Sodium-free fluid ingestion decreases plasma sodium during exercise in the heat

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Vrijens, D. M. J., and N. J. Rehrer. Sodium-free fluid ingestion decreases plasma sodium during exercise in the heat. J. Appl. Physiol. 86(6): 1847–1851, 1999.—This study assessed whether replacing sweat losses with sodium-free fluid can lower the plasma sodium concentration and thereby precipitate the development of hyponatremia. Ten male endurance athletes participated in one 1-h exercise pretrial to estimate fluid needs and two 3-h experimental trials on a cycle ergometer at 55% of maximum \( V\dot{O}_2 \) consumption at 34°C and 65% relative humidity. In the experimental trials, fluid loss was replaced by distilled water (W) or a sodium-containing (18 mmol/l) sports drink, Gatorade (G). Six subjects did not complete 3 h in trial W, and four did not complete 3 h in trial G. The rate of change in plasma sodium concentration in all subjects, regardless of exercise time completed, was greater with W than with G (\( -2.48 \pm 2.25 \) vs. \( -0.86 \pm 1.61 \) mmol·l\(^{-1}\)·h\(^{-1}\); \( P = 0.0198 \)). One subject developed hyponatremia (plasma sodium 128 mmol/l) at exhaustion (2.5 h) in the W trial. A decrease in sodium concentration was correlated with decreased exercise time (\( R = 0.674; P = 0.022 \)). A lower rate of urine production correlated with a greater rate of sodium decrease (\( R = -0.478; P = 0.0447 \)). Sweat production was not significantly correlated with plasma sodium reduction. The results show that decreased plasma sodium concentration can result from replacement of sweat losses with plain W, when sweat losses are large, and can precipitate the development of hyponatremia, particularly in individuals who have a decreased urine production during exercise. Exercise performance is also reduced with a decrease in plasma sodium concentration. We, therefore, recommend consumption of a sodium-containing beverage to compensate for large sweat losses incurred during exercise.

Hyponatremia; electrolytes; fluid balance

EXERCISE-INDUCED HYPONATREMIA (a plasma sodium concentration of <130 mmol/l, normal range 135–146 mmol/l) has been observed with increasing frequency during the last decade. Hyponatremia has been reported to occur in athletes during or after extraordinary physical efforts, especially in the heat, such as ultramarathons and ironman triathlons (7, 11, 12, 17, 18) and in the marathon (15, 23). Hyponatremia has also been reported with less strenuous exercise like a hike or a short march (24).

The incidence of hyponatremia has been reported to be from 0 to 29% (18, 21). A high proportion of collapsed runners (9%) have, however, been found to have hyponatremia (18). As a consequence, it has been stated that hyponatremia, and not dehydration, has become the greatest health risk among participants in very prolonged endurance events (18). Hyponatremia has been associated with life-threatening complications, including grand mal seizures, pulmonary edema, respiratory arrest, and coma with raised intracranial pressure, but also with less severe symptoms such as confusion, uncoordination, and weakness (12, 15, 17, 18, 23, 24).

There is no consensus in the literature regarding the cause of exercise-induced hyponatremia. Hiller et al. (10, 11) have attributed it primarily to salt depletion from massive sweat losses associated with net dehydration. Conversely, others have stated that excessive water intake and abnormal fluid shifts are the major etiologic factors (1, 7, 12, 15–17, 21). A lack of suppression of antidiuretic hormone (ADH) secretion could be another etiologic factor in the development of hyponatremia (8, 12, 15, 24).

The aim of this study was to assess whether plasma sodium concentration could be lowered by replacing sweat losses with a sodium-free beverage during exercise in the heat, which induces large sweat losses. Furthermore, a comparison was made between water (W) and a sodium-containing sports drink in terms of the change in plasma sodium.

