

Applied nutritional investigation

Postexercise rehydration in man: The effects of osmolality and carbohydrate content of ingested drinks

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Abstract

Objective: This study investigated the effect of the osmolality and carbohydrate content of drinks on their rehydration effectiveness after exercise-induced dehydration.

Methods: Six healthy male volunteers were dehydrated by $1.9 \pm 0.1\%$ of body mass by intermittent cycle ergometer exercise in the heat before ingesting one of three solutions with different carbohydrate contents and osmolalities over a period of 1 h. Thirty minutes after the cessation of exercise, subjects drank a volume that amounted to 150% (130–150, median [range]) of their body mass loss. Drinks contained 25 mmol/L Na^+ and 0%, 2%, or 10% glucose with osmolalities of (mean $\pm$ SD) 79 ± 4 , 193 ± 5 , and 667 ± 12 mosm/kg, respectively. Blood and urine samples were collected before exercise, after exercise, and 0, 1, 2, 3, 4, and 6 h after the end of the rehydration period.

Results: Significantly more of the ingested fluid was retained in the 10% trial ($46 \pm 9\%$) than in the 0% trial ($27 \pm 13\%$), with $40 \pm 14\%$ retained in the 2% trial. Subjects remained euhydrated for 1 h longer in the 10% glucose trial than in the 2% glucose trial. In the 2% glucose trial, plasma volume was elevated immediately after and 1 h after rehydration.

Conclusion: This study suggests that, following the rehydration protocol used, hypertonic glucose-sodium drinks may be more effective at restoring and maintaining hydration status after sweat loss than more dilute solutions when the sodium concentration is comparable. © 2009 Published by Elsevier Inc.

Keywords:

Dehydration; Fluid balance; Solution osmolality; Fluid retention; Urine production

Introduction

The loss of body water that occurs as a consequence of sweat loss during prolonged exercise is at least partly responsible for the progressive development of fatigue that eventually leads to the cessation of exercise in the heat [1–3]. Hypohydration is common after exercise that promotes large volumes of sweat loss, because the volume of fluid consumed during exercise is typically less than the volume of sweat lost [4]. Water and electrolytes lost during exercise should be replaced promptly in the postexercise period if a further bout of exercise is to be performed soon after.

Investigations that have systematically examined the effect of different drink volumes on the efficacy of postexercise

rehydration have observed that a volume of fluid greater than that of body mass loss is necessary to restore fluid balance after hypohydration induced by exercise [5,6]. The additional volume is necessary to account for ongoing renal and other water losses, but ingestion of large volumes over a short period provokes a diuretic response. Therefore, if a drink volume greater than that of body mass lost is to be consumed after exercise, the composition of the rehydration beverage is important to avoid a diuresis and to maintain an adequate hydration state.

It is well established that the sodium content of an ingested solution has a key role in postexercise rehydration. Shirreffs et al. [7] showed that a drink containing sodium at a concentration of 100 mmol/L was more effective, in terms of maintaining whole-body fluid balance, than drinks containing 0, 25, or 50 mmol/L of sodium after exercise when a volume greater than body mass lost was ingested. This was due to a lower urine output after ingestion of the 100-mmol/L sodium drink. Nose et al. [8] reported that ingestion of plain water after exercise resulted in

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a prompt diuresis due to a rapid reduction in plasma sodium concentration and osmolality. The electrolyte composition of ingested drinks has been shown to influence the time course and magnitude of postingestion changes in blood volume and composition. This in turn will influence the drive to drink and urine output, which have implications for rehydration [9]. In both of these studies [8,9], an ad libitum rehydration strategy was used and a drink volume of less than the body mass loss during exercise was ingested. These investigations highlight the importance of avoiding a rapid increase in plasma volume and corresponding reduction in sodium concentration and osmolality during postexercise rehydration to ensure that a diuresis does not occur and that retention of ingested fluid is maximized.

The effect of the carbohydrate content of ingested solutions on the effectiveness of a rehydration solution has not been systematically examined, but some investigators have shown that carbohydrate–electrolyte solutions are more appropriate rehydration solutions than water where rapid rehydration is required [10,11]. During these studies, a drink volume equal to that of body mass lost during exercise was ingested so subjects would have been dehydrated for the duration of the entire recovery period. It is not possible in these studies to separate any effects of the carbohydrate from those of the electrolytes. The potential positive role of carbohydrate in postexercise rehydration is based partly on observations that the presence in drinks of actively transported solutes, primarily carbohydrate and sodium, at low concentrations can increase the rate of water uptake in the small intestine due to active cotransport of solutes leading to an increased rate of water flux [12]. Intestinal water uptake is governed mainly by osmotic gradients, so hypertonic solutions may be inappropriate rehydration beverages where rapid rehydration is required [13] due to net movement of water into the small intestine [14]. Evans et al. [15] reported that ingestion of a 10% glucose solution, with an osmolality of 565 ± 5 mosm/kg, resulted in a reduction in plasma volume. This suggests that at least part of the water that moves into the small intestine after ingestion of a hypertonic solution originates from the vascular space.

