Effect of drink carbohydrate content on post-exercise gastric emptying, rehydration and the calculation of net fluid balance

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Running head: Carbohydrate rehydration

Abstract

The purpose of this study was to examine the gastric emptying and rehydration effects of hypotonic and hypertonic glucose-electrolyte drinks after exercise-induced dehydration. Eight healthy males lost ~1.8% body mass by intermittent cycling and rehydrated (150% of body mass loss) with a hypotonic 2% (2% trial) or a hypertonic 10% (10% trial) glucose-electrolyte drink over 60 min. Blood and urine samples were taken at pre-exercise, post-exercise, and 60, 120, 180 and 240 min post-exercise. Gastric and test drink volume were determined 15, 30, 45, 60, 90 and 120 min post-exercise. At the end of the gastric sampling period 0.3% (2% trial) and 42.1% (10% trial) (P<0.001) of the drinks remained in the stomach. Plasma volume was lower (P<0.01) and serum osmolality was greater (P<0.001) at 60 and 120 min during the 10% trial. At 240 min, 52% (2% trial) and 64% (10% trial) (P<0.001) of the drinks were retained. Net fluid balance was greater from 120 min during the 10% trial (P<0.001). When net fluid balance was corrected for the volume of fluid in the stomach, it was greater at 60 and 120 min during the 2% trial (P<0.001). These results suggest that the reduced urine output following ingestion of a hypertonic rehydration drink might be mediated by a slower rate of gastric emptying, but the slow gastric emptying of such solutions makes rehydration efficiency difficult to determine in the hours immediately after drinking, compromising the calculation of net fluid balance.

Key Words: glucose, exercise, dehydration, hypohydration

Introduction

Studies have frequently found that athletes finish exercise hypohydrated (Sawka et al., 2007), and when time availability between exercise bouts is short, fluid balance should be rapidly restored to avoid compromising subsequent exercise performance (Judelson et al., 2007).

For rapid and complete rehydration, drink volume is vital (Shirreffs, Taylor, Leiper, & Maughan, 1996); but provided drink volume is sufficient, drink composition will determine drink retention, and manipulation of sodium (Shirreffs & Maughan, 1998; Merson, Maughan, & Shirreffs, 2008), carbohydrate (Evans, Shirreffs, & Maughan, 2009a; Osterberg, Pallardy, Johnson, & Horswill, 2010) and protein (Seifert, Harmon, & DeClercq, 2006; James, Clayton, & Evans, 2011) concentration has been shown to affect rehydration.

Rehydration is composed of three inter-related processes: gastric emptying, intestinal absorption and fluid retention. Whilst one study (Mudambo, Leese, & Rennie, 1997) has suggested that gastric emptying might be slowed immediately post-exercise compared to after an overnight fast, little is known about what effects manipulating the energy or macronutrient content of drinks has on post-exercise gastric emptying. At rest, gastric emptying rate is closely related to drink energy density (Calbet & MacLean, 1997) and thus increasing drink carbohydrate concentration decreases the gastric emptying rate (Vist & Maughan, 1994). Additionally, drink osmolality can affect gastric emptying independently of carbohydrate content (Vist & Maughan, 1995). The rate of intestinal absorption is highly dependent on the rate of gastric emptying. Water uptake from the intestine is governed by osmotic gradients and the osmolality of ingested drinks, both of which determine the rate and direction of water flux (Leiper & Maughan, 1986). Shi et al. (1994) demonstrated that a hypotonic carbohydrate-electrolyte drink increased the rate of fluid absorption by 17% compared to a hypertonic carbohydrate-electrolyte drink. Similarly, Lieper and Maughan (1986) found that

perfusion of an isotonic drink into the intestine promoted fluid and electrolyte uptake from the intestine, but that perfusion of a hypertonic drink led to a net efflux of water and electrolytes into the intestinal lumen.

In situations where both post-exercise glycogen resynthesis and rehydration are required, the ingestion of hypertonic carbohydrate drinks might provide adequate carbohydrate for glycogen resynthesis whilst also providing water for rehydration. Rehydration studies have found that when a large volume of a hypotonic low sodium drink was ingested, substantial plasma volume expansion occurred, causing an acute reduction in serum osmolality and a large diuresis (Nose, Mack, Shi, & Nadel, 1988). In contrast, ingestion of a hypertonic 12% carbohydrate rehydration drink has been shown to attenuate the decline in serum osmolality, producing a less pronounced diuresis (Osterberg et al., 2010). The mechanism responsible for this effect is not fully understood, but might be related to the gastric emptying properties of the different drinks. The aim of this study was therefore to investigate the effect of hypotonic (2%) and hypertonic (10%) glucose-electrolyte drinks on gastric emptying and drink retention after exercise-induced dehydration.

Methods

After approval by the Nottingham Trent University School of Science and Technology Ethics Committee, eight males (24 (3) y, 79.5 (9.3) kg, 1.80 (0.08) m) completed a medical screening questionnaire and gave their written consent. Using the data of Evans et al. (2009a) and an alpha of 5% and a beta of 50%, it was determined that 8 subjects would be required to observe a significant difference in urine output.

Preliminary Testing

During the first preliminary visit, subjects orally inserted a 14 g gastric tube (Sonde Gastro-Duodenal Type Levin, Vygon Ltd, Cirencester, UK) and the stomach was emptied as much as possible. A recovery test was then performed, which involved instillation of 100 ml distilled water into the stomach, before the stomach contents were mixed by aspirating and re-injecting 30-50 ml of stomach contents continuously for 1 minute. Stomach contents were removed, and the gastric tube was considered to be positioned at the base of the stomach if 80-110 ml was recovered. The second visit involved an incremental exercise test on an electrically braked cycle ergometer (Excalibur Sport, Lode B.V., Groningen, Netherlands) to determine subject's peak aerobic power. Exercise started at 105 W and the intensity was increased by 35 W every 3 min until volitional fatigue. The third preliminary visit involved familiarisation with the dehydration and rehydration phases of the protocol described below, after which subjects remained in the laboratory for 1 h.

