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ORIGINAL ARTICLE

R.J. Maughan · J.B. Leiper

Sodium intake and post-exercise rehydration in man

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Abstract This study examined the effect of the sodium content of drinks on the rehydration process after exercise. Six healthy male volunteers were dehydrated by a mean (SEM) of 1.9(0.0) % of body mass by intermittent cycle exercise in a warm (32°C), humid (54% RH) environment. Subjects exercised on four occasions at weekly intervals with each trial beginning in the morning, 3 h after a standard breakfast. Over a 30-min period beginning 30 min after the end of exercise, subjects ingested one of the four test drinks in a volume equivalent to 1.5 times their body mass loss. Drink composition was constant except for the sodium (and matching anion) content. Sodium content of drinks A, B, C and D was 2, 26, 52 and 100 mmol·l^{-1}, respectively. Treatment order was randomised using a four-way crossover incomplete block design. Blood and urine samples were obtained before exercise, immediately before and after the rehydration period and at 0.5, 1.5, 3.5 and 5.5 h after the end of the rehydration period. Data were analysed by parametric or non-parametric statistical tests as appropriate. The volume of fluid consumed was the same on all trials [2045(45) ml]. From the 1.5-h sample onwards, a significant treatment effect on cumulative urine output was apparent, with the volume excreted being inversely related to the sodium content of the drink consumed. By the end of the trial, subjects were in net negative fluid balance on trials A [by 689(124) ml] and B [by 359(87) ml]; on trials C [− 2(79) ml] and D [+ 98(67) ml], subjects were approximately euhydrated. Cumulative urinary sodium output was higher on treatment D than on the other trials after 5.5 h. Plasma volume was lower after exercise than before; on trials B, C and D, plasma volume was higher than the pre-exercise value from 0.5 h after the end of the rehydration period onwards. On trial A, plasma volume was higher than the pre-exercise value at 3.5 and 5.5 h after the end of the rehydration period. At 1.5 h after the end of the rehydration period, the increase in plasma volume was greater on trials C and D than on trial A. These results suggest that the fraction of the ingested fluid that was retained was directly related to the sodium concentration.

Key words Dehydration · Rehydration · Fluid balance · Exercise · Electrolyte balance

R.J. Maughan · J.B. Leiper
Department of Environmental and Occupational Medicine, University Medical School, Aberdeen, Scotland

R.J. Maughan (✉)
University Medical School, Foresterhill, Aberdeen AB9 2ZD, Scotland

Introduction

Substantial losses of water and electrolytes may occur during prolonged exercise, especially when the ambient temperature and humidity are high, and sweat-induced hypohydration impairs exercise capacity (Sawka 1992). Replacement of water and electrolyte losses in the post-exercise period is of crucial importance for recovery, and is particularly important when repeated bouts of exercise have to be performed. The need for replacement will obviously depend on the extent of the losses incurred during exercise, but will also be influenced by the time and nature of subsequent exercise bouts. Rapid rehydration may also be important in events such as wrestling, boxing and weightlifting, where competition is by weight category. Competitors in these events frequently undergo acute thermal and exercise-induced dehydration to make weight; the time interval between the weigh-in and competition is normally about 3 h, although it may be longer. The practice of acute dehydration to make weight should be discouraged, as it reduces exercise performance and increases

the risk of heat illness, but it will persist and there is a need to maximize rehydration in the limited time available.

Ingestion of plain water after exercise results in a rapid fall in the plasma sodium concentration and in plasma osmolality (Nose et al. 1988a). These changes diminish the stimulus to drink (thirst) and increase urine output, and both of these effects will delay the rehydration process. In the study of Nose et al. (1988a), subjects exercised at low intensity in the heat for 90–110 min, inducing a mean dehydration of 2.3% of body weight, and then rested for 1 h before beginning to drink. When plain water was ingested together with placebo (sucrose) capsules, plasma volume was not restored until after 60 min. In contrast, when sodium chloride capsules were ingested with water to give a saline solution with an effective concentration of 0.45% (77 mmol·l^{-1}), plasma volume was restored within 20 min. In the NaCl trial, voluntary fluid intake was higher and urine output was less. The delayed rehydration in the water trial appeared to be a result of a loss of sodium, accompanied by water, in the urine caused by reduced plasma renin activity and aldosterone levels (Nose et al. 1988b).

In an earlier study where a more severe (4% of body weight) dehydration was induced in resting subjects by heat exposure, consumption over a 3-h period of a volume of fluid equal to that lost did not restore plasma volume or serum osmolality within 4 h (Costill and Sparks 1973). Ingestion of a glucose-electrolyte solution, however, did result in greater restoration of plasma volume than did plain water; this was accompanied by a greater urine production in the water trial. Where the electrolyte content of drinks is the same, it appears that neither the addition of carbohydrate (100 g·l^{-1}) nor carbonation has any effect on the restoration of plasma volume over a 4-h period after sweat loss corresponding to approximately 4% of body weight (Lambert et al. 1992). Gonzalez-Alonso et al. (1992) have recently shown that a dilute carbohydrate-electrolyte solution is more effective in promoting post-exercise rehydration than either plain water or a low-electrolyte diet cola. The difference in response to the drinks was primarily a result of differences in the volume of urine produced over the study period, and appeared to be related to the electrolyte content.

