

Rehydration following exercise in the heat: a look at alternative formulations and the role of plasma volume expansion in excess diuresis

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This is the preliminary report of a study designed by Luis F. Aragón and carried out in collaboration with Susan Shirreffs at Loughborough University during a forced leave of absence from the University of Costa Rica, between 2005 and 2007. The study was sponsored by the Gatorade Sports Science Institute®.

Background

Rehydrating an athlete or physically active person who incurs dehydration during exercise is important, especially when this person must fully recover within a short period of time such as when practicing twice a day or participating in tournaments. Rapid post-exercise rehydration is difficult to achieve, though, because humans ingesting large fluid volumes will produce large amounts of urine even if they are dehydrated. This will occur even in the presence of continued sweating while resting in the heat, which complicates matters even further.

Why does the body keep producing urine at such high rates, even in a dehydrated state? Sodium provides only a partial answer. It is known that sports drinks with 18 mEq/L of sodium will induce a lower urine output than pure water, but the difference is rather small and will not prevent the subject from reaching a negative fluid balance within a few hours. Shirreffs et al. (1996) were able to revert a 2%BM dehydration and keep the subjects in a slightly positive fluid balance 6 hours after rehydration, but only when providing 150 or 200% of the fluid lost and using a high concentration of sodium (61 mEq/L)⁶. In our own post-exercise rehydration experiments we have seen that drinking such large volumes of fluid in a short period of time is not practical, particularly with such salty fluids.

Interestingly, even with this high sodium content (61 mEq/L) urine output is higher, much higher than the obligatory rate of 1mL/min; at the other extreme, dehydrated athletes exercising in the heat are able to reduce urine output even lower than 1 mL/min for several hours². In their 1995 textbook on renal function, Valtin & Schafer⁷ show that an average normal adult human filters 180L/day, excreting 1.5 and

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D: 6% CHO, 7 mmol/l Na, 50 mmol/l K.
E: Evian water

reabsorbing 178.5, or 99.2% of the filtered load. In one of our studies (unpublished), adult subjects were dehydrated to about 2%BM before rehydrating with 150% of their estimated sweat loss; they were then monitored for four hours at rest. They should have filtered about 30 L, and yet they excreted 3 L of urine, which comes to a reabsorption of only 90% of the filtered load resulting again in a negative fluid balance.

It is clear from the studies of Shirreffs and colleagues that there is a strong effect of ingested volume on urine production. Several authors have tried to “pace” the rehydration process, providing the fluid over a longer period of time in the hope of inducing a lower urine output, but the results are equivocal.^{3, 4, 5, 8} It is possible that the ideal pace of fluid intake has not been identified.

It is also clear from these and other studies that fluids with enough sodium will promote a rapid plasma volume expansion with rehydration. Quick plasma volume restoration may be a great thing during exercise, but it is hereby suggested that it is not so great in the post-exercise rehydration, because it is probably the pure mechanical effect of this plasma expansion that is causing increased diuresis even in the presence of dehydration.

Sodium tends to draw water with it from one fluid compartment to another thru its osmotic effect. Sodium is the most abundant cation in extracellular fluid, its positive charge balanced mainly by chloride. In the intracellular fluid, potassium is the most important cation, with organic phosphates such as creatine phosphate balancing the electric charge. Potassium might be a good electrolyte for post exercise rehydration because it may promote the fluid to go to the intracellular space. This may be the reason why Aragón-Vargas and Madriz showed coconut water (high in potassium but very low in sodium) to be more effective for post-exercise rehydration than pure water¹.

Therefore, the goal of this study was to test different beverage formulations intended to result in a significantly lower acute plasma volume expansion from that obtained with water or a conventional sports drink such as Gatorade, and to evaluate the strength of acute plasma volume expansion as a stimulus for excess diuresis in the presence of moderate dehydration. If a particular beverage formulation could be identified which results in a small acute plasma volume expansion, this beverage would be expected to be better for a quick, effective post exercise rehydration.