Experimental Protocol

All subjects completed two experimental trials in a randomised counterbalanced order, separated by at least 7 days. Trials commenced after an overnight fast, except 500 ml water consumed 1.5 h before arrival. In the 24 h preceding the first experimental trial, subjects recorded their dietary intake and physical activity, and repeated these dietary and physical activity patterns in the 24 h before the second experimental trial. Subjects were asked to avoid strenuous physical activity and alcohol ingestion during this 24 h.

Upon arrival at the laboratory a blood sample was obtained by venepuncture of an antecubital vein (pre-exercise), after which a urine sample was collected and body mass was measured (wearing dry boxer shorts only) (Adam CFW150; Adam Equipment Co Ltd, Milton Keynes, UK). Subjects then commenced exercise in a temperature (35 (0.2)°C) and humidity (68.4 (6.1)% relative humidity) controlled environment (Design Environmental Ltd, Ebbw Vale,

UK) until a body mass loss (BML) of 1.6% was achieved. Exercise began at an intensity of 50% peak aerobic power and subjects exercised in 10 min blocks separated by 5 min rest, during which they were weighed. After the desired BML was achieved, subjects were given 10 minutes to shower, followed by 5 min rest in a comfortable environment, before body mass was measured (wearing dry boxer shorts only) to determine the total BML.

A 21 gauge cannula was then inserted into an antecubital vein and subjects inserted the gastric tube, before a blood sample (0 min) was taken and subjects provided a urine sample. The stomach was then emptied and the recovery test was performed.

Subjects then ingested a volume of drink (l) equivalent to 150% of their total BML (kg) over a period of 1 h, in 4 aliquots of equal volume. Subjects ingested the first aliquot of drink, which contained 10 $mg \cdot l^{-1}$ phenol red dye (VWR International, Lutterworth, UK), at 0 min and had 1 min to finish the drink. Further aliquots provided at 15, 30 and 45 min, contained no phenol red, and were consumed in 1, 5 and 5 min, respectively. Drinks were made up ~1 h before consumption. Drinks contained either 2% (2% trial) or 10% (10% trial) glucose, additional sodium chloride to give a sodium concentration of ~30 $mmol \cdot l^{-1}$, and 100 $ml \cdot l^{-1}$ of sugar free squash (Table 1).

Following rehydration, subjects rested in the laboratory (24.2 (0.9)°C; 42.6 (11.0)% relative humidity) for 3 h, with urine and blood samples obtained every hour (60, 120, 180 and 240 min). If subjects needed to urinate before the hourly time point they could, except in the 15 min before each blood sample. This urine was then pooled with the urine produced at the next hourly time point. All blood samples (5 ml) were taken after at least 15 min seated in a comfortable environment. Immediately before each urine sample, subjects were asked to rate their subjective feelings of thirst, stomach fullness, bloating, hunger, tiredness, alertness, concentration, head soreness, dryness of mouth, refreshedness and energy using a 100 mm

visual analogue scale, with 0 mm representing ‘not at all’ and 100 mm representing ‘very’. Additional questions using 100 mm visual analogues scale on sweetness, saltiness, bitterness and pleasantness of drinks were asked at 60 min.

Gastric Sampling

Gastric volume was measured using double sampling gastric aspiration (Beckers, Rehrer, Brouns, Ten Hoor, & Saris, 1988). A sample of the initial aliquot of drink was retained for analysis. Following ingestion of the initial aliquot of drink, the stomach contents were mixed as previously described and a sample (2.5 ml) was retained. At each sampling point, the stomach contents were mixed, before a sample (2.5 ml) was aspirated. Five ml of phenol red solution was then added to the stomach, and the stomach contents were mixed again before a further sample (2.5 ml) was taken. Gastric and drink volume were calculated from changes in phenol red concentrations. Gastric samples were also obtained after each drink had been ingested, to calculate the dilution of dye concentration at each drinking point.

Gastric volume was measured at 15, 30, 45, 60, 90 and 120 min. The concentration of the phenol red in the 5 ml aliquot added to the stomach was 0.5 $g \cdot l^{-1}$ at 15, 30, 45 and 60 min and 1 $g \cdot l^{-1}$ at 90 and 120 min.

Calculations

Net fluid balance (NFB) was calculated from sweat losses during exercise, estimated from BML (kg), drink volume ingested during rehydration (ml) (D) and cumulative urine output (ml) (U) (Maughan, Shirreffs, & Leiper, 2007).

$$NFB_n = 0 - (BML*1000) + D - U$$

Corrected net fluid balance was calculated to account for the volume of fluid remaining in the stomach (GV).

Corrected $NFB_n = NFB_n - GV_n$

Sample Analysis

Of each blood sample, 1.3 ml was mixed with EDTA (1.75 $mg \cdot l^{-1}$) and placed in ice, before plasma was separated by centrifugation (3000 g, 10 min, 3°C). A further 1.3 ml blood was mixed with EDTA (1.75 $mg \cdot l^{-1}$) and was used for analysis of hemoglobin by the cyanmethemoglobin method and hematocrit by microcentrifugation. Hemoglobin and hematocrit values were used to estimate changes in blood, red cell and plasma volume, relative to pre-exercise (Dill & Cositll, 1974). The remainder of the blood sample was allowed to clot, before serum was separated by centrifugation (3000 g, 10 min, 3°C). Serum was analyzed for osmolality by freezing point depression (Gonotec Osmomat 030 Cryoscopic Osmomter; Gonotec, Berlin, Germany), whilst plasma was stored at -80°C and analyzed for glucose concentration by the glucose oxidase peroxidase amino antipyrine phenol method (Randox Daytona, Randox, Crumlin, UK).

Volume and osmolality were determined for each urine sample. Drink samples were analysed for osmolality, as well as sodium and potassium concentration by flame photometry (Corning Clinical Flame Photometer 410C; Corning Limited, Essex, UK).

Phenol red concentrations in gastric aspirates and drink samples were analyzed by spectrophotometry after dilution (1:20) with NaOH-$NaHCO_3$ (200:500 $mmol \cdot l^{-1}$) buffer.