It is clear from these studies that addition of sodium to fluids consumed after exercise-induced dehydration reduces the urine volume output and increases the fraction of the ingested fluid that is retained. Rehydration after exercise can only be achieved if the sodium lost in sweat is replaced as well as the water, and it might be suggested that rehydration drinks should have a sodium concentration similar to that of sweat. There is a limited amount of information on the electrolyte content of human sweat, largely as a consequence of the problems associated with sweat collection, but the available data suggest that the normal range may be from 20 to 80 mmol·l^{-1} (Verde et al. 1982). Since the sodium content of sweat appears to vary so widely, no single formulation will meet this requirement for all individuals in all situations. The upper end of the normal range for sweat sodium concentration (80 mmol·l^{-1}), however, is similar to the sodium concentration of many commercially produced oral rehydration solutions (ORS) intended for use in the treatment of diarrhoea-induced dehydration. The ORS recommended by the World Health Organisation for rehydration in cases of severe diarrhoea has a sodium content of 90 mmol·l^{-1} (Walker-Smith 1992). By contrast, the sodium content of most sports drinks which are promoted for replacement of sweat losses is in the range of 10–25 mmol·l^{-1} and is even lower in some cases. Most commonly consumed soft drinks contain virtually no sodium (less than 4 mmol·l^{-1}).

Several of the studies described above have compared commercial products, and the test drinks have contained a variety of electrolytes in varying concentrations, together with different types and amounts of carbohydrate. The aim of the present study was to examine the effects of systematic variations in the sodium content of ingested fluids on the effectiveness of fluid replacement after exercise in man.

Methods

Six healthy male subjects volunteered to take part in this investigation, and all completed the study. The experimental procedures were approved by the Joint Ethical Committee of Aberdeen University and Grampian Health Board and the study was conducted in accordance with accepted ethical standards. Subjects were informed of the nature of the investigation before their written consent to participate was obtained. All of the subjects regularly participated in some form of recreational physical activity, but none was engaged in a specific training programme at the time of this investigation, and none was heat-acclimatised. Local day-time temperature at the time of the study did not exceed 20°C. Physical characteristics [mean (SEM)] of the subjects were: age, 31 (4) years; height, 1.80 (0.02) m; body mass, 70.2 (2.6) kg; maximum oxygen uptake ($\dot{V}O_{2max}$), 56.3 (2.4) ml·$kg^{-1}min^{-1}$. $\dot{V}O_{2max}$ was determined during an incremental exercise test on an electrically braked cycle ergometer as part of the preliminary procedures carried out within 2 weeks of the beginning of the study period.

Subjects took part in an initial familiarisation trial followed by four experimental trials at weekly intervals. All experimental trials began in the morning, 3 h after a standard breakfast which included fluids, but no caffeine. Subjects were required to abstain from strenuous exercise for at least 48 h prior to each test. They were requested to follow, as far as was possible, the same pattern of physical activity during this period for each of the trials. During this 48-h period, a record of food intake was kept on the preliminary trial and this was reproduced on each of the experimental trials.

On reporting to the laboratory, subjects remained fully clothed and were seated in a room maintained at a temperature of approximately 20°C for 15 min before an initial 10-ml blood sample was obtained from a superficial forearm vein. All blood samples were obtained without interuption of the circulation. A urine sample was then obtained; the subject emptied his bladder as completely as possible and the entire volume was collected. Nude body mass was

then measured and subjects dressed in shorts, socks and shoes before the dehydration procedure began.

Dehydration was achieved by intermittent cycle ergometer exercise at an intensity calculated to be approximately 60% of $\dot{V}O_{2max}$ for each subject. All exercise was carried out on a friction-braked ergometer in a room maintained at a temperature of 32°C and 54% relative humidity. The exercise periods lasted 10 min and were separated by 5-min rest periods. Immediately upon completion of each exercise bout, subjects removed their clothing and dried themselves as completely as possible before nude body mass was measured. The intention was to dehydrate each subject by 2% of body mass, and the exercise bouts were repeated until body mass was reduced by approximately 1.8%; it was established in preliminary studies that the remaining 0.2% would be lost by continuing perspiration after the end of exercise. When the target mass was reached, subjects were allowed 15 min to cool off and shower before a final measurement of body mass was obtained. A large variability in sweat rate was observed between subjects, and the mean time necessary to achieve the desired body mass loss was 94(6) min. The time for each subject to achieve the desired weight loss was, however, rather constant from week to week.