Before reaching the intestine, ingested fluids must be emptied from the stomach. The rate of gastric emptying of ingested fluids is determined primarily by the volume, osmolality, and energy density of the gastric contents. When the volume is constant, the energy density, or carbohydrate concentration in the case of carbohydrate solutions, seems to be the main consideration [16,17]. Ingestion of an energy-dense, hypertonic solution reduces the rate of gastric emptying and intestinal absorption compared with hypotonic drinks and may offer a gradual return to pre-dehydration levels. This may be beneficial in terms of rehydration because it will prevent large increases in blood volume and tend to limit any decrease in the circulating sodium concentration, thus maintaining plasma concentrations of vasopressin and so resulting in a smaller loss of fluid in the urine.

The aim of this study therefore was to examine whether a high-carbohydrate hypertonic solution was an effective re-

hydration solution after exercise-induced dehydration. It was hypothesized that ingestion of high-carbohydrate hypertonic solutions would be effective in restoring and maintaining net fluid balance after exercise-induced dehydration.

Materials and methods

Six healthy young adult men (mean $\pm$ SD, age 26 ± 5 y, height 173 ± 6 cm, body mass 72.1 ± 5.5 kg, and peak oxygen uptake 3.6 ± 0.7 L/min) volunteered to take part in this investigation. The study had prior approval from the Loughborough University ethical advisory committee (reference no. R06/P18). All subjects provided written informed consent and completed a medical screening questionnaire before participating in this investigation.

Two preliminary trials were performed before beginning the experimental trials. In the first of these, peak oxygen uptake was measured by a discontinuous, incremental cycle ergometer test to determine the intensity of exercise to be used to promote sweat loss. During the second preliminary trial, subjects completed the dehydration and rehydration procedures that they would undertake in the subsequent experimental trials, which are described fully below, but were free to leave the laboratory immediately after the rehydration period.

Three experimental trials were undertaken by each subject and a solution with a different carbohydrate content and therefore different osmolality was ingested in each trial. Experimental trials were separated by a period of at least 7 d and took place at the same time of the morning after an overnight fast. Subjects followed similar physical activity and nutritional intake patterns during the 24 h before each experimental trial. For this, subjects completed a food and activity diary during the 24 h before the first experimental trial and replicated this diary in the 24 h before the subsequent experimental trials. Subjects were asked to ingest 500 mL of water approximately 1 h before entering the laboratory in an effort to ensure a consistent level of hydration status.

After arrival at the laboratory, subjects sat in a comfortable environment in an upright position for a period of 15 min before a blood sample was obtained from an antecubital vein by venous puncture. The subject then emptied his bladder and the full urine sample was retained. As with all subsequent urine collections, the subject was asked to empty his bladder as fully as possible. A subjective feelings questionnaire was completed. These questionnaires asked the subject to record his feeling relating to thirst, stomach fullness, bloatedness, hunger, tiredness, alertness, concentration, and head soreness on a 10-cm visual analog scale, with 0 cm representing “not at all” and 10 cm representing “very.”

Subjects were weighed nude to the nearest 10 g on a digital weighing scale (Adam Equipment, Milton Keynes, United Kingdom) before undertaking the dehydration protocol, which consisted of intermittent cycle ergometer exercise at an intensity of $58 \pm 2\%$ peak oxygen uptake at an ambient temperature of $35.3 \pm 0.2^\circ\text{C}$ and a relative

humidity of $59 \pm 2\%$. Subjects exercised for 10 min before resting for 5 min during which time nude body mass was measured, after drying as thoroughly as possible, to determine the extent of body mass loss. The exercise/rest sequence was repeated as often as necessary to induce a body mass loss of about 2% of initial mass. When subjects approached 2% loss, exercise was halted and the subject was given 10 min to shower and dry before a final body mass measurement was obtained. Fifteen minutes after completing the exercise period subjects sat in a room maintained at $23.8 \pm 0.6^\circ\text{C}$ for a further 15 min during which time a 21-g cannula was inserted into a superficial forearm vein. This remained in position for the duration of the trial and was kept patent between sample collections by flushing with heparinized isotonic saline. After this 15-min period of seated upright rest, i.e., 30 min after the end of exercise, blood and urine samples were obtained and a subjective feelings questionnaire completed.