More specifically, the purpose of this study was to compare the effectiveness of five drinks at rehydrating subjects following intermittent exercise in the heat. The drinks

evaluated in the study were:

- A: 1% CHO, 6.5 mmol/l Na, 4.5 mmol/l K, 3.3 g/l creatine monohydrate.
- B: 6% CHO (2% glucose, 4% sucrose), 35 mmol/l Na, 10 mmol/l K.
- C: 6% HCO (2% glucose, 4% sucrose), 18 mmol/l Na, 50 mmol/l K, 3.3 g/l creatine monohydrate.
- D: 6% CHO (2% glucose, 4% sucrose), 7 mmol/l Na, 50 mmol/l K.
- E: Evian bottled water.

Methods

Subjects: 10 healthy volunteers (7 male, 3 female), with no known history of cardiovascular, metabolic or renal disease were recruited to take part in the study and all successfully completed it. Their mean \pm SD characteristics were age 21 ± 1 y, height 178 ± 9 cm, mass 74.1 ± 9.7 kg.

Protocol: Five experimental trials were undertaken by all subjects after completion of one familiarization trial. For the latter, subjects undertook a trial in which a shortened version of the experimental sessions was completed. This served to verify that exercise intensity was correct (2 Watts per kg body mass) and ensured the subject could complete the trial.

For the experimental trials, subjects reported to the laboratory once a week, in the morning, for five consecutive weeks. At this time they were in a fasted and euhydrated state after having standardized their lifestyle and diet for the preceding 24h. A baseline urine and blood sample was collected and a subjective feelings questionnaire completed. Subjects then had their nude body mass measured and commenced exercise. The exercise was undertaken in environmental conditions of $34\pm 2^{\circ}\text{C}$ and $62\pm 5\%$ relative humidity and was intermittent in nature with 10 min of cycling being followed by 5 min rest. This pattern was repeated until subjects had lost almost 2% of their body mass. On completion of exercise subjects were allowed a 15 min period in which to have a shower and cool down before having their nude body mass remeasured. They then took a seat in a cooler environment.

Twenty-five minutes after the end of exercise subjects completed a second subjective feelings questionnaire, then, 5 min later (exactly 30 min after the end of exercise) a blood sample was collected from them immediately before they were asked to provide a second urine sample. The one-hour rehydration period then began and subjects consumed a volume equivalent to 150% of body mass loss of one of the five test drinks on each of their five experimental trials (Table 1), with the trial order being allocated according to a balanced randomized design. At the end of the one hour rehydration period subjects completed another subjective feelings questionnaire, and gave a further blood and urine sample. These three procedures were then repeated 1, 2, 3 and 4h later.

TABLE 1: DRINK COMPOSITION

	Drink				
	A	B	C	D	E
Carbohydrate solution (%)	1	6	6	6	0
Na ⁺ (mmol/l)	6.5	35	18	7	0
K ⁺ (mmol/l)	4.5	10	50	50	0
Creatine monohydrate (g/l)	3.3	0	3.3	0	0

For each blood sample 5 ml was collected without stasis. For each urine sample subjects were asked to empty their bladders as fully as possible and to collect the entire sample.

Sample analysis: The glucose and haemoglobin concentration and haematocrit of each blood sample was determined by the GOD-PAP, cyanmethaemoglobin and microcentrifugation methods respectively. Each urine sample's volume was measured.

Statistical analysis: Data is expressed as means \pm SD. Data was analysed by repeated measures ANOVA followed by a one-way ANOVA and Tukey or Dunnett's post hoc tests. Statistical significance was set at $P < 0.050$. Error bars are omitted from some figures for clarity.