Subjects then resumed a seated position and a 21-gauge butterfly cannula was introduced into a superficial forearm vein for blood sampling; this remained in place for the remainder of the study period. A second blood sample was obtained after 15 min of seated rest (30 min after the end of exercise) and this was followed by collection of a second urine sample. Over the following 30 min, subjects remained seated and ingested one of the test drinks in a volume (in ml) equal to 1.5 times the mass (in g) lost during the dehydration period; drinks were given in three equal volumes, each to be consumed within a 10-min period. The order of allocation of treatments to subjects was randomised using a four-way crossover incomplete block design. All drinks were flavoured with sugar-free lemon squash, and glucose at a concentration of 90 $mmol \cdot l^{-1}$ was added. Sodium salts were added to give a sodium concentration of 2, 26, 52 and 100 $mmol \cdot l^{-1}$ for drinks A, B, C and D, respectively. Measured osmolality of the drinks was: A, 108(2); B, 158(1); C, 206(1) and D, 300(1) $mosmol \cdot kg^{-1}$.

Further blood and urine samples were collected immediately upon completion of the rehydration period, and at 0.5, 1.5, 3.5 and 5.5 h after the end of this period. No food or fluid, other than the test drink, was allowed until after the last samples had been collected. If any subject required to pass urine at a time other than one of the scheduled collection times, this sample was retained and mixed with that obtained at the next scheduled time point. Drink acceptance was assessed with a seven question, 10-cm visual analogue scale which was completed at the beginning of the rehydration period after the first portion of the drink had been consumed. The same questionnaire was completed at the end of the rehydration period.

One week prior to the first experimental test, all subjects completed a familiarisation trial which was identical in all respects except that sample collection was carried out for only 2 h after the end of the rehydration period.

Analytical procedures

Part (4 ml) of each blood sample was mixed with anticoagulant (EDTA, 1.5 $mg \cdot ml^{-1}$) and used for measurement of haemoglobin (by conversion to cyanmethaemoglobin and comparison of the resultant optical density with that of a known standard) in duplicate and spun haematocrit in triplicate. These results were used to calculate changes in blood and plasma volumes relative to the value immediately before rehydration began, as described by Dill and Costill (1974). The remainder of each blood sample was allowed to clot and the serum separated by centrifugation. Serum samples were analysed for sodium and potassium concentrations by flame photometry and for chloride concentration by coulometric titration. Serum osmolality was measured by freezing point depression.

The total volume of each urine sample was measured and a portion used for measurement of electrolyte concentration and osmolality using the same methods as used for serum analysis. Cumulative urine output was calculated, and net fluid balance was calculated based on body mass loss, volume of fluid ingested and urinary volume.

Statistical analysis

Data found to be normally distributed were analysed with parametric statistical tests. Non-parametric analysis was applied to those data sets which deviated from normality. Normally distributed data were subjected to an initial two-way repeated measures analysis of variance, followed by Duncan's multiple range test where appropriate. Data not normally distributed were initially examined by a Kruskall-Wallis test, followed by a Mann-Whitney test where a significant treatment effect was detected. Differences between treatments were accepted as being significant when a P value of less than 0.05 was obtained. Results in the text, tables and figures are expressed as mean (SEM) or as median (range) as appropriate.

Results

Mean body mass loss over all trials was 1.9(0.0)% of the pre-exercise mass, and analysis of variance showed no evidence of a difference between the four test days. The volume of fluid ingested on each trial was 50% greater than the measured body mass loss, and was therefore also the same [2045(45) ml] on all trials.

Urine volume and composition

Cumulative urine output was not different between trials immediately after or at 30 min after the end of the rehydration period (Fig. 1). At no time point were trials

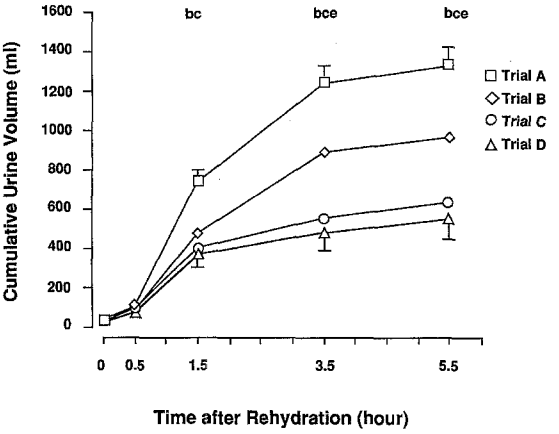

Fig. 1 Cumulative urine output over time. The pre-exercise sample and the sample obtained immediately after exercise are not included in the total. Significant treatment effects were seen 1.5 h ($P < 0.05$), 3.5 h ($P < 0.001$) and 5.5 h ($P < 0.001$) after the end of the rehydration period. Significant differences between treatments are indicated on Figs. 1–6 as follows: *a* A vs B, *b* A vs C, *c* A vs D, *d* B vs C, *e* B vs D, *f* C vs D