The test drink was given in a volume that amounted to 150% of body mass loss and was given in four equal aliquots over a period of 60 min. One subject was unable to drink the required volume during the first trial and therefore drank 130% of body mass loss during all trials. The responses of this subject were not different from those of the other five subjects, so he was not excluded from the results. Drinks were warmed to a temperature of $37 \pm 0^\circ\text{C}$ to avoid the peripheral vasoconstriction that may result from ingesting cool solutions [18] and that would influence the blood-borne parameters that were measured. Drinks contained 0%, 2%, or 10% glucose with added sodium and flavoring. The composition of each of the solutions is presented in Table 1. After the rehydration period, blood and urine samples were obtained at 0, 1, 2, 3, 4, and 6 h after rehydration. Subjective feelings questionnaires were also completed at these times. Subjects remained seated in an upright position for 15 min before collection of blood samples so that previously reported postural changes in blood and plasma volume were avoided [19,20]. A final body mass measurement was made at the end of the 6-h recovery period.

Free water clearance during each hour of the recovery period was calculated using the equation $\text{FWC} = V(1 - U_{\text{osm}}/S_{\text{osm}})$, where FWC, is free water clearance, V is urinary flow rate, U_{osm} is urine osmolality, and S_{osm} is serum osmolality.

Table 1
Composition of rehydration solutions used in the present study*

Trial	Osmolality (mosm/kg)	Na ⁺ concentration (mmol/L)	K ⁺ concentration (mmol/L)	Cl ⁻ concentration (mmol/L)
0% glucose	79 ± 4	32 ± 1	0.5 ± 0.1	27 ± 2
2% glucose	193 ± 5	32 ± 1	0.4 ± 0.1	26 ± 3
10% glucose	667 ± 12	31 ± 0	0.4 ± 0.1	27 ± 2

* Drinks contained distilled water, glucose, lemon flavoring, and 25 mmol/L of NaCl. Values are means $\pm$ SDs.

Sample analysis

Blood samples were analyzed for hemoglobin concentration by the cyanmethemoglobin method, hematocrit by microcentrifugation, and glucose concentration by the glucose oxidase peroxidase amino-antipyrine phenol (GOD-PAP) method (Randox, Crumlin, United Kingdom). Hemoglobin and packed cell volume values were used to estimate percentage of changes in blood, red cell, and plasma volumes as described by Dill and Costill [21].

An aliquot of whole blood was centrifuged at $1500 \times g$ for 15 min at 4°C before serum was removed and kept for analysis of osmolality by freezing-point depression (Gonotec Osmomat 030 Cryoscopic Osmometer; Gonotec, Berlin, Germany), sodium and potassium concentrations by flame photometry (Corning Clinical Flame Photometer 410C; Corning Ltd., Halstead, Essex, United Kingdom), and chloride concentration by coulometric titration (Jenway Chloride Meter; Jenway Ltd., Dunmow, Essex, United Kingdom).

The total volume of urine produced at each time point was recorded and a sample retained for analysis of osmolality and electrolyte concentrations using the methods described earlier.

All analyses were performed in duplicate, with the exception of the hematocrit measurements, which were made in triplicate.

Statistical analysis

All data were found to be normally distributed using the Kolmogorov-Smirnov test and are, therefore, presented as mean $\pm$ standard deviation. Data were analyzed using two-factor repeated measures analysis of variance (ANOVA). One-way ANOVA followed by Tukey's or Dunnett's pairwise comparisons were used as post hoc tests to locate differences. Level of significance was taken as $P < 0.05$, and this level of significance applies unless otherwise stated.

Where results of one-way ANOVA are reported, a partial η -squared (η_p^2) value is presented as an estimate of effect size.

Statistical analysis was performed using SPSS 12.0 for Windows (SPSS Inc., Chicago, IL, USA).

Results

Subjects' pre-exercise body mass was the same in all trials ($P = 0.992$, $\eta_p^2 = 0.001$). Body mass lost during exercise was the same in all trials ($P = 0.994$, $\eta_p^2 = 0.001$) and amounted to 1.35 ± 0.11 , 1.35 ± 0.18 , and 1.34 ± 0.17 kg in the 0%, 2%, and 10% glucose trials, respectively, equivalent to a reduction in body mass of $1.9 \pm 0.1\%$. The mean exercise time necessary to achieve this loss of mass was 45 ± 8 min. This time was not different between the trials ($P = 0.785$, $\eta_p^2 = 0.032$). Because body mass loss was the same in each trial, drink volume was also the same during

