Sodium replacement and fluid shifts during prolonged exercise in humans

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Abstract In the study presented here, we examined the effects of a close to complete replacement of sweat water and Na⁺ losses on fluid shifts during exercise. Six cyclists performed three 4-h rides at 55% of their peak oxygen uptake in a 20°C environment while consuming 3.85 l of an 8% carbohydrate solution containing 5, 50 or 100 mEq l⁻¹ of Na⁺. Increases in Na⁺ intake reduced renal free water clearance from around 40 ml h⁻¹ to −8 and −121 ml h⁻¹ and led to a decrease in urine volume from =1.0 to 0.5 l (P < 0.05). In contrast, the 3.5–3.9 l fluid and 150–190 mEq Na⁺ losses in sweat were similar in each trial, as were the =80 mEq K⁺ losses in sweat and urine and the 282–288 mosmol kg⁻¹ plasma osmolalities. During the low-Na⁺ trial, plasma osmolality was maintained by a =1.3 l contraction of extracellular fluid (ECF) with the loss of =200 mEq Na⁺. However, in the other trials, =1.3 l of water was lost from the intracellular fluid. During the medium-Na⁺ trial, a loss of only =40 mEq Na⁺ maintained ECF volume, and during the high-Na⁺ trial, a gain of =160 mEq Na⁺ expanded the ECF by =0.8 l. However, corresponding changes in plasma volumes from −0.20 to 0.15 l had no effect on cardiovascular drift or thermoregulation. These data suggest that during prolonged exercise of moderate intensity under mild environmental conditions when sweat rates are =0.9 l h⁻¹, complete Na⁺ replacement maintains plasma volume and reduces dehydration, but when fluid intake matches sweat rate, has little effect on plasma osmolality.

Keywords Sweat · Urine · Dehydration · Electrolytes · Water compartments

Introduction

If no fluid is ingested during prolonged exercise, plasma sodium concentration ([Na⁺]) and osmolality rise to values that depend upon the loss of water and electrolytes in sweat (Cade et al. 1972; Greenleaf and Brock 1980; Montain and Coyle 1992b; Powers et al. 1990). Plasma osmolality rises because more water is lost in sweat than Na⁺ and the water can come from both the extracellular fluid (ECF) and the intracellular fluid (ICF) volumes (Nose et al. 1988a). Since increases in plasma osmolality and falls in plasma volume (PV) reduce skin blood flow (Montain and Coyle 1992a; Nose et al. 1990), it is important for athletes to replace fluid losses in events where dehydration is sufficient to make hyperthermia a primary concern (Coyle and Hamilton 1990; Nadell et al. 1990; Noakes 1993). High rates of fluid replacement help to maintain thermoregulation by preventing increases in plasma [Na⁺] and osmolality.

When athletes drink either water or commercially available carbohydrate solutions containing up to 25 mEq Na⁺ l⁻¹ in sufficient volumes to match their sweat rates during prolonged exercise, their plasma [Na⁺] and osmolality decrease to similar extents (Barr et al. 1991; McConnel et al. 1997). Under these circumstances, fluid ingestion prevents increases in plasma osmolality but has no major effect on reductions in PV (Barr et al. 1991; Cade et al. 1972; Greenleaf and Brock 1980; McConnel et al. 1997; Powers et al. 1990). A failure of fluid ingestion to significantly attenuate the declines in PV during exercise is probably due to a decrease in plasma osmolality suppressing the anti-diuretic activity of arginine-vasopressin (AVP). Low plasma AVP concentrations decrease the ECF volume by increasing renal free water clearance at rest and during exercise (Brandenberger et al. 1989; Nose et al. 1988c). A fall in ECF volume prevents a dangerous decrease in plasma [Na⁺] when large volumes of fluid are consumed without electrolyte replacement. These observations raise the question of whether athletes should attempt to
replace all of their fluid and electrolyte losses during prolonged exercise in order to maintain ECF and PV. While most studies have focussed on the replacement of water and carbohydrate during exercise (Dennis et al. 1997), relatively little attention has been paid to the replacement of electrolytes. The ingestion of NaCl at concentrations of up to \( \geq 5\% \) is generally accepted as unpalatable and “may not be normally necessary except when (electrolyte) losses are exceptionally large” (Shirreffs et al. 1996). Electrolyte replacement has been considered important only in studies of rehydration after exercise (Costill and Sparks 1973; Gonzales-Alonso et al. 1992; Maughan and Leiper 1995; Maughan et al. 1994, 1996; Nielsen et al. 1986; Nose et al. 1988b; Shirreffs and Maughan 1998; Shirreffs et al. 1996). During rehydration, the effects of electrolyte intake on ECF and ICF volumes have been well characterised, but in studies of dehydration during exercise, the main interest has been on the falls in PV rather than on fluid balance and inter-compartmental fluid shifts (Barr et al. 1991; Cade et al. 1972; Greenleaf and Brock 1980; McConnel et al. 1997; Powers et al. 1990).

In the study presented here, we examined how electrolyte replacement effects fluid shifts during exercise in six cyclists who rode at 55% of their peak oxygen uptake (\( \dot{V}O_2\text{peak} \)) for 4 h in a moderate (20°C) environment and replaced their sweat losses with fluid containing Na\(^+\) at final concentrations of 5, 50 and 100 mEq\(\cdot\)L\(^{-1}\). Our hypothesis was that replacement of all of the Na\(^+\) and water lost in sweat would improve the overall fluid balance and maintain plasma [Na\(^+\)] and PV during exercise.