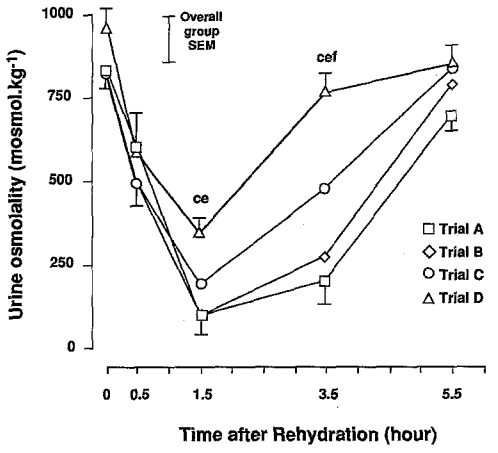

Fig. 2 Urine osmolality. Significant treatment effects were seen on the samples obtained 1.5 h ($P < 0.05$) and 3.5 h ($P < 0.001$) after the end of the rehydration period

A and B significantly different from each other, nor were C and D different from each other. Significant treatment effects were seen at 1.5 h, 3.5 h and 5.5 h after the end of the rehydration period. From the 1.5-h sample point onwards, cumulative urine output was greater on trial A than on trials C and D. At 3.5 h and 5.5 h, urine output on trial B was greater than on trial D.

All four test conditions showed a similar level of urine osmolality before and immediately after the rehydration period (Fig. 2). By the time of the next sample (1.5 h after the end of the rehydration period) when urine volume was greatest, urine osmolality had fallen on all trials, with a significant treatment effect. Urine osmolality was higher after treatment D than after A or B. Two hours later, mean urine osmolality had increased on all trials, but a significant treatment effect was still apparent. There was no significant treatment effect observed at the time of the last sample.

Cumulative urine sodium and potassium output is shown in Table 1. In spite of the smaller volume of urine output on trial D, cumulative urinary sodium output was higher on this trial than on any of the others by the end of the study period. The potassium content of all drinks was the same, but a significant treatment effect on urinary potassium output was seen at 1.5 h, 3.5 h and 5.5 h after the end of the rehydration period; output on trial D was higher than on trials B and C at these times, but was higher than on trial A only at the 1.5-h sample point.

Fluid balance

Net fluid balance is calculated relative to the time point immediately prior to exercise. As described in the Methods, care was taken to ensure that subjects arrived at the laboratory in a euhydrated state on each of the trials; the constancy of the pre-exercise body mass suggests that this was the case. Measured sweat loss, the volume of fluid consumed and the urine output were then used to calculate whole body net fluid balance. The pre-exercise urine sample is not included in these calculations. There was no difference between trials after exercise, after ingestion of the test drinks, or 30 min later (Fig. 3). By 1.5 h after the end of the rehydration period, however, a significant treatment effect was observed. There was no difference between trials B, C and D, where subjects remained in positive fluid balance, but already at this time, subjects were in negative fluid balance on trial A. By the end of the study period, subjects were in negative fluid balance on trials A [by 689(124) ml] and B [by 359 (87) ml], and on C [− 2(79) ml] and D [98(67) ml] subjects were approximately in balance. Apart from trials C and D, all trials were different from each other.

Since the volume of fluid lost as sweat and the volume ingested were the same on all trials, these differences reflect the differences in urine output described above. The fraction of the drink which is retained is closely related to the sodium content (Table 2). At the

Table 1 Cumulative urine sodium and potassium [mean (SEM); mmol] output at each of the sample points. The pre-exercise sample and the sample obtained before the test drinks were consumed are not included in the calculations

Time after rehydration (h)	Trial				Differences
	A	B	C	D	
Sodium output					
0	3 (1)	3 (1)	2 (1)	3 (16)	–
0.5	9 (3)	8 (3)	5 (1)	9 (2)	–
1.5	15 (5)	12 (4)	12 (1)	26 (3)	D > B, C
3.5	29 (8)	20 (4)	18 (2)	42 (3)	D > B, C
5.5	37 (9)	27 (5)	28 (3)	61 (6)	D > A, B, C
Potassium output					
0	1.9 (0.3)	1.9 (0.4)	2.1 (0.6)	1.6 (0.3)	–
0.5	5.2 (1.1)	4.6 (0.7)	4.9 (1.5)	5.1 (1.2)	
1.5	10.7 (1.9)	8.5 (0.8)	12.2 (1.1)	18.9 (1.4)	D > A, B, C
3.5	23.3 (3.7)	14.6 (1.0)	18.1 (1.2)	30.9 (1.4)	D > B, C
5.5	28.9 (4.0)	17.9 (1.4)	22.9 (1.7)	37.1 (1.3)	D > B, C

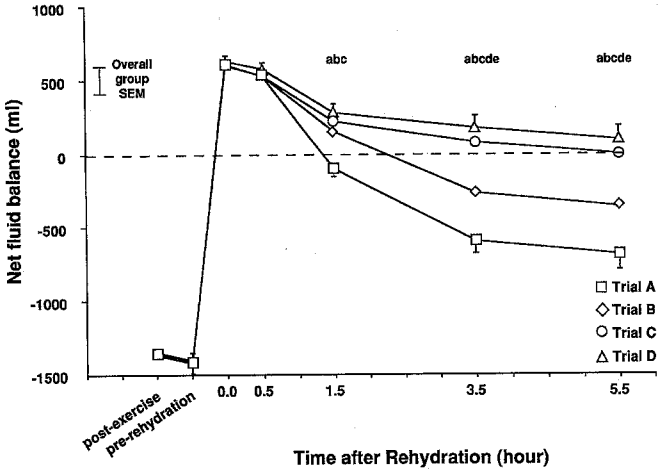

Fig. 3 Net fluid balance, calculated from the volumes of sweat loss, fluid ingested and urine output over the course of the experiment. The pre-exercise urine sample is not included in these calculations