Results

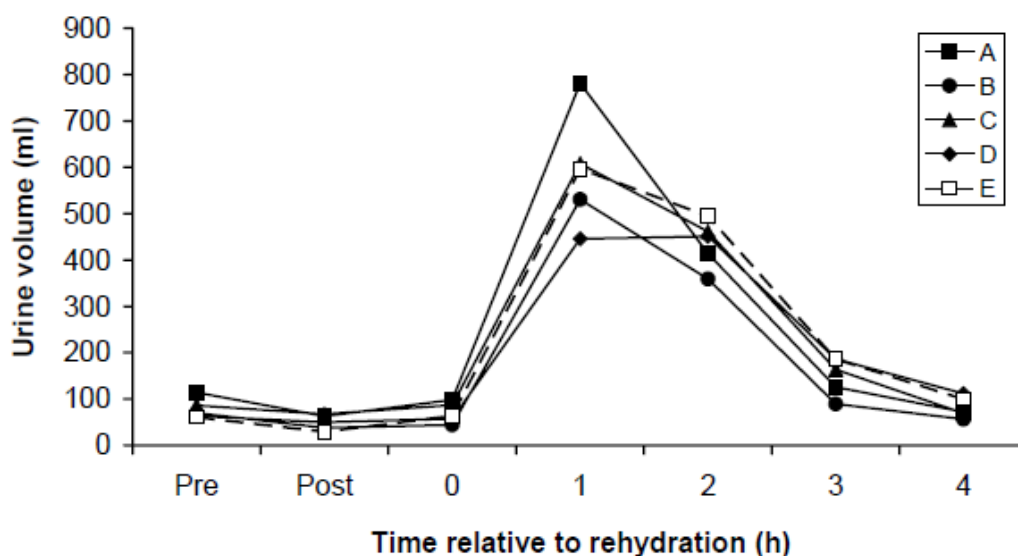
The subjects' pre-exercise body mass was the same for all trials (A, 73.87 ± 9.43 kg; B, 73.75 ± 9.17 kg; D, 74.23 ± 10.29 kg; E, 74.08 ± 10.31 kg; $P=1.000$) and there was a substantial body mass loss over all trials equating to 1.38 ± 0.25 kg by the end of the exercise period. This is equivalent to a level of dehydration of 1.9 ± 0.2 % of pre-exercise body mass.

The time taken to reach the target body mass during the dehydration period was not significantly different between trials ($P = 0.996$), and took on average 52 ± 8 minutes. There was no evidence of heat acclimation or a training effect, as mean sweat rate was the same from week to week over the duration of the study ($P = 0.999$). Sweat loss was similar for each trial, therefore the volume of fluid consumed during the rehydration period was not significantly different between trials ($P = 0.996$), with a mean intake for A of 2096 ± 372 ml, B of 2076 ± 373 ml, C of 2093 ± 411 ml, D of 2073 ± 395 ml and E of 2034 ± 393 ml.

Urine output and fluid balance

Urine volume (Figure 1) was smallest immediately before and after the rehydration period (time point post and 0). Peak urine output occurred between 1-2 hours after the rehydration period with a tendency for urine output to decline over the remaining hours of the study.

FIGURE 1. URINE VOLUME OVER TIME. POINTS ARE DISPLAYED AS MEAN VALUES.



A: 1% CHO, 6.5 mmol/l Na, 4.5 mmol/l K, 3.3 g/l creatine monohydrate
 B: 6% CHO, 35 mmol/l Na, 10 mmol/l K.
 C: 6% HCO, 18 mmol/l Na, 50 mmol/l K, 3.3 g/l creatine monohydrate
 D: 6% CHO, 7 mmol/l Na, 50 mmol/l K.
 E: Evian water

The cumulative urine output from the start of the rehydration period to the end of the study over the course of each trial is shown in figure 2. Repeated measures analysis of variance indicated there was a significant difference between trials over the duration of the study ($P = 0.14$). However, there was no difference between trials in the total volume of urine produced by the end of the trial ($P = 0.120$; figure 3).

FIGURE 2. CUMULATIVE URINE VOLUME FROM THE START OF THE REHYDRATION PERIOD TO THE END OF THE STUDY. POINTS ARE DISPLAYED AS MEAN VALUES.