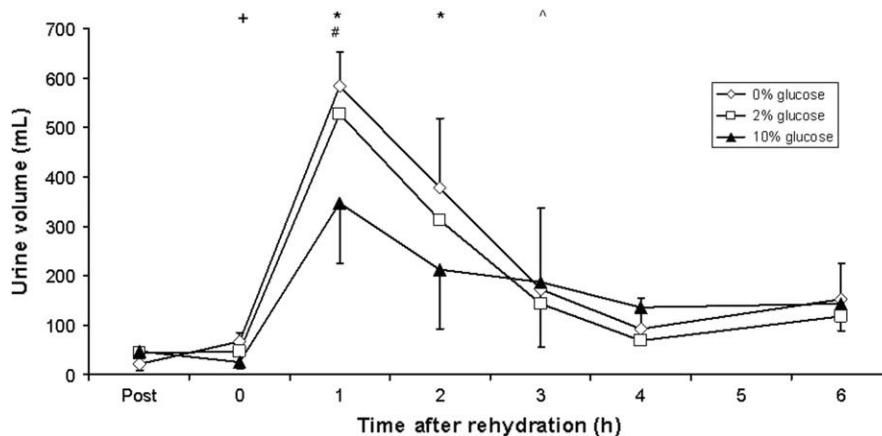


Fig. 1. Urine volume produced at each time point. The pre-exercise sample is not shown. Points are means $\pm$ SDs. +, 0% glucose time point greater than 10% glucose time point; #, 0% and 2% glucose time points greater than 10% glucose time point; *, 0%, 2%, and 10% glucose time points greater than Post; ^, 0% and 10% glucose time points greater than Post.

the trials ($P = 0.911$, $\eta_p^2 = 0.012$) and amounted to 1962 ± 247 mL. Body mass at the end of the 6-h recovery period was not different between trials ($P = 0.999$, $\eta_p^2 < 0.001$).

Urine output and net fluid balance

The volume of urine excreted immediately after the rehydration period (0 h) was different between trials ($P = 0.001$, $\eta_p^2 = 0.582$) and was greater in the 0% glucose trial than in the 10% glucose trial ($P = 0.001$). The greatest urine output during all trials occurred in the first hour after the rehydration period (Fig. 1). Urine volume at this time point was different between trials ($P = 0.002$, $\eta_p^2 = 0.557$). Subsequent analysis showed urine volume at this time point to be similar in the 0% (585 ± 67 mL) and 2% (528 ± 101 mL) glucose trials ($P = 0.594$), but lower during the 10% (347 ± 121 mL) glucose trial than the 0% ($P = 0.002$) and 2% ($P = 0.017$) glucose trials. One-way ANOVA showed a general effect over time during the 0% ($P < 0.001$, $\eta_p^2 = 0.828$), 2% ($P < 0.001$, $\eta_p^2 = 0.723$), and 10% ($P < 0.001$, $\eta_p^2 = 0.600$) glucose trials. The volume of urine excreted was greater than postexercise levels 1 and 2 h after the rehydration period in all trials and 3 h after the rehydration period in the 0% and 10% glucose trials. Total urine output over the recovery period was not different between trials (Table 2).

Net fluid balance (Fig. 2) was calculated using data for sweat loss, drink volume ingested, and urine production. It

was assumed for this purpose that all mass loss incurred during exercise was in the form of water, and water formed by the oxidation of substrate was ignored [22]. One-way ANOVA showed a general effect over time during the 0% ($P < 0.001$, $\eta_p^2 = 0.909$), 2% ($P < 0.001$, $\eta_p^2 = 0.842$), and 10% ($P < 0.001$, $\eta_p^2 = 0.908$) glucose trials. Subjects were in negative fluid balance after the dehydration protocol. All subjects drank enough to achieve a positive fluid balance at the end of the rehydration period if all of the ingested fluid had been assimilated into the body water pool by this time. However, it is likely that some of the ingested fluid was still in the stomach or the intestinal lumen and this volume is likely to have been different during the different trials. Two hours after the rehydration period, subjects were in greater net fluid balance in the 10% glucose trial than in the 0% and 2% glucose trials. During the 0% glucose trial, subjects returned to a state of negative fluid balance 2 h after rehydration. During the 2% glucose trial, subjects returned to negative fluid balance 3 h after rehydration. Subjects remained euhydrated for 1 h longer in the 10% glucose trial than in the 2% glucose trial, i.e., returned to negative fluid balance 4 h after rehydration.

The percentage of ingested drink that was retained was calculated using drink volume and urine output data. Neither the volume of drink consumed nor the cumulative urine output was significantly different between trials, but, 6 h after the rehydration phase, $27 \pm 13\%$, $40 \pm 14\%$, and $46 \pm 9\%$ of the ingested solution had been retained during the 0%,

Table 2
Fluid balance*

	0%	2%	10%	ANOVA
Total drink volume (mL)	1981 ± 202	1979 ± 288	1926 ± 252	0.911
Total urine output (mL)	1447 ± 332	1219 ± 430	1051 ± 235	0.165
Volume retained at 6 h (mL)	534 ± 267	760 ± 214	875 ± 184	0.053
Fraction retained at 6 h (%)	27 ± 13	40 ± 14	46 ± 9	0.046

ANOVA, analysis of variance

* Values for total urine output do not include the first sample collected after the end of the fluid ingestion period. The volume retained and the fraction retained refer to the volume and fraction, respectively, of the ingested drink that were not accounted for by urine loss. Values are means $\pm$ SDs.