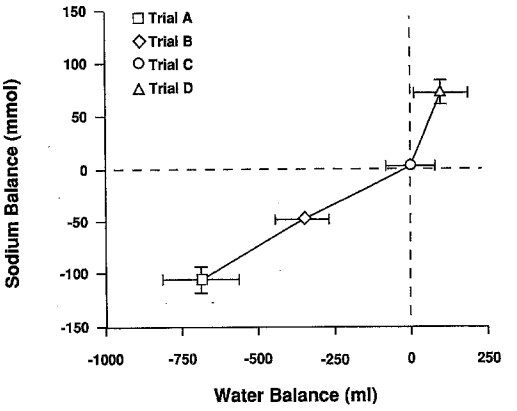

Fig. 4 Relationship between calculated sodium and water balances at the last sampling time point, based on measured input and output, assuming a sodium content of 50 mmol·l^{-1} in the sweat lost during the dehydration period

Table 2 Percentage [mean (SEM)] of ingested drink retained, calculated from the volume consumed and the cumulative urine output

Time after rehydration (h)	Trial				Differences
	A	B	C	D	
0	99 (0)	99 (0)	99 (0)	99 (0)	–
0.5	95 (1)	96 (1)	95 (1)	97 (0)	–
1.5	64 (4)	77 (3)	81 (3)	82 (3)	A < B, C, D
3.5	40 (6)	57 (4)	73 (4)	77 (3)	A < B, C, D; B < C, D
5.5	36 (6)	53 (4)	69 (4)	74 (3)	A < B, C, D; B < D

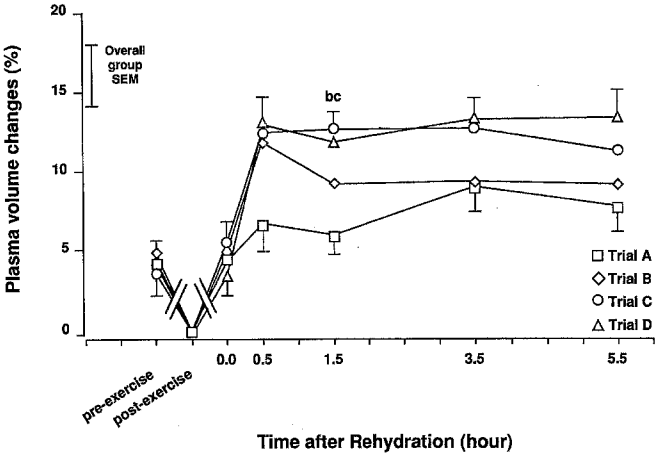

Fig. 5 Changes in plasma volume over time. Plasma volume changes are calculated relative to the sample obtained 45 min after the end of exercise, immediately before rehydration began

end of the study period, 36(6)% of the ingested volume was retained on trial A, 53(4)% on trial B, 69(4)% on trial C, and 74(3)% on trial D. If net sodium balance is calculated from urine and sweat losses (assuming a constant mean sweat sodium concentration of 50 mmol·l^{-1}), a close correlation (Pearson product moment, $r = 0.80$) between net water balance and net sodium balance at the end of the study is observed (Fig. 4).

Blood and plasma changes

No blood samples were collected until 30 min after the end of the exercise period but blood and plasma volumes were still less at this time than before exercise on all trials, with no differences between the different treatments in the magnitude of the calculated decrease (Fig. 5). Over the 5.5 h following completion of the fluid ingestion period, plasma volume increased on all trials, and the pattern of change was essentially similar for all drinks, with a statistically significant treatment effect being observed only at 1.5 h after the end of the rehydration period. Pairwise comparisons (Duncan's multiple range test) revealed a significantly smaller increase in plasma volume on trial A (6.8%) than on trials C (12.4%) and D (12.0%).

No significant treatment effects on serum sodium concentration were observed, nor were any changes in serum sodium concentration observed to occur over time on any of the trials (Table 3). In contrast, both treatment and time effects were observed for serum potassium concentration. There was a trend for serum potassium concentration to fall during the post-ingestion period and to be lower on the trials with the higher sodium intake (Table 4). In trials B and D, serum potassium remained lower at the end of the study period than in the pre-exercise sample, whereas it had returned to the pre-exercise value on the other two trials.