Statistical Analysis

Data was analyzed using SPSS 18.0 (Chicago, IL, USA). All data were checked for normality of distribution using a Shapiro-Wilk test. Data containing two factors were then analyzed using two-way repeated measures ANOVA. Significant differences were located using Bonferroni adjusted paired t-tests for normally distributed data or Bonferroni-adjusted

Wilcoxon signed-ranked tests for non-normally distributed data. Data containing one factor were analyzed using paired t-tests or Wilcoxon signed-ranks tests as appropriate. Differences were considered significant at $P \leq 0.05$. Normally distributed data are presented as means (SD), while non-normally distributed data are presented as median (range).

Results

There was no difference in any of the measured pre-exercise variables (Table 2a) or any of the variables measured during exercise (Table 2b) or rehydration (Table 2c).

Gastric volumes

Residual gastric volume was 30 (8-117) ml and was not different between trials (P=0.607). Total gastric volume (Fig. 1a) was greater during the 10% trial than during the 2% trial from 15 min after ingestion of the initial bolus of test drink until 120 min (P<0.001). The volume of drink remaining in the stomach (Fig. 1b) followed the same pattern, and the volume of drink present in the stomach at the end of the gastric sampling period was 7 (5) ml (2% trial) and 893 (175) ml (10% trial) (P<0.001), representing 0.3 (0.2)% (2% trial) and 42.1 (6.6)% (10% trial) of the total drink volume ingested. The mean volume of gastric secretions present in the stomach at each time point was greater after ingestion of 10% drink (79 (36) ml) compared to the 2% drink (40 (5) ml) (P=0.005).

Urine output, osmolality, drink retention and net fluid balance

Urine output (Fig. 2) showed main effects of trial (P=0.001), time (P<0.001) and trial x time interaction (P=0.005). Urine output was greater at 60 min (P=0.046) and 120 min (P=0.005) on the 2% trial compared to the 10% trial. Total urine output after drinking was greater

during the 2% trial (1025 (219) ml) compared to the 10% trial (746 (210) ml) (P=0.003), therefore a greater amount of the 10% drink was retained (64 (11)% vs. 52 (10)%) (P<0.001).

The dehydration phase of the experiment increased urine osmolality (Table 3a) compared to pre-exercise during both trials (P<0.001). Urine osmolality was greater during the 10% trial than during the 2% trial 60 min after exercise (P=0.015). Additionally, urine osmolality at 120 min was lower than pre-exercise during the 2% trial (P=0.002) and tended to be lower during the 10% trial (P=0.054).

Whole body net fluid balance (Fig. 3) was significantly negative on both trials (P<0.001) at the end of exercise (0 min) and had become significantly positive on both trials at the end of rehydration (60 min) (P<0.001). From the end of rehydration, net fluid balance declined during both trials, but was only significantly negative compared with pre-exercise during the 2% trial from 180 min onwards (P<0.003). Whole body net fluid balance was also greater during the 10% trial compared to the 2% trial from 120 min onwards (P<0.003).

Corrected net fluid balance (Fig. 3, dashed lines) was calculated to account for volumes of fluid that remained in the stomach and was significantly more negative at 60 and 120 min during the 10% trial compared to the 2% trial (P<0.001). Corrected net fluid balance was significantly lower than pre-exercise at 0 min during the 2% trial (P<0.005), and at 0, 60 and 120 min during the 10% trial (P<0.01).

Plasma volume and serum osmolality

Exercise induced a similar reduction in plasma volume (Table 3b) between trials (P=0.385). Plasma volume was greater during the 2% trial than during the 10% trial at 60 and 120 min (P<0.01). Compared to pre-exercise, plasma volume was reduced at 0 min during the 2% trial (P=0.001) and at 0 and 60 min during the 10% trial (P<0.01) and was greater than pre-

exercise from 60 to 120 min (P<0.05) during the 2% trial. The estimated change in blood volume mirrored those of plasma volume, whilst there was no change in red cell volume (P>0.05).

Serum osmolality (Table 3c) was greater during the 10% trial than during the 2% trial at 60 and 120 min post-exercise (P<0.01). Additionally, serum osmolality was greater than pre-exercise at 0 min during the 2% trial (P=0.017) and at 60 min during the 10% trial (P=0.001), and was lower than pre-exercise at 120, 180 and 240 min during the 2% trial (P<0.01).

Plasma glucose concentration

Pre-exercise plasma glucose concentration (Table 3d) was not different between trials (P=0.412), but was greater during the 10% trial compared to the 2% trial at 120 and 180 min (P<0.05). Compared to pre-exercise, plasma glucose concentration at 60 min was increased during the 2% trial (P=0.016) and tended to be increased during the 10% trial (P=0.064) and at 180 min was decreased during the 2% trial (P=0.030).

Subjective feelings questionnaires

There was a main effect of trial for stomach fullness (P<0.001) (Fig. 4a), bloatedness (P<0.001) (Fig. 4b) and hunger (P=0.002) (Fig. 4c), with these subjective feelings greater during the 10% trial compared to during the 2% trial from 60 min onwards (P<0.01). There were significant main effects of time for subjective feelings of thirst (P<0.001), stomach fullness (P<0.001), bloatedness (P<0.001), hunger (P<0.001) and dryness of mouth (P<0.001). At the end of the rehydration period, the 10% glucose drink was perceived to be more sweet (P=0.002), and tended to be perceived as more bitter (P=0.058) than the 2% glucose drink, but there was no difference in the perceived saltiness (P=0.409) or pleasantness (P=0.147) of the drinks.

Discussion

The results of this investigation demonstrate that following exercise-induced dehydration, a hypertonic 10% glucose-electrolyte drink emptied from the stomach at a slower rate, led to a slower restoration of plasma volume and over the duration of this study resulted in a reduced urine output compared to a hypotonic 2% glucose-electrolyte drink, when a volume of 150% of BML was ingested.