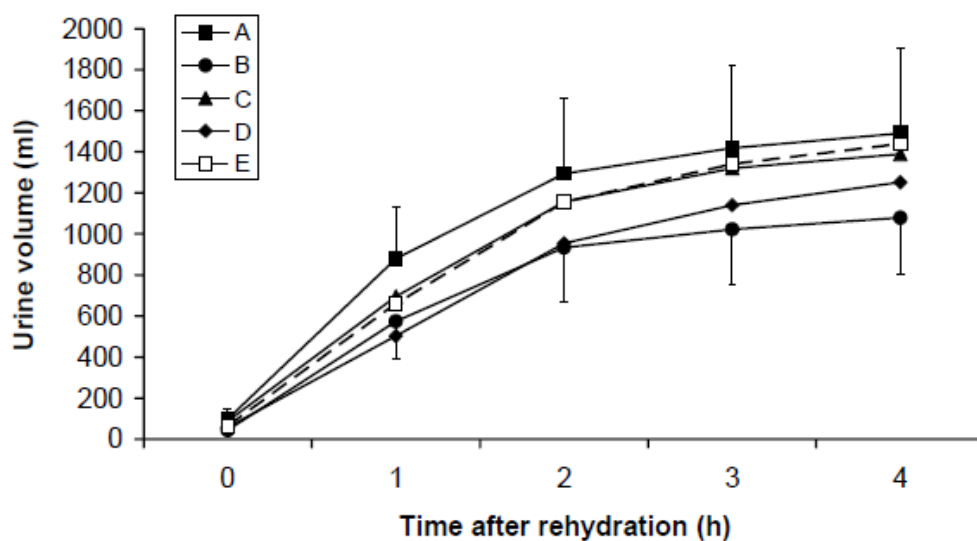
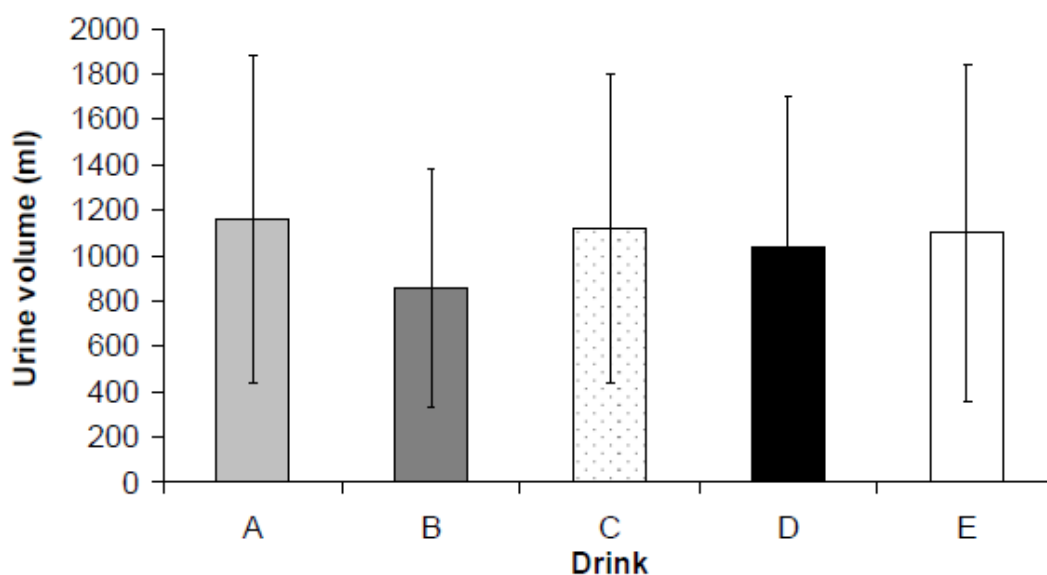