Serum osmolality changed over time on all trials, but Kruskall-Wallis analysis showed no significant differ-

Table 3 Serum sodium concentration [median (range); m mol · l^{-1}] at each time point during the trials

	Trial			
	A	B	C	D
Pre-exercise	139 (135–150)	138 (136–142)	140 (135–141)	139 (136–153)
Post-exercise	138 (135–151)	138 (135–140)	140 (136–143)	140 (138–156)
Time after rehydration (h)				
0	136 (133–151)	138 (135–141)	137 (135–143)	140 (138–153)
0.5	136 (133–150)	136 (134–139)	138 (134–141)	139 (135–151)
1.5	135 (133–151)	137 (135–138)	138 (136–144)	140 (136–150)
3.5	135 (133–148)	137 (135–140)	137 (135–141)	139 (137–148)
5.5	135 (134–146)	137 (135–142)	138 (136–139)	138 (137–150)

Table 4 Serum potassium concentration [median (range); mmol·l^{-1}] at each time point during the trials

	Trial				Differences
	A	B	C	D	
Pre-exercise	4.3 (3.8–5.4)	4.4 (3.8–4.7)	4.2 (3.6–4.8)	4.1 (4.0–4.4)	–
Post-erercise	4.0 (3.6–4.3)	4.1 (3.6–4.6)	4.0 (3.6–4.0)	3.8 (3.7–4.3)	–
Time after rehydration (h)					
0	4.3 (4.1–4.5)	3.8 (3.6–4.6)	4.0 (3.5–4.1)	3.8 (3.4–4.2)	A > C, D
0.5	3.9 (3.7–4.1)	4.1 (3.4–4.5)	3.7 (3.4–4.1)	3.9 (3.4–4.2)	–
1.5	4.0 (3.7–4.1)	3.5 (3.4–4.1)	3.5 (3.5–3.8)	3.5 (3.2–3.7)	A > C, D
3.5	3.9 (3.8–4.0)	3.6 (3.4–4.1)	3.6 (3.4–3.9)	3.5 (3.3–3.6)	A > C, D
5.5	4.1 (4.0–4.4)	3.7 (3.4–4.1)	3.8 (3.6–3.9)	3.6 (3.4–3.9)	A > B, C, D

Table 5 Serum osmolality [median (range); mosmol·kg^{-1}] at each time point on each of the experimental trials

	Trial			
	A	B	C	D
Pre-exercise	290 (272–299)	292 (289–298)	294 (289–298)	290 (278–296)
Post-exercise	294 (277–303)	294 (293–296)	298 (295–300)	292 (278–299)
Time after rehydration (h)				
0	290 (273–299)	291 (286–298)	295 (292–298)	294 (278–300)
0.5	284 (268–294)	287 (282–293)	290 (284–294)	289 (274–297)
1.5	284 (267–294)	287 (285–290)	288 (287–291)	286 (273–291)
3.5	283 (267–289)	288 (286–292)	289 (288–290)	286 (270–292)
5.5	284 (266–290)	286 (282–290)	287 (283–290)	286 (271–291)

ences between treatments at any time (Table 5). There was a tendency for an increase in serum osmolality on all trials between the pre-exercise blood sample and the first post-exercise sample, but this did not reach statistical significance. On treatments A, B and C the osmolality was lower than the initial value at all times after the 1.5-h post-rehydration sample, but no such significant difference was observed for treatment D.

Drink acceptance and palatability

No significant differences between drinks were observed in the subjects' responses to any of the palatability questions, although some trends were evident (Table 6). It should be borne in mind that these were not commercially formulated test beverages, but were concocted using a low-calorie, low-electrolyte lemon drink

Table 6 Drink acceptability [mean (range)] was assessed using a 10-cm visual analogue scale. In the scale "0" indicated minimum and "10" for maximum rate for each factor

Acceptability factor	Trial			
	A	B	C	D
Initial taste				
Refreshing	7 (3–10)	7 (5–9)	6 (5–7)	5 (0–8)
Thirst quenching	6 (3–10)	7 (5–8)	6 (5–8)	5 (1–8)
Sticky mouth feel	5 (0–8)	6 (2–8)	6 (2–9)	5 (2–10)
Sweet taste	5 (2–8)	6 (3–8)	6 (5–9)	5 (2–9)
Salty taste	1 (0–2)	2 (0–7)	2 (0–7)	4 (0–9)
Fruity taste	6 (3–8)	6 (5–7)	7 (5–7)	5 (3–7)
Soapy taste	4 (2–5)	3 (0–5)	4 (1–7)	6 (3–10)
Final taste				
Refreshing	5 (4–7)	6 (2–9)	4 (1–6)	4 (0–6)
Thirst quenching	5 (2–9)	6 (2–9)	5 (5–6)	5 (1–7)
Sticky mouth feel	4 (1–9)	5 (1–8)	4 (1–9)	6 (2–10)
Sweet taste	6 (2–9)	6 (3–9)	6 (5–8)	6 (4–7)
Salty taste	1 (0–2)	2 (0–4)	3 (0–7)	4 (0–10)
Fruity taste	6 (3–9)	5 (4–7)	5 (4–7)	5 (0–8)
Soapy taste	4 (2–5)	4 (1–8)	5 (1–7)	6 (2–10)

with the addition of glucose and sodium salts. In spite of the variations in the sodium content of the test drinks, and of the extremely high sodium concentration (100 mmol·l^{-1}) in solution D, the tendency for ratings of saltiness to increase as the sodium concentration increased was not statistically significant. No subject complained at any time about the taste of any of the drinks or about the volume of fluid that they were required to consume.