Post-exercise nutritional requirements are often multifactorial in nature and following dehydrating endurance exercise, rehydration as well as resynthesis of glycogen stores is likely to be required. For maximal resynthesis of muscle glycogen a carbohydrate ingestion rate of ~1.2 $g \cdot kg^{-1} \cdot h^{-1}$ is required (Betts & Williams, 2010). When rehydration is also required, carbohydrate based drinks provide carbohydrate for muscle glycogen resynthesis, as well as water for rehydration. Evans, Maughan, and Shirreffs (2009b) reported that following cycling exercise in the heat, similar amounts of a 2% glucose drink (2539 (436) ml) and 10% glucose drink (2173 (252) ml) were ingested over a 2 h rehydration period. In their subjects, this equated to carbohydrate ingestion rates of ~0.3 $g \cdot kg^{-1} \cdot h^{-1}$ and 1.4 $g \cdot kg^{-1} \cdot h^{-1}$ with the 2% and 10% glucose drinks, respectively (Evans et al., 2009b). This suggests that hypertonic carbohydrate drinks might help facilitate post-exercise muscle glycogen resynthesis and rehydration in situations where both are required and food is not consumed.

It is generally accepted that in order to achieve complete rehydration after exercise, it is necessary to consume a volume of fluid in excess of that lost to account for on-going water losses through sweat and urine production (Mitchell, Grandjean, Pizza, Starling, & Holtz, 1991; Shirreffs et al., 1996). As long as a sufficient volume of a rehydration drink is consumed, the rate of ingestion (Jones, Bishop, Green, & Richardson, 2010) and the

composition (Shirreffs & Maughan, 1998; Seifert et al., 2006; Merson et al., 2008; Evans et al., 2009a; Osterberg et al., 2010; James et al., 2011) of the drink determine how well the drink is retained. The addition of electrolytes, specifically sodium, has been shown to increase the fraction of the ingested drink that is retained (Shirreffs & Maughan, 1998), and more recent investigations have shown that increasing the carbohydrate content of a rehydration drink resulted in an increased drink retention (Osterberg et al., 2010). The results of the present study are in line with these findings, as despite consuming a similar volume of rehydration drink on each trial, total urine output was 278 (175) ml greater during the 2% trial compared to the 10% trial, and at the end of the study, whole body net fluid balance was more negative during the 2% trial. These studies have investigated the effects of mild hypohydration (~2% body mass loss) at level commonly reported in an applied setting (Sawka et al., 2007), but it remains to be seen whether these effects remain at higher levels of hypohydration. Furthermore, the difference in fluid balance between the trials of the present study (~0.3% body mass) and that of other rehydration studies (<1% body mass) is unlikely to have any effect on exercise performance (Sawka et al., 2007). At present post-exercise rehydration has only been investigated in response to a one off acute bout of dehydrating exercise and it remains to be seen whether training athletes might accrue significant levels of hypohydration over multiple training sessions sufficient to impair performance.

The reduced total urine output observed during the 10% trial is likely due to acute changes in circulating arginine vasopressin (AVP) concentration. Plasma osmolality has been shown to have a profound effect on concentrations of AVP, with linear regression analysis showing AVP concentrations change by 0.41 $pmol \cdot l^{-1}$ per 1 $mosmol \cdot kg^{-1}$ change in plasma osmolality (Bayliss, 1987). Serum osmolality was lower during the 2% trial than during the 10% trial at 60 and 120 min, and consequently urine output at these time points was greater during the 2% trial. This suggests that the greater total urine output during the 2% trial, was likely due to

lower concentrations of circulating AVP, particularly during the first 2 h after ingestion of the initial bolus of test drink.

Changes in blood and plasma volume can also have an influence on drink retention, and the carbohydrate concentration of rehydration drinks has been observed to affect plasma volume response (Evans et al., 2009a; Evans et al., 2011). Evans, Shirreffs, and Maughan (2009c) demonstrated that ingestion of a hypertonic drink causes a reduction in plasma volume, whereas ingestion of a hypotonic drink results in the expansion of plasma volume. Previous investigations have demonstrated that hypotonic drinks are quickly absorbed in the small intestine, resulting in a rapid appearance in the extracellular fluid (Hunt, Elliott, Fairclough, Clark, & Farthing, 1992; Shi et al., 1994), whereas hypertonic drinks cause a transient secretion of water into the intestinal lumen to establish an osmotic gradient suitable for fluid uptake from the intestine (Leiper & Maughan, 1986). The present study supports these findings, as compared to pre-exercise, plasma volume immediately after rehydration was reduced during the 10% trial (-5.9 (2.8)%), but was increased during the 2% trial (+6.7 (2.7)%). This suggests that during the 10% trial, water may have moved into the intestinal lumen to reduce the osmolality of the drink, temporarily delaying the restoration of plasma volume. This likely resulted in an increased serum osmolality, which would be expected to result in an increase in AVP concentration and an attenuation of the diuretic response. In contrast, the hypotonic drink appeared rapidly in the extracellular fluid, reduced serum osmolality and stimulated a greater diuretic response.

Whilst the data for whole body net fluid balance suggest that restoration of fluid balance was enhanced following ingestion the 10% glucose-electrolyte drink compared to a 2% glucose-electrolyte drink, the determination of corrected net fluid balance which takes into account the volume of fluid in the stomach shows that this is not the case, at least for the 2 hours after exercise (Fig. 3). The finding that 42.1 (6.6) % of the 10% drink remained in the stomach 120

min after exercise suggests that some drink was likely to still be present in the stomach and/or intestines at 180 and 240 min and that whole body net fluid balance is likely over estimated at these time points in the 10% trial. Although gastric volume is a powerful regulator of gastric emptying, the rate of gastric emptying of hypertonic solutions appears to be relatively linear (Vist & Maughan, 1995; Maughan, Leiper, & Vist, 2004; Evans, Shirreffs, & Maughan, 2011), at least when gastric volume is greater than 400 ml. In the present study, gastric volume decreased in a linear manner between 60 and 120 min (r^2=0.997). Using the rate of gastric emptying of the hypertonic drink between 60 and 120 min for each individual subject and assuming that gastric emptying remained linear, it would have taken an estimated 249 (54) min for the 10% drink to completely empty from the subjects' stomach. This is still likely to be an overestimate of how quickly the 10% drink emptied from the stomach as the rate of gastric emptying of a solution is well known to decrease exponentially as gastric volume decreases (Vist & Maughan, 1994; Vist & Maughan, 1995). The data demonstrate that although a hypertonic 10% glucose-electrolyte drink reduced urine output after drinking compared to a hypotonic 2% glucose-electrolyte solution, whether this infers enhanced fluid balance is questionable as a large proportion of drink remained in the gastrointestinal tract for several hours after drinking.