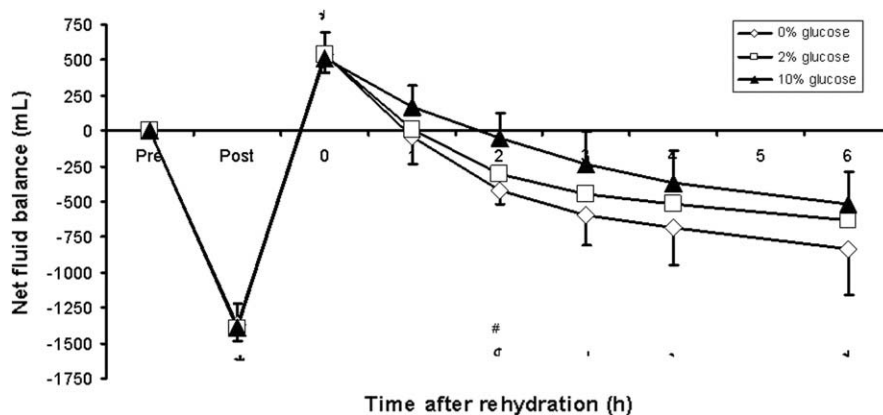


Fig. 2. Net fluid balance during all trials. Points are means $\pm$ SDs. #, 10% glucose time point greater than 0% and 2% glucose time points; \$, 0% glucose time point different from Pre; +, 0% and 2% glucose time points different from Pre; *, 0%, 2%, and 10% glucose time points different from Pre. Post, sample obtained after exercise; Pre, sample obtained before exercise.

2%, and 10% glucose trials, respectively (Table 2; $P = 0.046$, $\eta_p^2 = 0.337$). The fraction of the ingested drink volume that was retained during the 0% trial was lower ($P = 0.04$) than that during the 10% trial.

Urine electrolyte composition and osmolality

The amounts of Na^+ , K^+ , and Cl^- consumed were the same during all trials and amounted to 62 ± 7 mmol ($P = 0.640$, $\eta_p^2 = 0.058$), 0.9 ± 0.2 mmol ($P = 0.131$, $\eta_p^2 = 0.237$), and 53 ± 9 mmol ($P = 0.906$, $\eta_p^2 = 0.013$), respectively. Total urinary excretion of these electrolytes after exercise was not different between trials, and levels were 55.8 ± 17.0 mmol ($P = 0.142$, $\eta_p^2 = 0.229$), 47.3 ± 14.0 mmol ($P = 0.306$, $\eta_p^2 = 0.146$), and 45.7 ± 13.6 mmol ($P = 0.131$, $\eta_p^2 = 0.237$) for Na^+ , K^+ , and Cl^- , respectively.

Pre-exercise urine osmolality was not different between trials ($P = 0.984$, $\eta_p^2 = 0.002$) and levels were 504 ± 169 , 528 ± 294 , and 521 ± 244 mosm/kg in the 0%, 2%, and 10% glucose trials, respectively. Change in urine osmolality over time was the same in all trials.

Blood and serum measurements

Blood ($P = 0.005$) and plasma ($P < 0.001$) volumes were significantly increased from pre-exercise values by $4.6 \pm 3.7\%$ and $9.0 \pm 4.9\%$, respectively, at the end of the rehydration period in the 2% glucose trial (Fig. 3). Plasma volume remained elevated in the 2% glucose trial 1 h after rehydration ($P = 0.031$) but there were no differences from baseline at any time in the 0% and 10% glucose trials.

Pre-exercise blood glucose concentration was not different between trials ($P = 0.835$, $\eta_p^2 = 0.024$) and levels were 5.0 ± 0.6 , 5.1 ± 0.5 , and 5.2 ± 0.5 mmol/L on the 0%, 2%, and 10% glucose solutions, respectively. After ingestion of the drinks, blood glucose concentration was significantly elevated from pre-exercise values at the end of the 1-h rehydration period (7.9 ± 0.6 mmol/L) after ingesting the 2% glucose solution and immediately after (9.6 ± 1.1 mmol/L) and 1 h after (7.7 ± 1.0 mmol/L) ingesting the 10% glucose solution. At the end of the rehydration period and 1 h after rehydration, blood glucose concentration was greater in the 10% glucose trial than

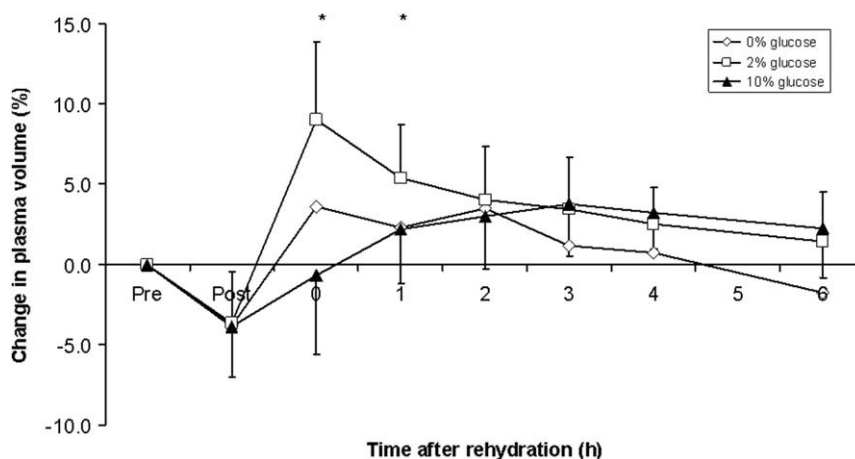


Fig. 3. Estimated percentage change in plasma volume when the pre-exercise sample is taken as the baseline value. Points are means $\pm$ SDs. *, 2% glucose time point greater than Pre.