MATERIALS AND METHODS

Subjects. Ten trained men, age 24.8 ± 2.8 (SD) yr, body weight 75.8 ± 6.0 kg, maximum \( V\dot{O}_2 \) consumption (\( V\dot{O}_{2\text{max}} \)) 62.67 ± 7.31 ml O\(_2\)·min\(^{-1}\)·kg\(^{-1}\), participated in this study. Each subject gave written informed consent. The study was approved by the Ethics Committee of the Southern Regional Health Authority of New Zealand.

Maximal aerobic capacity testing. Maximal aerobic capacity (\( V\dot{O}_{2\text{max}} \)) was determined with each subject’s own bicycle on a Kingcycle ergometry system (Kingcycle, High Wycombe, Bucks, UK). The protocol consisted of a warm-up for 7–10 min followed by graded exercise beginning at 150 W for 2 min and increasing by 30 W every 2 min, until voluntary exhaustion (20). Online gas analysis was conducted and recorded every 20 s with the use of a SensorMedics 2900 (SensorMedics, Yorba Linda, CA) gas-analysis system.

Experimental design. All the experimental sessions (1 pretrial and 2 trials) were performed in an environmental chamber maintained at 34°C and 65% relative humidity. One fan was continually on, and subjects had access to a cold damp towel. Subjects wore cycling shorts, shoes, and socks. They cycled on the same system and bicycle as in the maximal exercise test.

Pretrial. A pretrial was performed to estimate each subject’s rate of sweat loss. Subjects were weighed nude after voiding and were asked to cycle at an intensity corresponding to 55% of their \( V\dot{O}_{2\text{max}} \) for 1 h. Twice during this hour the \( V\dot{O}_2 \) consumption values were checked with the Metamax Exergirometry System (Cortex, Frankfurt, Germany), and the cycle intensity was adjusted if necessary. Subjects received 250 ml of distilled W to drink 20 and 40 min after the start of exercise. After completion of the trial, subjects were given one clean cotton towel and were instructed to dry themselves thoroughly after which nude body weight was recorded. Fluid...
loss was estimated by subtracting posttrial body weight from pretrial body weight plus ingested fluid.

Experimental trials. Each subject consumed a diet of his choice before the first trial but was required to eat this same diet before the second trial. The last meal was consumed 2 h before each trial. They were also instructed to drink 1 liter of Gatorade (G; 63 g carbohydrate, 18 mmol/l sodium, and 3 mmol/l potassium) the evening before each trial. On the day of the trial before coming to the laboratory, they could drink W ad libitum. In addition, the subjects were instructed to refrain from strenuous exercise for 24 h before each trial.

The trials were planned to consist of 3 h of cycling at 55% VO2max, during which the subjects consumed either W or a sodium-containing beverage (G). The fluid was given every 15 min at a rate equal to the fluid loss, which was determined in the pretrial. A randomized crossover design was used. At least 7 days separated the trials, which were conducted at the same time of day for each subject. Criteria established for terminating a trial before the planned 3 h were 1) a plasma sodium level <130 mmol/l, 2) a rectal temperature >39.5°C, or 3) volitional exhaustion.

A rectal thermistor was inserted 11 cm past the anal sphincter, and rectal temperature was continuously monitored and recorded at 15-min intervals. Heart rate was monitored (Polar Electro) continuously and was recorded every 15 min. Each subject's rating of perceived exertion (RPE), determined from a Borg scale (3), was recorded every hour.

Nude body weight after voiding and drying was recorded before and after the trial. The urine was collected and analyzed for sodium. The volumes of urine produced during and immediately after the trials were recorded. The amount of sodium lost in the urine was estimated by multiplying the volume of urine produced during and after the trial by the sodium concentration in the urine.