The rate of gastric emptying and intestinal absorption of ingested drinks are essential for the maintenance of plasma volume and a prompt return to euhydration (Leiper, 1998). It is currently recommended that after exercise, a volume in excess of BML is consumed to ensure complete rehydration (Sawka et al., 2007). Evidence suggests that slightly hypotonic drinks are ideal in situations when swift replacement of fluid losses is desirable, as rapid gastric emptying and intestinal absorption mean that ingested fluid reaches the peripheral circulation quickly to restore plasma volume (Leiper & Maughan, 1986; Hunt et al., 1992). However, when large volumes of drink are consumed, substantial plasma volume expansion is likely,

which results in an acute reduction in serum osmolality and consequently a reduction in AVP concentration, causing a large diuresis (Nose et al., 1988), unless a high concentration of sodium is present (Shirreffs & Maughan, 1998). In contrast, ingestion of large volumes of hypertonic drinks is likely to cause an efflux of water into the intestinal lumen, leading to a delayed restoration of plasma volume and the maintenance of serum osmolality (Evans et al., 2009c), which might attenuate the decline in AVP concentration and reduce the observed diuresis. The results of the current study suggest that the short-term reduction in urine output observed when a hypertonic carbohydrate drink was ingested after exercise-induced dehydration might be mediated by a reduced rate of gastric emptying. Given that a proportion of a hypertonic solution will remain in the gastrointestinal tract for some time after drinking, this reduced urine output does not necessarily imply enhanced rehydration. Evans et al. (2011) have recently shown that following repeated ingestion of a 10% hypertonic glucose-electrolyte drink after an overnight fast, gastric emptying and fluid uptake were slower than following ingestion of a 2% hypotonic glucose-electrolyte drink. The results of the present investigation are consistent with these findings, as the volume of test drink remaining in the stomach was greater during the 10% trial compared to the 2% trial from 15 min after ingestion until the end of the gastric sampling period, and this reduced the rate of fluid uptake.

Rate of gastric emptying is an important consideration for rehydration drinks (Leiper, 1998). Results of the current study confirm that if the aim of rehydration is rapid fluid replacement, hypotonic drinks should be consumed, as they are quickly emptied from the stomach, leading to a rapid appearance in the extracellular fluid. However, this leads to an acute decrease in serum osmolality and stimulates diuresis (Nose et al., 1988). Although hypertonic glucose-electrolyte drinks decrease total urine output after rehydration (Osterberg et al., 2010), the location of the fluid is an important consideration. Gastric emptying has been identified as the

main reason for the reduced rate of fluid uptake (Evans et al., 2011), so therefore by monitoring the rate of gastric emptying in the current study an estimate was formulated as to how much of the drink remained in the stomach. Corrected net fluid balance (Fig. 3) was calculated to account for the volume of test drink remaining in the stomach at each sampling point. Whilst fluid remains in the stomach, it is not contributing to rehydration, so assessing net fluid balance by conventional methods may be impractical. Corrected net fluid balance gives a much clearer perspective of how much of the ingested drink is available for restoration of body water loss. Although it must be noted that the volume of drink contained within the intestines could not be determined during the present investigation. As shown in Figure 3, corrected net fluid balance did not become positive over the 120 min after the onset of drinking and given the slow rate of gastric emptying of the 10% drink, it is unlikely that corrected net fluid balance would have become positive at any time point during the 10% trial. In contrast, during the 2% trial, corrected net fluid balance became positive immediately after rehydration (60 min). It should also be noted that ingestion of hypertonic drinks could lead to the secretion of water into the intestinal lumen, delaying plasma volume restoration, which may not be considered ideal in situations where rapid restoration of plasma volume and rehydration is the main objective. Furthermore, ingestion of the 10% drink resulted in greater subjective feelings of bloating, stomach fullness and reduced feeling of hunger. In a practical setting, where *ad libitum* drink ingestion will take place, this may lead to the cessation of drinking before a positive net fluid balance has been attained, although a recent study found no differences in *ad libitum* drink ingestion between 0, 2 and 10% glucose-electrolyte drinks (Evans et al., 2009c).

In conclusion, compared to the ingestion of a hypotonic 2% glucose-electrolyte drink, ingestion of a hypertonic 10% glucose-electrolyte drink after exercise-induced dehydration resulted in a slower rate of gastric emptying and a reduction in total urine output after

drinking. It appears that the delayed rate of gastric emptying of the hypertonic glucose-electrolyte drink might explain the increased drink retention observed in this and previous experiments. The delayed rate of gastric emptying of the 10% glucose-electrolyte drink augmented a slower recovery of plasma volume, consequently attenuating the decline in serum osmolality and reducing urine output in the 2 h after the onset of drink ingestion. However, whilst ingestion of a large volume of a hypertonic 10% glucose-electrolyte drink resulted in an acute reduction in urine output compared to a hypotonic 2% glucose-electrolyte drink, the location of the fluid retained needs to be given careful consideration when determining net fluid balance. The slower rate of gastric emptying of hypertonic drinks means ingestion of such drinks in situations where recovery periods are short (2-3 h) might not be appropriate.

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Table 1. Composition of test drinks. Values are means (SD).

	2% drink	10% drink
Energy ($kJ \cdot l^{-1}$)	400	1760
Osmolality ($mosmol \cdot kg^{-1}$)	193 (2)	656 (3)
Carbohydrate ($g \cdot l^{-1}$)	20	100
Sodium ($mmol \cdot l^{-1}$)	29 (0)	29 (0)
Potassium ($mmol \cdot l^{-1}$)	0.4 (0.1)	0.4 (0.1)

Table 2. Pre-exercise variables (a), exercise variables (b) and rehydration variables (c). Values are means (SD).