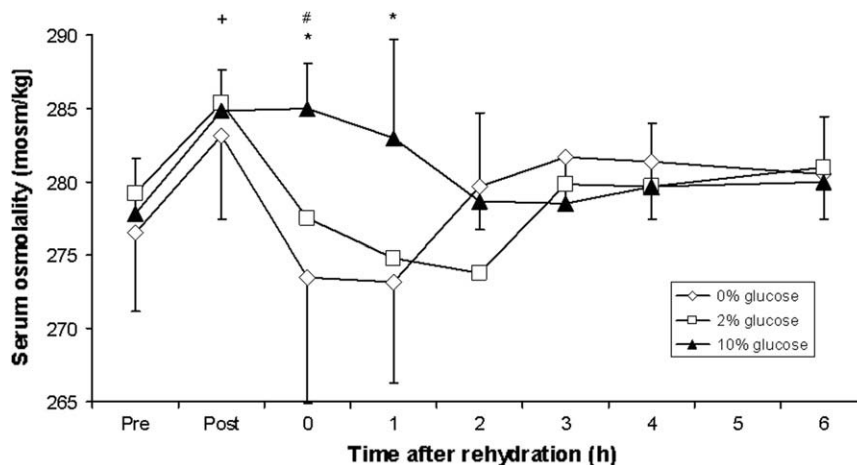


Fig. 4. Changes in serum osmolality. Points are means $\pm$ SDs. +, 2% glucose time point greater than Pre; #, 10% glucose time point greater than Pre; *, 10% glucose time point greater than 0% glucose time point.

in the 0 and 2% glucose trials. Blood glucose concentration was greater in the 2% glucose trial than in the 0% glucose trial at the end of the rehydration period. Two hours after the rehydration period, blood glucose concentration was lower in the 2% glucose trial than in the 10% glucose trial.

Pre-exercise values for serum osmolality amounted to 277 ± 5 , 279 ± 3 , and 278 ± 4 mosm/kg in the 0%, 2%, and 10% glucose trials, respectively ($P = 0.537$, $\eta_p^2 = 0.079$; Fig. 4). This increased to 283 ± 6 , 285 ± 3 , and 285 ± 3 mosm/kg in the 0%, 2%, and 10% glucose trials, respectively, but this change was significant only in the 2% glucose trial ($P = 0.042$). Immediately after rehydration, serum osmolality was increased from baseline levels in the 10% glucose trial ($P = 0.045$). Serum osmolality was greater in the 10% glucose trial than in the 0% glucose trial 0 and 1 h after rehydration. No significant differences between trials were observed in serum electrolyte measurements.

Free water clearance

One hour after rehydration, free water clearance was greater ($P = 0.006$) during the 0% glucose trial than the 10% glucose trial and tended ($P = 0.055$) to be greater in the 2% glucose trial than in the 10% glucose trial (Fig. 5). Four hours after rehydration, free water clearance was greater ($P = 0.037$) in the 10% glucose trial than in the 2% glucose trial.

Subjective feeling questionnaires

Subjects reported a greater feeling of stomach fullness in the 10% glucose trial compared with the 0% glucose trial 0 and 1 h after the end of the rehydration period and a greater feeling of being bloated in the 10% glucose trial compared with the 0% and 2% glucose trials 0, 1, and 4 h after the end of the rehydration period. Subjects reported a greater

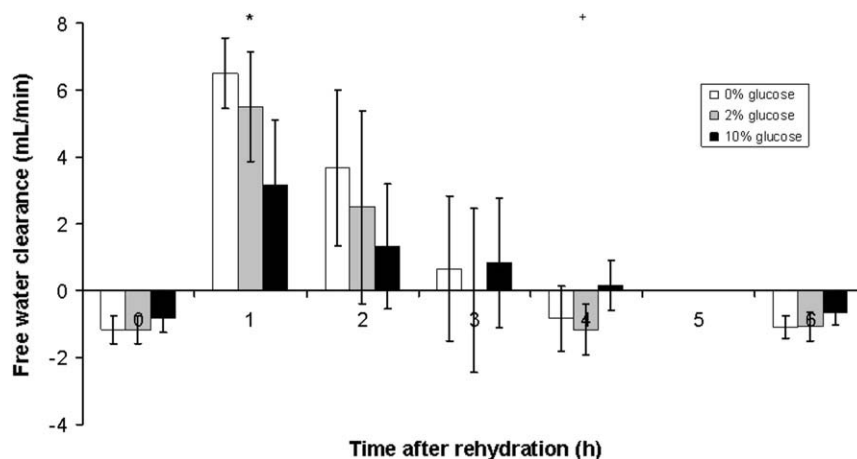


Fig. 5. Free water clearance during each hour of the recovery period. Points are means $\pm$ SDs. *, 0% glucose time point greater than 10% glucose time point; +, 10% glucose time point greater than 2% glucose time point.