FIGURE 3. TOTAL VOLUME OF URINE PRODUCED OVER THE REHYDRATION AND RECOVERY PERIOD. POINTS ARE DISPLAYED AS MEAN VALUES

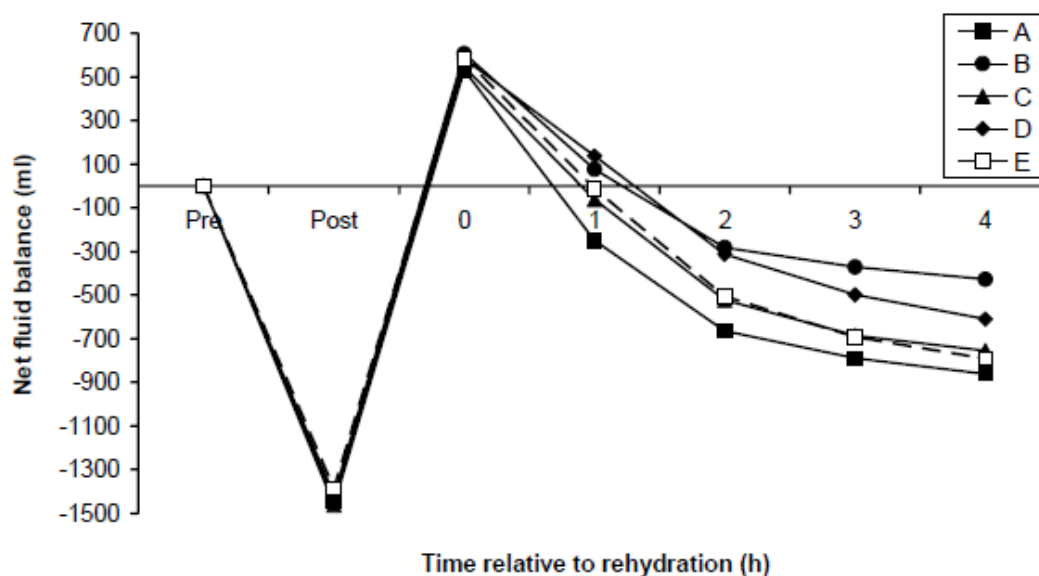


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Whole body net fluid balance (figure 4) was calculated from the volume of sweat lost during the dehydration period, the volume of drink consumed during the rehydration period and the urine volume produced over the subsequent hours. There was a significant difference between trials from 1h after the end of the rehydration period until the end of the study ($P > 0.028$) such that subjects were in a more positive hydration status on Trial B than they were on trial A. There were no other differences between any trials at any time. However, on all trials subjects returned to and remained in a state of negative fluid balance from 2 hours after the rehydration period.

FIGURE 4. WHOLE BODY NET FLUID BALANCE. PRE-EXERCISE URINE VOLUMES WERE NOT INCLUDED IN THESE CALCULATIONS. POINTS ARE MEAN VALUES.



Blood volume change

Changes in blood, plasma and red cell volume were calculated from measures of haemoglobin concentration and haematocrit according to Dill and Costill (1974). All calculations were made relative to the post-exercise time point.

There was no difference between trials in the calculated change in either blood ($P = 0.734$, figure 5) or plasma volume ($P = 0.595$, figure 6). There was a tendency for a change in blood volume over time, but this did not reach statistical significance ($P = 0.077$). The increase in plasma volume at the end of the rehydration period (0h) on trial A was significantly greater than both the pre and post exercise values ($P = 0.006$). Similarly on Trial C, the increase in plasma volume 1 and 3h after the end of the rehydration period was greater than the post-exercise value.

FIGURE 5. CALCULATED CHANGE IN BLOOD VOLUME. CALCULATIONS ARE MADE RELATIVE TO THE POST-EXERCISE BLOOD SAMPLE. POINTS ARE MEAN VALUES.