	2% Trial	10% Trial	*P* value
a) Pre-trial variables			
Body mass (kg)	79.5 (9.3)	79.4 (8.9)	0.808
Serum osmolality (mosmol·kg^{-1})	290 (4)	290 (4)	0.931
Urine osmolality (mosmol·kg^{-1})	377 (175)	414 (216)	0.248
b) Exercise variables			
Body mass loss (%)	1.8 (0.1)	1.8 (0.1)	0.280
Workload (W)	142 (18)	142 (16)	0.871
Exercise time (min)	57 (6)	57 (7)	0.624
Heat exposure (min)	87 (11)	89 (10)	0.625
c) Rehydration variables			
Drink volume (ml)	2129 (171)	2108 (188)	0.332
Drink temperature (°C)	20 (1)	20 (1)	0.600

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525**Table 3.** Urine osmolality (mosmol·kg^{-1}) (a), change in plasma volume relative to pre-
526exercise (%) (b), serum osmolality (mosmol·kg^{-1}) (c) and blood glucose (mmol·l^{-1}) (d) at each
527hour after exercise. Values are means (SD).

		Time after exercise (min)				
	Pre-exercise	0	60	120	180	240
a) Urine Osmolality (mosmol·kg^{-1})						
2%	377 (175)	770 (115) ‡	383 (236) *	81 (50) ‡	315 (219)	634 (242)
10%	414 (216)	770 (93) †	554 (237)	192 (226)	297 (239)	436 (305)
b) Change in plasma volume (%)						
2%	0 (0)	-3.8 (2.2) ‡	6.7 (2.7) ‡ *	4.2 (2.0) ‡ *	2.5 (3.0)	2.5 (2.1)
10%	0 (0)	-4.3 (2.0) †	-5.9 (2.8) †	-1.9 (4.3)	-1.3 (4.7)	3.3 (3.8)
c) Serum Osmolality (mosmol·kg^{-1})						

2%	290 (4)	294 (4) ‡	287 (5) *	285 (4) ‡ *	284 (5) ‡	286 (3) ‡
10%	290 (4)	292 (4)	296 (4) †	292 (4)	287 (3)	286 (3)
d) Blood Glucose (mmol·l^{-1})						
2%	5.1 (0.7)	4.8 (0.3)	7.7 (1.5) ‡	4.1 (0.4) *	4.1 (0.3) ‡ *	4.3 (0.2)
10%	4.9 (0.3)	4.9 (0.6)	8.4 (3.1)	6.3 (2.1)	5.7 (1.2)	4.4 (0.8)

* mean values were different between trials (P<0.05). ‡ 2% trial different to pre-exercise (P<0.05). † 10% trial different to pre-exercise (P<0.05).

Figure legends

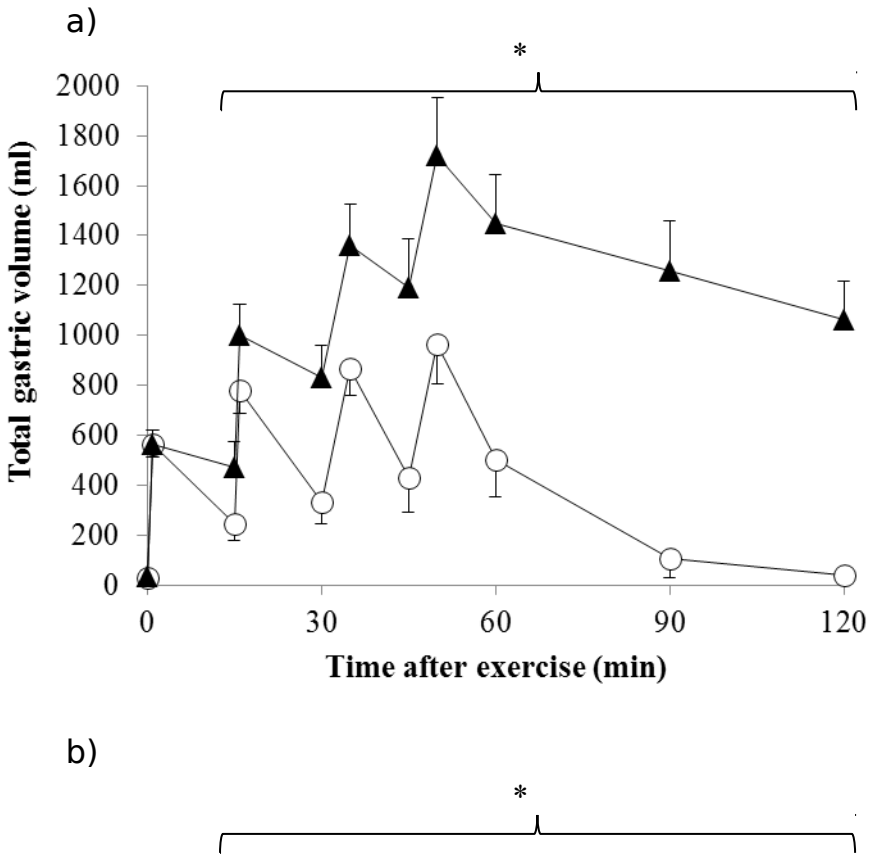
Fig. 1. Total volume of fluid in the stomach (ml) (a) and the total volume of drink in the stomach (ml) (b) during the 2% (○) and 10% (▲) trials. * mean values were different between trials (P<0.05). Points are mean values with vertical error bars representing standard deviations.

Fig. 2. Urine output (ml) at each hour after exercise during the 2% (○) and 10% (▲) trials. * mean values were different between trials (P<0.05). ‡ 2% trial different to 0 min (P<0.05). † 10% trial different to 0 min (P<0.05). Points are mean values with vertical error bars representing standard deviations.

Fig. 3. Net fluid balance (ml) during the 2% (○) and 10% (▲) trials, as well as when corrected for volume of drink in the stomach during the 2% (●) and 10% (Δ) trials. * mean values for net fluid balance different between trials (P<0.05). ‡ 2% trial different to pre-exercise for net fluid balance (P<0.05). † 10% trial different to pre-exercise for net fluid balance (P<0.05). # mean values for corrected net fluid balance different between trials (P<0.05). § 10% trial for corrected net fluid balance different to pre-exercise (P<0.05). Points are mean values with vertical error bars representing standard deviations.