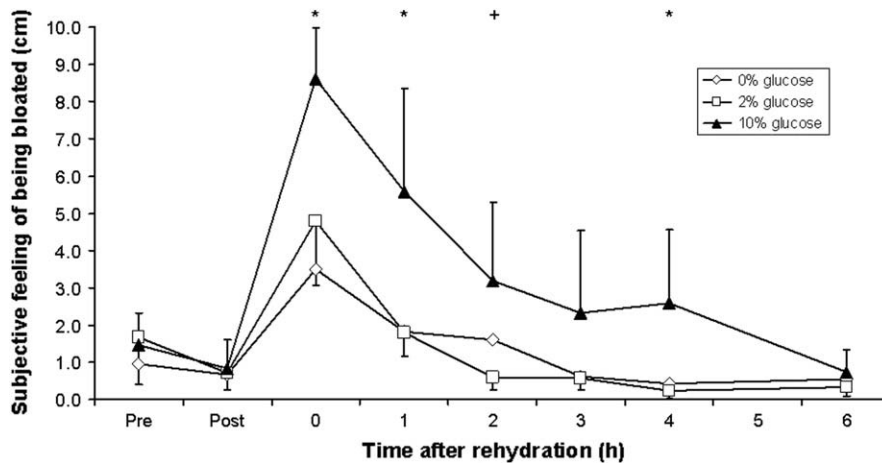


Fig. 6. Reported subjective feelings of bloatedness. Data are means $\pm$ SDs. *, 10% glucose time point greater than 0% and 2% glucose time points; +, 10% glucose time point greater than 2% glucose time point.

feeling of being bloated 2 h after drinking the 10% glucose solution compared with the 2% glucose solution (Fig. 6).

Discussion

The results of this study suggest that ingestion of a hypertonic glucose–electrolyte solution with an osmolality of 667 ± 12 mosm/kg may be more effective in promoting and maintaining postexercise rehydration than ingestion of the same volume of more dilute solutions with the same electrolyte content when a volume of 150% (130–150) of body mass lost is ingested over a period of 1 h. After exercise-induced dehydration by about 2% of body mass, subjects retained significantly more of the volume ingested during the 10% glucose trial than the 0% glucose trial and remained euhydrated for 1 h longer during the 10% glucose trial than the 2% glucose trial.

Previous studies have demonstrated that perfusion of the human small intestine with hypotonic carbohydrate–electrolyte solutions results in rapid increases in plasma volume [23,24] due to active cotransport of carbohydrates and sodium leading to enhanced water uptake [12]. The present study supports these observations, because plasma volume increased compared with the pre-exercise value by $9.0 \pm 4.9\%$ immediately after the rehydration phase in the 2% glucose trial. In contrast, ingestion of the same volume of a 0% or 10% glucose solution did not cause any significant change in blood or plasma volumes. Hypertonic solutions result in a transient net secretion of water into the small intestine due to the osmotic gradient that is established after ingestion of these solutions [14], and this has the effect of causing a reduction in plasma and extracellular fluid volume [15]. If sodium is absent from ingested drinks, or is present at only low concentrations, it too will be secreted in the upper part of the small intestine until an equilibrium is established [13]. For these reasons, it has been suggested that hypotonic solutions with moderately high sodium concentrations are the most effective option when rapid and complete fluid

replacement is required, and that hypertonic and electrolyte-free solutions are likely to be less effective rehydration solutions [13].

The present study suggests that energy-dense, hypertonic solutions may be effective for restoration of sweat-induced water losses and maintenance of hydration status because subjects remained euhydrated for a longer period after ingestion of the hypertonic 10% glucose solution compared with the hypotonic 2% glucose solution or the glucose-free solution. The rapid appearance in the plasma of ingested fluid may be counterproductive when there is a need to replace fluid losses. Urine output, although not significantly different, was greater during the 2% glucose trial than the 10% glucose trial in five of the six subjects who participated in this study, perhaps due to changes in circulating concentrations of arginine vasopressin (AVP). Although circulating AVP levels were not measured in the present study, calculation of free water clearance provides a good estimation of AVP response [25]. The free water clearance data presented suggest that the extent of AVP secretion was different between the trials, resulting in greater water retention in the early hours of recovery.