Discussion

The results of this study demonstrate that addition of sodium to fluids ingested after exercise-induced dehydration has an effect on the restoration of fluid balance. From 90 min after the end of the rehydration period onwards, a significant effect of the sodium content of the ingested fluid on the cumulative urine output was observed. Urine volume over the few hours after ingestion of the test solutions was inversely proportional to the sodium concentration of the drinks ingested. In this study, a total volume of approximately 2050 ml was consumed on each of trials after exercise, and the difference in total urine output between the sodium-free solution and the drink with the highest sodium concentration amounted to 359 ml after 1.5 h and to 765 ml after 5.5 h. Considering the small volumes of fluids which athletes habitually ingest during exercise, these volumes are of some significance for situations where a further bout of exercise must be performed.

Previous studies have shown that the ingestion of plain water after exercise-induced dehydration results in a rapid fall in plasma osmolality and in the plasma sodium concentration (Nose et al. 1988a), and both of these effects will stimulate urine output. In the present study, a large volume of dilute urine was produced after ingestion of the drink with the lowest sodium concentration (2 mmol·l^{-1}); in the 60 min between 0.5 h and 1.5 h after the end of drinking, urine output amounted to 634(73) ml on trial A, 378(68) ml on trial B, 308(58) ml on trial C, and to only 298(70) ml on trial D. There was, however, no difference in the serum sodium concentration between trials at any time point, nor did the serum sodium concentration change over time on any of the trials. The reason for the better maintenance of the circulating sodium concentration in the present study than in earlier reports is not clear. In the study of Nose et al. (1988a), an ad libitum fluid intake was allowed, and the replacement volume consumed over 3 h was 1100 ml when plain water was taken, and 1216 ml when water plus sodium chloride was ingested; the mean fluid loss during the rehydration period was 1619 ml and 1417 ml respectively, for the two trials. In spite of the negative fluid balance which persisted, therefore, the subjects showed a fall in serum osmolality and sodium concentration.

The absence of a difference in serum sodium concentration between trials in the present study may be explained by two factors. One is a trend for the urinary sodium output to be related to the intake, but this effect in itself cannot account for more than a small part of the total sodium exchange. Total sodium intake was 4(0) mmol on trial A, 53(3) mmol on trial B, 107(5) mmol on trial C and 207(9) mmol on trial D. The cumulative urinary losses during the post-rehydration period on these four trials were 37(9), 27(5), 28(3) and 61(6) mmol, respectively. Sweat sodium losses were not calculated owing to the difficulties in obtaining a reliable estimate of the sweat sodium concentration, but the volume loss was the same on all trials and it is reasonable to assume that sodium losses were also not significantly different between trials. A second factor contributing to the absence of a difference between trials in serum sodium concentration is the greater expansion of plasma volume on the trials where sodium was added to the test drinks. Although the magnitude of these differences is rather small, similar changes are also likely in the extravascular extracellular space, which would accommodate some of this sodium. On trial D, plasma volume was expanded by a mean of 9.6% at the end of the study period relative to the pre-exercise value. Assuming that the total body water content of these subjects was 38.9 l and that the extracellular space amounted to 17.2 l (Moore et al. 1963), this would represent an expansion of the total extracellular space of 1650 ml if the relative expansion of the extracellular fluid was the same as that of the plasma volume. This last assumption seems reasonable in view of the rapid exchange of water between the plasma and the extracellular fluid, but cannot be verified from the available data.

Comparisons between trials permit some calculations to be made regarding the disposition of the ingested sodium. At the end of the measurement period, the mean difference in net fluid balance between trials A and D is 787 ml. If all of this is accounted for by extracellular fluid, the amount of sodium in this space would be 112 mmol. Considering the assumptions involved, this is reasonably close to the calculated difference of 140 mmol between sodium intake and urinary sodium output. The volume difference between trials A and C was 687 ml, corresponding to 98 mmol of sodium. The calculated difference between sodium intake and urinary loss on trial C was 79 mmol.