Fig. 4. Subjective feelings (mm) of stomach fullness (a), bloating (b) and hunger (c) during the 2% (○) and 10% (▲) trials. * mean values different between trials (P<0.05). ‡ 2% trial different to pre-exercise (P<0.05). † 10% trial different to pre-exercise (P<0.05). Points are median values.

Figure 1.



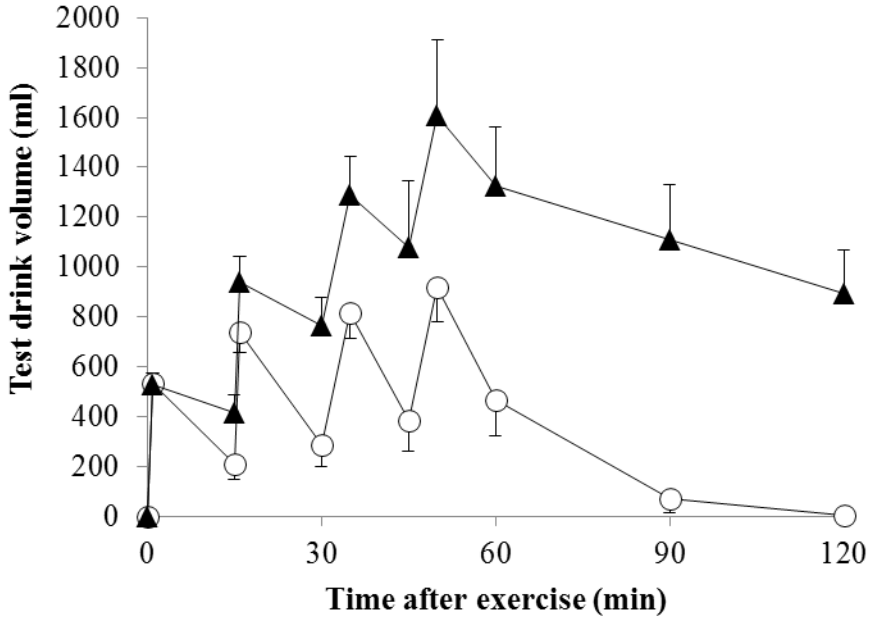

Test drink volume (ml)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
30
60
90
120
Time after exercise (min)

Figure 2.

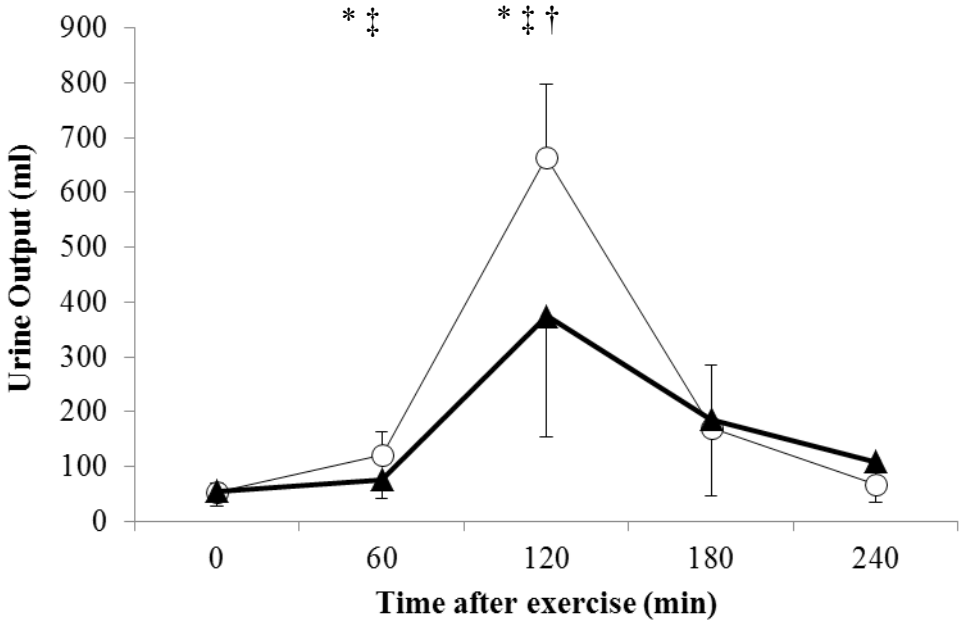

* ‡
* ‡ †
Urine Output (ml)
900
800
700
600
500
400
300
200
100
0
0
60
120
180
240
Time after exercise (min)

Figure 3.