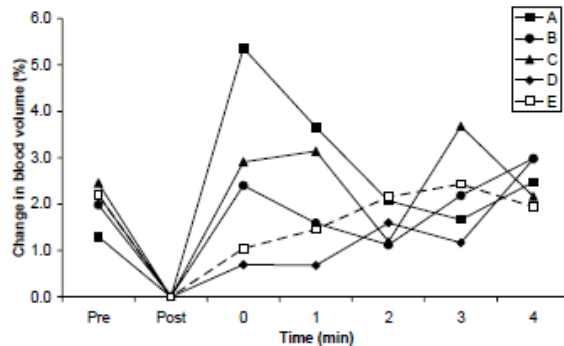
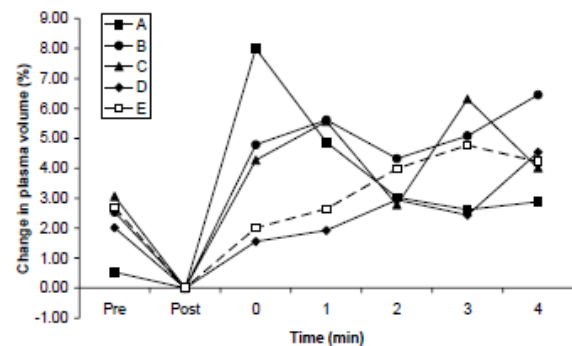
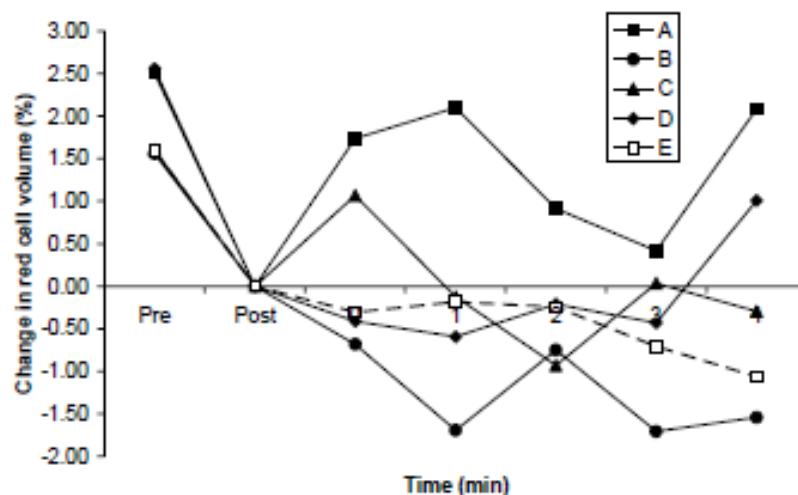


FIGURE 6. CALCULATED CHANGE IN PLASMA VOLUME. CALCULATIONS ARE MADE RELATIVE TO THE POST-EXERCISE BLOOD SAMPLE. POINTS ARE MEAN VALUES.



There was no difference between trials in the calculated change in red cell volume ($P = 0.507$, figure 7) and neither were there any significant changes over time ($P = 0.144$).

FIGURE 7. CALCULATED CHANGE IN RED BLOOD CELL VOLUME. CALCULATIONS ARE MADE RELATIVE TO THE POST-EXERCISE BLOOD SAMPLE. POINTS ARE MEAN VALUES.



Drink perception

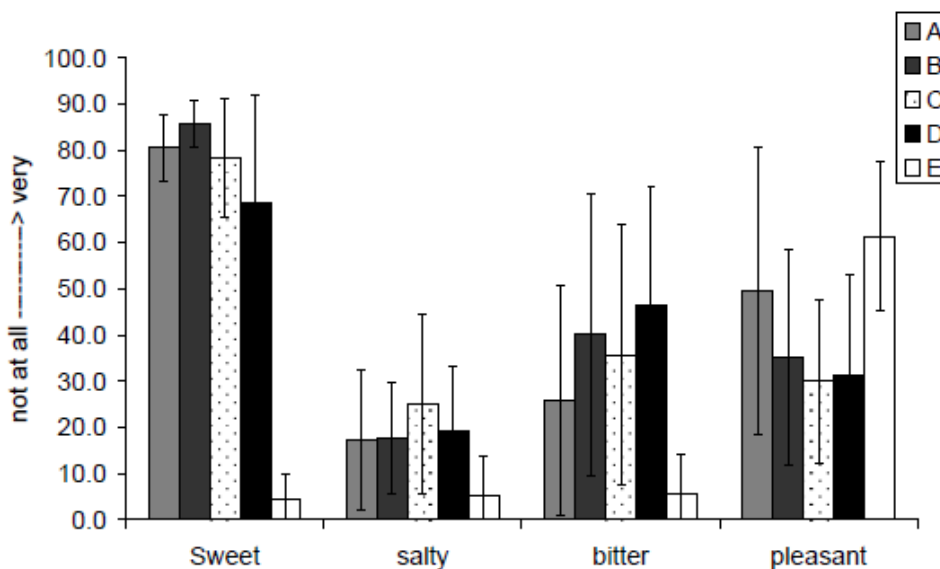
No subject had any difficulties consuming the drinks. Drinks A, B, C and D were not reported as being more or less pleasant than each other (figure 8). However, Drink E (Evian water) was reported as being significantly more pleasant than both Drinks C and D ($P < 0.037$).