The subjects did, of course, incur a sodium deficit by the loss of sodium-containing sweat during the exercise period, and this must be taken into account in any calculations of electrolyte balance. A wide range of values for the sodium concentration in sweat is to be found in the published literature, with most values being in the range 20–80 mmol·l^{-1} (Costill 1977; Verde et al. 1982). If a value of 50 mmol·l^{-1} is accepted as an average, the mean sodium loss during these trials would have been approximately 70 mmol on each of the trials. On trial A, therefore, where sodium intake was only about 4 mmol and urine sodium output amounted to 37 mmol, subjects would have been in negative sodium balance to the extent of about 103 mmol at the end of the trial, as well as in net negative water balance of 689 ml. Again, the numbers correspond well with the assumption that the fluid deficit is drawn from the extracellular space; based on the measured mean serum sodium concentration in this study, 689 ml of extracellular fluid contains approximately 98 mmol of sodium. In contrast, the sodium content of 689 ml of intracellular water is no more than about 7 mmol, based on the assumption of an intracellular concentration of 10 mmol·l^{-1} (Lentner 1981). This provides clear, albeit circumstantial, evidence of the validity of the assumption that the fluid deficit incurred is derived primarily from the extracellular space. Applying similar calculations to the other trials produces the data shown in Fig. 4.

These calculations are based on the assumption of a sweat sodium concentration of 50 mmol·l^{-1}, close to the middle of the range of values reported in the literature (Maughan 1991). Substituting a lower value, closer to the lower end of the range of values commonly reported in the literature, disturbs the relationship between the measured balances for water and sodium. Such a value would only be possible if a substantial part of the water loss was derived from the intracellular space. If a higher sweat sodium concentration is substituted, the closeness of the relationship is again disturbed. Substituting a range of values from 10–80 mmol·l^{-1} gives the family of curves shown in Fig. 6. Exact balance for both water and sodium is achieved when a mean value for sweat sodium concentration of 51 mmol·l^{-1} is used. This estimate does, of course, neglect the role of potassium and other cations present in sweat. It may be, therefore, that this results in a slight over-estimate of the sweat sodium concentration.

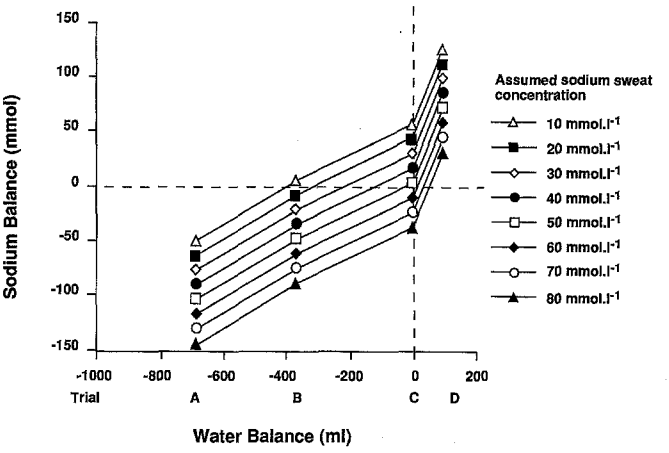

Fig. 6 Calculated sodium and water balances at the end of the trial. These data are obtained by substituting into the calculation values for sweat sodium concentration in the range 10–80 mmol·l^{-1}. If the assumption that the subjects were exactly in water and sodium balance at this time is true, then the mean sweat sodium concentration must have been 51(3) mmol·l^{-1}

Substituting individual data for the mean values used in these sample calculations, and retaining the assumption that all individuals were in exact water and sodium balance at the last sampling point, gives a range of sweat sodium concentrations of 38–61 mmol·l^{-1} [51(3) mmol·l^{-1}] for the subjects used in this study. These calculations result in estimates of sweat sodium composition which are remarkably close to the measured values reported in the literature (Maughan 1991). If total sweat loss and total exercise time are used to calculate the mean sweat rate for the individual subjects, a significant positive relationship between sweat rate and estimated sweat sodium concentration is observed ($r = 0.76$). This provides some circumstantial support for the validity of these calculations, as direct measurements of sweat composition reported in the literature also indicate a positive relationship between sweat rate and sodium concentration (Costill 1977).

The requirement for sodium replacement after dehydration stems from its role as the major cation present in sweat. Sodium is also the most abundant cation of the extracellular fluid; only about 2.4% of the total body sodium content is located in the intracellular space (Edelman and Leibman 1959). It has been speculated that inclusion of potassium, the major cation in the intracellular space, would enhance the replacement of intracellular water after exercise and thus promote rehydration (Nadel et al. 1990). It appears that inclusion of potassium is as effective as sodium in retaining water ingested after exercise-induced dehydration. Addition of either ion will significantly in-

crease the fraction of the ingested fluid which is retained, but, when the volume of fluid ingested is equal to that lost during the exercise period, there is no additive effect of including both ions as would be expected if they acted independently on different body fluid compartments (Maughan et al. 1994). Potassium losses in sweat are low, however, compared with the total body potassium content, and the distribution of the potassium lost in sweat between the different body compartments is unclear. Replacement of sodium, therefore, appears to remain the first priority, even though some degree of intracellular dehydration may persist unless the potassium losses are replaced.

In the absence of any information on the hormonal changes occurring during these trials, the mechanisms responsible for the observed effects remain the subject of speculation. The results do, however, clearly indicate the importance of the sodium content of ingested fluids for the post-exercise rehydration process. They also suggest that, if no other electrolyte source is consumed, there may be benefits in increasing the sodium content of fluids ingested after exercise to levels above those present in most commonly used drinks.

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