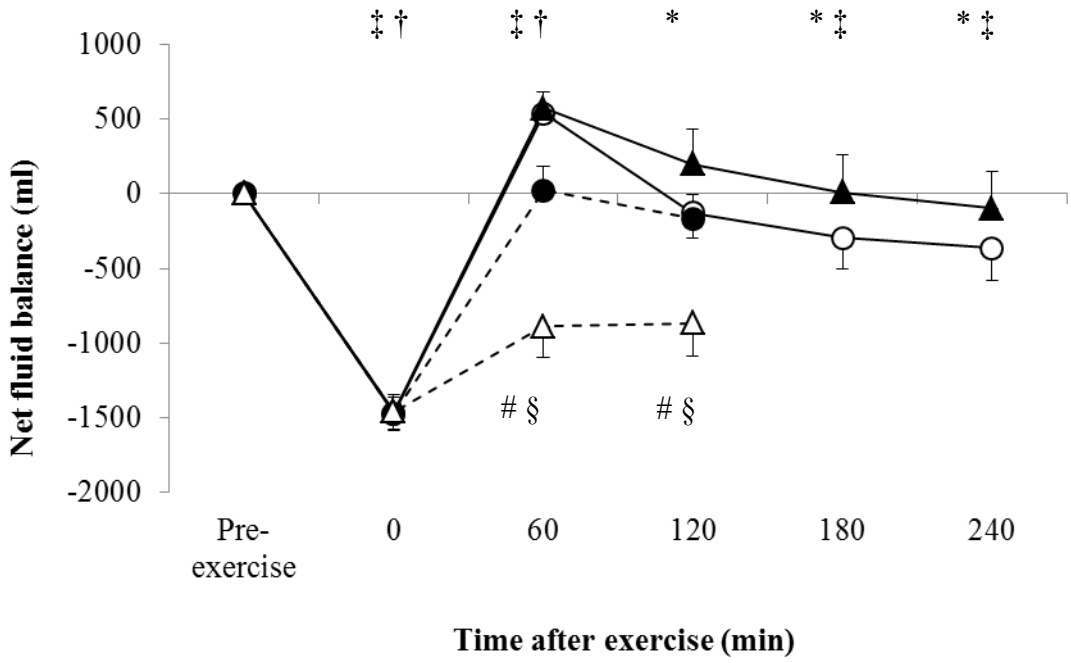
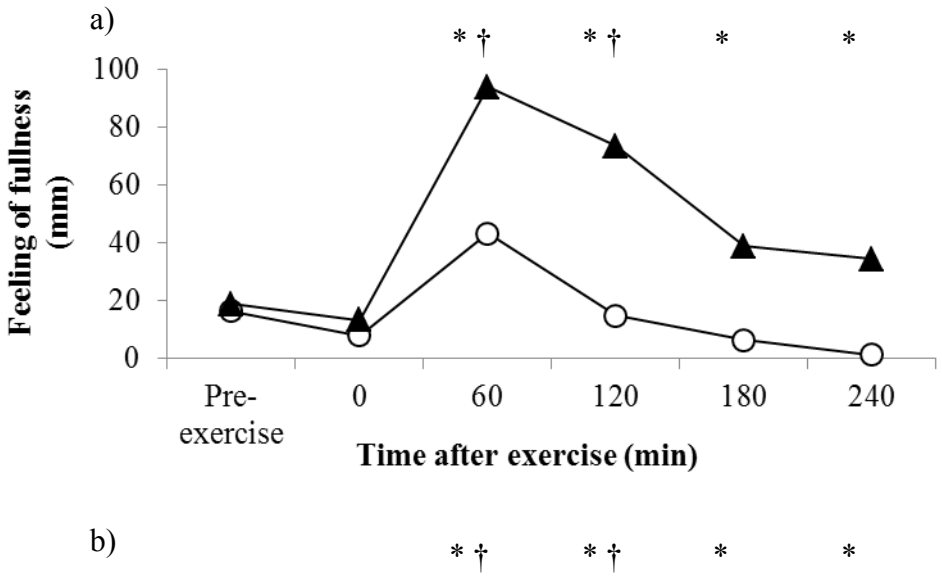
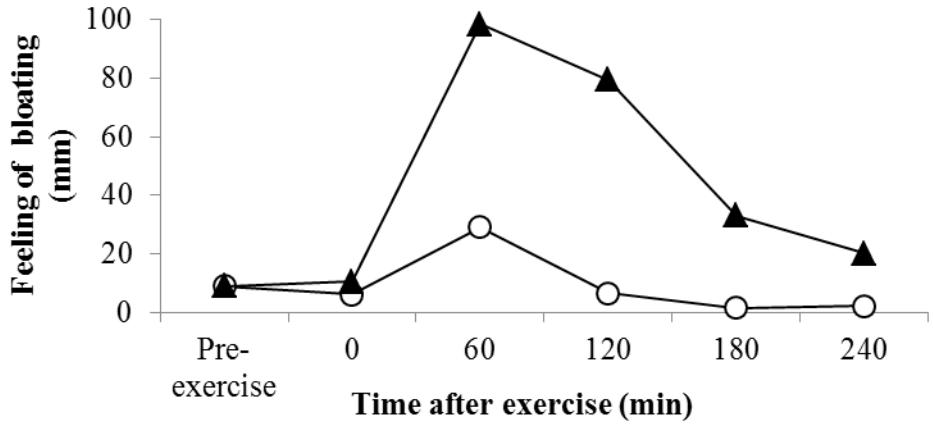
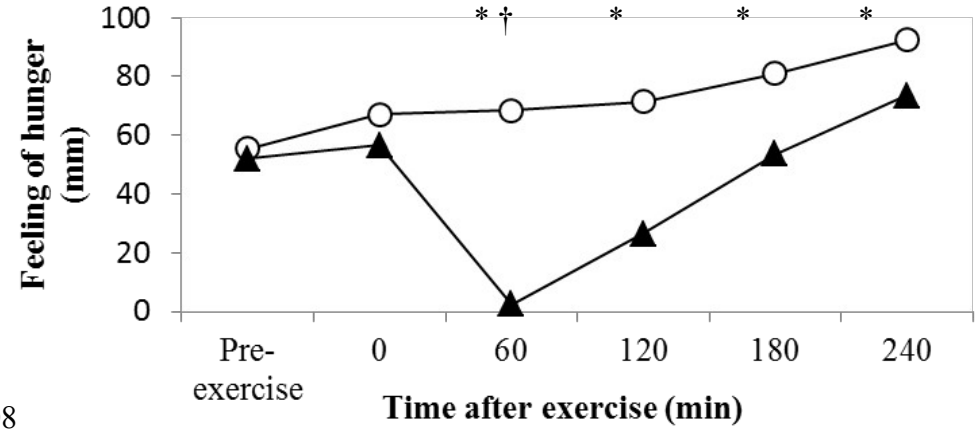

‡ †
‡ †
*
* ‡
* ‡
1000
500
0
-500
-1000
-1500
-2000
Net fluid balance (ml)
§
§
Pre-exercise
0
60
120
180
240
Time after exercise (min)

Figure 4.


a)
* †
* †
*
*
100
80
60
40
20
0
Feeling of fullness (mm)
Pre-exercise
0
60
120
180
240
Time after exercise (min)
b)
* †
* †
*
*


Feeling of bloating (mm)
100
80
60
40
20
0
Pre-exercise
0
60
120
180
240
Time after exercise (min)

c)


Feeling of hunger (mm)
100
80
60
40
20
0
* †
*
*
*
Pre-exercise
0
60
120
180
240
Time after exercise (min)