Drinks A, C and D were all reported as being similar in sweetness, while drink B was perceived as being sweeter than Drink D ($P = 0.034$, figure 8). Drink E was less sweet than all the other drinks ($P = 0.000$).

None of the drinks were perceived as being salty with average ratings ranging from 5.4 out of 100 for water (Drink E) to 25.2 out of 100 for Drink C (figure 8). With the exception of drink C being perceived as more salty than drink E ($P = 0.025$), the drinks were reported to be of similar saltiness.

The drinks were recorded as being similar in bitterness with the exception of Drink E which was reported to be less bitter than Drinks B and D ($P > 0.026$, figure 8).

FIGURE 8. DRINK PERCEPTION. BAR HEIGHTS ARE MEAN VALUES.



Subjective feelings

There was a large inter-individual variability in subjects' subjective feelings. However, there was no significant difference in the feelings of the subjects between trials in any measure assessed.

Subjects reported to be very thirsty immediately after the dehydration period, but this was suppressed immediately after the rehydration period (figure 9). However it returned to starting levels by the end of the study. By the end of the rehydration period subjects generally felt that their stomach was very full regardless of the drink consumed (figure 10) but no drink suppressed hunger for a prolonged period and in general subjects ended each trial feeling hungry (figure 11). The feelings of tiredness

(figure 12), alertness (figure 13), and ability to concentrated (figure 14) fluctuated over the course of the study but did not differ between trials at any time.

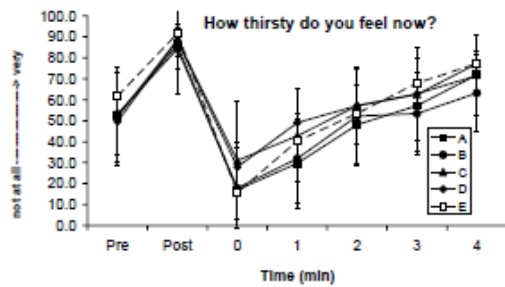


FIGURE 9. SUBJECTIVE FEELINGS OF THIRST.

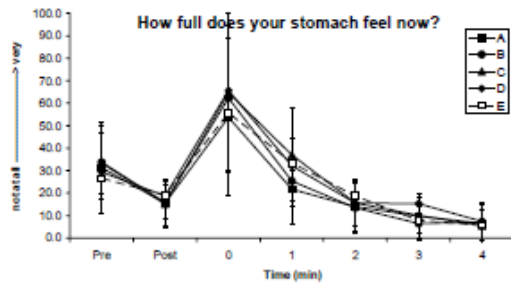


FIGURE 10. SUBJECTIVE FEELINGS OF STOMACH FULLNESS.

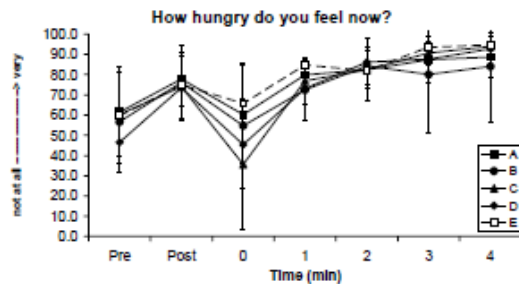


FIGURE 11. SUBJECTIVE FEELINGS OF HUNGRY.