**Methods**

Six endurance-trained cyclists, who regularly rode for > 90 min-day\(^{-1}\) on 4-6 days\(\cdot\)week\(^{-1}\), participated in this study. The study was approved by the Research and Ethics Committee of the Faculty of Medicine of the University of Cape Town, and all subjects gave their written, informed consent to participate, before the trial.

**Subjects and preliminary testing**

The mean (SEM) age, mass, height, predicted surface area (\(A_D\)), estimated PV, \(\dot{V}O_2\text{peak}\) and sustained peak power output (\(W_\text{peak}\)) of the subjects were 23 (1) years, 80 (3) kg, 182 (2) cm, 2.02 (0.02) m\(^2\), 3215 (44) ml, 4.8 (0.2) l\(\cdot\)min\(^{-1}\) and 395 (10) W, respectively. \(A_D\) was predicted from the subject’s mass and height using the equation of Du Bois and Du Bois (1916). PV was estimated from the subject’s \(A_D\) using the equation of Retslaff et al. (1969). The standard error of estimate for this prediction is 357 ml for (Caucasian) males and 241 ml for non-obese (Caucasian) females (Retslaff et al. 1969).

\(\dot{V}O_2\text{peak}\) and \(W_\text{peak}\) were determined 1 week before the experimental trials in an incremental exercise test to exhaustion on an electronically braked cycle ergometer (Lode, Groningen, The Netherlands), as described by Hawley and Noakes (1992). Results from the incremental exercise test were used to set the work rate in the experimental trials to correspond to 55% of each cyclist’s \(\dot{V}O_2\text{peak}\).

**Experimental trials**

Each subject performed three experimental trials in random order, each separated by 1 week. Experimental trials were undertaken at the same time of day after 24 h of no strenuous physical activity. Equal hydration before each trial was achieved by asking the subjects to consume similar amounts of food and fluid in the 24 h before each ride, and to refrain from ingesting any alcohol or caffeine. Records of each subject’s diet and exercise were kept to aid compliance with the requests over the 3 weeks of testing. Equal hydration was confirmed by similar pre-trial body masses, plasma [Na\(^+\)] and plasma osmolalities (Table 1).

On the morning of a trial, the subjects consumed a standardised breakfast consisting of three slices of toast with jam (\(\geq 100\) g of carbohydrate) and 250 ml of water, 90 min before coming to the laboratory. At the laboratory, each subject urinated, weighed himself in the nude to the nearest 100 g on a Seca precision balance scale (Model 770, Bonn, Germany) and inserted a thermistor probe 10–12 cm beyond the anal sphincter (YSI 400 Probe, Simson Electric, Elgin, Illinois, USA). The thermistor probe was connected to a YSI Telethermometer (Simson Electric) and used to record rectal temperature (\(T_r\)) to the nearest 0.1°C. A three-lead electrocardiogram (Lohmeier M607, Lohmeier, Munich, Germany) was then attached to the subjects chest to monitor heart rate during the trials, and a 20-gauge Teflon cannula was inserted into an antecubital vein and connected to a three-way stopcock. This cannula was used for the collection of venous blood samples (14 ml each) and was flushed periodically with 2–3 ml of sterile saline containing heparin (5 IU.ml\(^{-1}\)) to prevent blood clotting.

The subject then sat for 20 min rest, during which time a resting blood sample was drawn, and an area of his forearm was cleaned with distilled water and dried with a gauze swab, in preparation for the collection of sweat during exercise. Sweat was collected into an electrolyte-free plastic bag (340 x 240 mm), which was attached to the area with waterproof tape, as described by Nose et al. (1988a). In order to minimise any possible hydremosis, successive bags were attached to alternate forearms every 20 min during exercise.

Once the preparations were complete, the subjects entered an environmental chamber that was set at an ambient temperature of 20±1°C, a relative humidity of 70±5% and a wind speed of 2.5 m.s\(^{-1}\) (9 km.h\(^{-1}\)). While in the chamber, the subjects performed a series of eight 25-min cycle rides at 55% of their \(\dot{V}O_2\text{peak}\), separated by 5-min rest intervals. During each rest interval, the subject urinated (if possible), towelled themselves dry and weighed themselves in the nude. The volume of any urine passed was noted and a sample was frozen for subsequent analyses of osmolality and electrolyte content.

During the trials, the subjects drank 400 ml of an 80-g.l\(^{-1}\), 4.5 chain-length glucose polymer solution containing 4.6 mEq.l\(^{-1}\) of Na\(^+\) at the start of exercise, and then consumed 150 ml of the same solution every 10 min until 20 min before the end of the ride. During one trial, the subjects consumed just the carbohydrate-electrolyte solution, and during the other two trials, they also ingested gelatine capsules that contained either 398 or 836 mg of

**Table 1** Measures of hydration status prior to the start of each of the three trials. Data are given as the mean (SEM)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Na(^+) intake (mEq(\cdot)L(^{-1}))</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Starting body mass (kg)</td>
<td>80.4 (3.0)</td>
</tr>
<tr>
<td>Plasma osmolality (mosmol.l(^{-1}))</td>
<td>286.2 (1.1)</td>
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<tr>
<td>Plasma sodium concentration (mmol.l(^{-1}))</td>
<td>136 (0.6)</td>
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