat exchange with the environment. If any of these areas is compromised, it is possible that exercise will not continue for long.

In addition, a net increase in fluid volume with ingestion of large volumes may improve body heat storage capacity. The added net fluid gain (fluid ingestion minus sweat and urine losses throughout the trial) in the no-drink trial equated to 1.1 litres in the 15% carbohydrate trial and 2.3 litres in the 2% carbohydrate trial. This fluid volume difference in heat storage capacity, combined with the additional heat storage capacity from ingesting fluids at 14°C, and then equilibration of these
fluids with mean body temperature, has been calculated to allow as much as an additional 8.3 min of exercise in the 2% carbohydrate trial and 3.8 min of exercise in the 15% carbohydrate trial compared with the no-drink trial. These calculated improvements in exercise capacity were based on a specific heat capacity of water of 4.184 J·kg$^{-1}$·°C$^{-1}$, a mean body temperature calculated for the exercise period in each trial using 0.8:0.2 weighting of core to skin temperature (Kenney, 1998), and an estimated heat production of 650 J·s$^{-1}$. From these calculations, it can be seen that it is important to account for ingested fluid volume and temperature where small differences in exercise capacity are expected. Indeed, ingestion of large fluid volumes at 14°C may have a similar effect on heat storage capacity as pre-cooling before exercise in the heat. Gonzalez-Alonso et al. (1999) observed that pre-exercise cooling of core temperature by 1.5°C increased exercise capacity by 17 min. Pre-cooling would allow for greater heat storage but also would increase central blood volume because of peripheral vasoconstriction; both of these effects were evident in the present study. Although we observed a much greater improvement in median exercise time between trials (46.7 min between the 2% carbohydrate and no-drink trials; 13.1 min between the 15% carbohydrate and no-drink trials) than the pre-cooling study of Gonzalez-Alonso et al. (1999), we conclude that although the heat storage capacity effect was important, it was not the main factor responsible for the improved exercise capacity in the present study.

Substrate oxidation and metabolic responses to exercise

The marked elevation of blood glucose concentration in response to the ingestion of carbohydrate drinks in the present study indicates that the drinks were emptied and absorbed well. That none of the participants experienced any gastrointestinal distress during the trials tends to confirm this. Preliminary studies in our laboratory have indicated that participants are usually able to tolerate ingestion of large volumes of water but unable to tolerate ingestion of large volumes of high-carbohydrate drinks (>15% carbohydrate). This accounts for the differences in the volume of drink administered on the trials in the present study.

The lack of any difference in the rate of carbohydrate or fat oxidation between trials in the present study rules out the possibility of an effect of carbohydrate or fluid provision on substrate oxidation and, in particular, on muscle glycogen utilization. This result is in line with the conclusion of Febbraio et al. (1996), who noted that, during prolonged exercise in the heat, fatigue must be related to factors other than carbohydrate availability. Some authors have suggested that exogenous carbohydrate provided during exercise may account for a large fraction of the total carbohydrate oxidation during the latter stages of endurance exercise, when muscle glycogen content has declined to low values (Coyle et al., 1986; Murray et al., 1989). Based on the results of the present study, we are unable to support these claims; however, because we did not measure exogenous carbohydrate oxidation or muscle glycogen depletion, we cannot dismiss this possibility.

It is also clear from the pattern of response of blood glycerol and serum free fatty acids concentration during exercise that there was a marked blunting of lipolysis on the 15% carbohydrate trial, with a more moderate effect on the 2% carbohydrate trial. This effect of carbohydrate ingestion on fat mobilization has often been observed (Carlson et al., 1991) and, during prolonged exercise at this intensity, a reduction in the rate of lipolysis may result in a greater rate of glycogen degradation, which could influence exercise capacity. This was evidenced in previous studies where the availability of fat as a substrate was reduced by the administration of nicotinic acid (Kajser et al., 1978). However, despite this blunting of lipolysis, no effect on carbohydrate or fat oxidation was observed, indicating that the changes in blood-borne substrate availability did not alter overall oxidation of carbohydrate or fat by the exercising muscle.

Conclusions

The results of the present study indicate that fluid replacement in the form of a large volume of a dilute glucose–electrolyte drink (2% carbohydrate) that replaced 156 ± 49.5% of fluid losses, or a smaller volume of a concentrated carbohydrate–electrolyte drink (15% carbohydrate) that replaced 101 ± 36.8% of fluid losses, can delay the onset of fatigue during exercise in the heat compared with the ingestion of no fluids. The 2% carbohydrate drink resulted in the largest delay in onset of fatigue, indicating that fluid replacement in excess of fluid losses with a dilute carbohydrate–electrolyte drink is beneficial during exercise in the heat. This result also supports earlier research, indicating that large fluid volumes and dilute glucose–electrolyte solutions are most beneficial (Pitts et al., 1944; Maughan et al., 1996). The present results might have been influenced by the effectiveness of the 2% carbohydrate drink at restoring blood and plasma volume, attenuating cardiovascular drift and maintaining blood glucose concentration; however, such a drink does not appear to be linked with improved thermoregulation or alterations in substrate metabolism.
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References