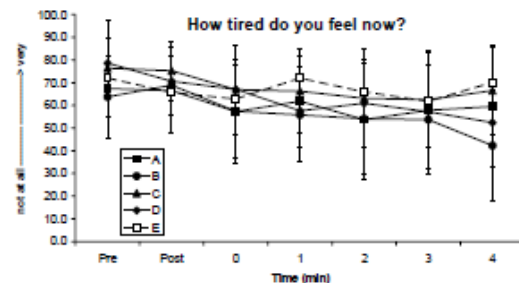


FIGURE 12. SUBJECTIVE FEELINGS OF TIREDNESS.

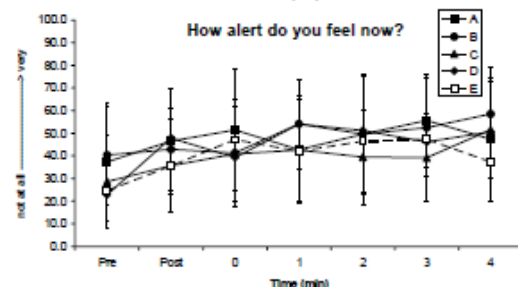


FIGURE 13. SUBJECTIVE FEELINGS OF ALERTNESS.

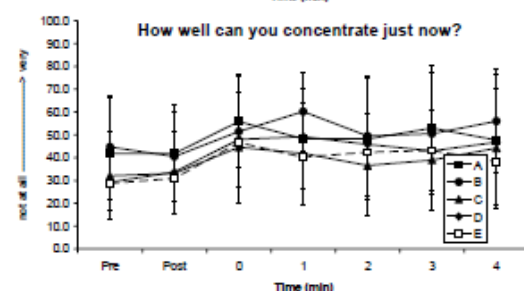


FIGURE 14. SUBJECTIVE FEELINGS OF CONCENTRATION.

Discussion

In short, the results of the study were not as expected, with the exception of the timeline of the plasma volume expansion and cumulative urine output for drink A, the low-carbohydrate, low-electrolyte drink with creatine monohydrate. In this case, the increase in plasma volume immediately post rehydration was paralleled by a quick increase in urine output, more marked than for the other drinks. After the four hours of follow-up, however, cumulative urine output was similar for all beverages.

Drinks with a high potassium content were significantly less pleasant than bottled water, but not different from the other CHO-electrolyte drinks. Otherwise, there were no important palatability issues with the drinks at this intake volume (approximately 2 liters). We would expect very clear differences between the bottled water (E) and all high-electrolyte beverages (B, C, and D) in the rating of saltiness, as the latter all contained 45 mmol/L of chloride salts (sodium and potassium) or more, but only drink C was significantly different from water and even then not very high in rating (25.2 on a scale from 0 to 100); this is a puzzling result. Subjective feelings of thirst, fullness, hunger, tiredness, and alertness behaved as expected over time, but there were no significant differences among drinks.

The most important result from this study was that no difference in fluid retention was observed among drinks. This is surprising, because even if the new, experimental drinks could have failed to achieve a lower urine output, conventional sports drinks with a 6% CHO concentration and 20 mmol/L or more sodium have been shown to result in lower urine output than bottled water^{1,6}. We are unable to explain this discrepancy with our study, as it is not apparently an issue of statistical power. Because a pilot study (unpublished) using a slightly different formulation for the high-potassium beverages showed a different tendency, the validity and potential of the rationale presented in this report should not be discarded. This issue warrants additional research.

A final word is necessary regarding the formulation of high-potassium drinks, for the sake of future experiments. In our pilot study, several participants experienced severe diarrhea with two of the drinks. We proceeded to stop the experiments and reveal the code for the drinks. The problematic beverages were both the high-potassium drinks, which had been formulated with monopotassium phosphate, a conventional ingredient of commercially available sports drinks. This ingredient is innocuous at the normally used concentrations, but in the case of the present study, the amount needed to provide 50 mEq/L of potassium was too high. At the required concentration, monopotassium phosphate works as a laxative in humans. The experiment reported hereby used potassium chloride, which caused no digestive problems.

References

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