Arginine vasopressin release is influenced by plasma osmolality and, to a lesser extent, by blood volume. Linear regression analysis has suggested that circulating concentrations of vasopressin fluctuate by 0.41 pmol/L per unit change in plasma osmolality, whereas a decrease in blood volume of 8–10% is necessary to stimulate AVP release [26]. It would seem that any differences in circulating AVP concentration in the present study are likely to be due to differences in serum osmolality observed between trials rather than changes in blood volume.

It is now accepted that to return to a state of euhydration it is necessary to allow for ongoing obligatory water losses by ingesting a volume greater than that of the body mass loss as described by Shirreffs et al. [6]. It is also generally accepted that, provided that an appropriate amount of fluid is ingested, sodium intake has a major role in restoring fluid homeostasis

[7,9,27]. The importance of sodium ingestion stems from it being the major ion lost in sweat and its role in maintaining plasma concentration of vasopressin and aldosterone so that a diuresis will not occur due to sharp reductions in plasma osmolality and increases in plasma volume [9]. The amount of sodium that will be required will vary between individuals even when the volume of sweat loss is constant, due to the large interindividual variation in the sweat sodium content [4]. Shirreffs et al. [7] gave subjects drinks containing 0, 25, 50, or 100 mmol/L of sodium in a volume equal to 150% of sweat loss after exercise-induced dehydration of about 2% of body mass. The measured sweat sodium concentration was 49 ± 19 mmol/L, and the total loss (64 ± 39 mmol) in sweat during the exercise period was greater than that ingested in trials 0 and 25. Urine production over the 6-h recovery period was inversely related to the amount of sodium ingested. Subjects were in whole-body negative sodium balance in trials 0 (104 ± 48 mmol) and 25 (65 ± 30 mmol) and essentially in balance in trial 50 (13 ± 29 mmol) but were in positive sodium balance in trial 100 (75 ± 40 mmol). Only in trial 100 were subjects in positive fluid balance at the end of the 6-h post-rehydration sampling period. The results of the present study suggest that the carbohydrate content and osmolality of ingested drinks also have a major role in restoring fluid balance after exercise-induced dehydration. Because subjects were in a state of negative fluid balance before the end of all trials, it would appear that the amount of sodium ingested is still the main consideration when formulating rehydration solutions.

Current oral rehydration therapy guidelines suggest that hypotonic carbohydrate–electrolyte solutions should be consumed when there is a need for rapid fluid replacement [13,28], but if the aim of fluid ingestion is to maintain fluid balance for a prolonged period, then ingestion of hypotonic carbohydrate–electrolyte solutions may be inappropriate due to the differences in urine output that have been observed in the present study. It is not possible from the results of the present study to say whether the avoidance of large fluctuations in serum osmolality and plasma volume observed after ingestion of a 10% glucose solution is due to a reduced rate of fluid delivery to the small intestine [16,17] or due to the delayed rate of fluid absorption in the intestine.

Because exercise intensity and time to achieve mass loss were the same during all trials, the reduction in muscle glycogen content will likely have been similar in each of these trials. A rough estimate would suggest that 45 min of exercise at an oxygen cost of about 2.2 L/min, assuming a 50% contribution from muscle glycogen to oxidative metabolism, would result in use of about 60–70 g of glycogen. The mean volume of fluid ingested after exercise was approximately 2 L, which would provide 40 g of carbohydrate in the 2% trial and 200 g of carbohydrate in the 10% trial. Assuming complete restoration of muscle glycogen in the 10% trial, the amount of water stored in muscle in association with this glycogen would be about 60–200 mL: this depends on the value accepted for the storage of glycogen in

association with water, but it is probably closer to the lower end of this range [22]. This may have made a small contribution to the success of the 10% glucose solution in maintaining fluid balance.

The results of the present study suggest that hypertonic glucose–electrolyte solutions are effective rehydration solutions, but this may not be the case when ad libitum fluid intake is allowed. Ingestion of the 10% glucose solution resulted in subjects reporting a greater sensation of stomach fullness and feeling more bloated after the rehydration period compared with the 0% and 2% glucose solutions. In practice, where ad libitum fluid intake takes place, this may result in a cessation of fluid ingestion before positive fluid balance has been attained, thereby hindering the rehydration process. The choice of rehydration drinks may also be influenced by the time scale of the recovery period. Where long periods are available, water and food ingested in sufficient amounts will ensure complete rehydration [29].

Conclusions

The results of this study demonstrate that a hypertonic 10% glucose–electrolyte solution with an osmolality of 667 ± 12 mosm/kg was more effective in maintaining a state of euhydration after exercise-induced dehydration of $1.9 \pm 0.1\%$ body mass than a 2% glucose solution with an osmolality of 193 ± 5 mosm/kg and a 0% glucose solution with an osmolality of 79 ± 4 mosm/kg. The carbohydrate content and osmolality of ingested solutions are important considerations in the postexercise period.

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