Blood sampling and analyses. During each trial, venous blood samples were obtained from an indwelling catheter (22G, Becton Dickinson, Madrid, Spain) in an antecubital vein. A resting sample was obtained after the subject had been sitting for 10 min. Blood was drawn after 15 min of exercise, at 30 min, and every 0.5 h thereafter. In total, during each experiment 30 ml of blood were drawn. Blood samples were immediately transferred into tubes containing lithium heparin. Whole blood samples were analyzed in triplicate shortly after collection for hematocrit by using microcentrifugation. Microcentrifugation was conducted with a Hawkseye microcentrifuge set at maximal speed for 5 min. The remaining blood was centrifuged, and the plasma was separated for sodium and glucose, and lactate and aldosterone analyses. When analyses were not performed immediately, plasma and urine samples were stored at -80°C. The glucose and lactate assays were done on a Cobas Fara II clinical analyzer (Roche Diagnostics, Basel, Switzerland) in a single run.

Aldosterone was assayed by radioimmunoassay (Coat-a-Count Aldosterone, Diagnostic Products, Los Angeles, CA, A Buck Scientific model PFP7; East Norwalk, CT) flame photometer was used to analyze the blood for sodium changes during the trials, to evaluate for criteria to terminate a trial early if a risk of hyponatremia was present. For sodium values to be used in the statistical data analysis, plasma and urine were analyzed at a later date on a Hitachi 717 analyzer (Hitachi Instruments and Boehringer Mannheim). A coefficient of variation of ~1% was obtained for sodium analyses on the Hitachi analyzer.

Changes in plasma volume (PV) were calculated according to the formula of Van Beaumont (22)

\[
\text{%change } PV = \left(100 - \frac{Hct_{\text{pre}}}{100}\right) \times 100 \left(\frac{Hct_{\text{pre}} - Hct_{\text{post}}}{Hct_{\text{post}}}\right)
\]

where Hctpre and Hctpost are pretrial and posttrial hematocrit samples, respectively.

Sweat loss was estimated by change in body weight corrected for urinary losses and fluid intake. Rates of sweat loss and urine production were calculated by dividing by exercise time.

Statistical analyses. To detect a difference in plasma sodium concentration of 3 mmol/l, a minimum of eight subjects was needed. This was based on a SD of the plasma sodium measurements of 1.5 mmol/l, with a power of 0.90 for paired t-tests with P = 0.05.

T-tests were performed to analyze differences in fluid loss, urinary loss, weight loss, rate of change in plasma sodium concentration, and exercise time in W vs. G trials. Two-way ANOVAs were performed to compare changes over time in plasma sodium, glucose, lactate, and aldosterone concentrations and for heart rate and rectal temperature between W and G. Regression analyses were performed to assess correlations between exercise time and the rates of change in plasma concentration change, and for change in plasma sodium concentration between urinary sodium loss and the change in plasma sodium concentration change over time. Two-way ANOVAs were performed to compare changes over time in plasma sodium concentration change, between urinary sodium loss and the change in plasma sodium concentration change and the rate of urine production, between sweat rate and plasma sodium concentration change, and between RPE and exercise time. Data are expressed as means ± SD. P < 0.05 was accepted as statistically significant.

RESULTS

Trial completion. Four of the ten subjects completed 3 h of cycling in both the W and G trials. Two subjects completed the G trial but terminated the W trials at 2 h and 2 h 30 min because of volitional exhaustion. One subject had to quit the W trial after 1 h 15 min because his rectal temperature exceeded 39.5°C. One subject had to vomit after 2 h 15 min and terminated the G trial. The remaining subjects who quit did so because volitional exhaustion was reached. During the W trial the mean duration of exercise was 2.5 ± 0.6 h, and during the G trial it was 2.7 ± 0.4 h. This difference was not significant.

Plasma sodium. Several blood samples from two subjects were lost; therefore, these two subjects were excluded from the statistical analyses of blood parameters. A two-way, repeated-measures ANOVA for plasma sodium was performed by using only data from trials in which subjects completed 3 h of exercise. Repeated-measures ANOVA confirmed that the plasma sodium decrease was greater (P = 0.0007) with W than with G (Fig. 1). The rate of plasma sodium change was observed to be greater with W than with G when all trials were included, regardless of exercise time (2.48 ± 2.25 vs. 0.86 ± 1.61 mmol·l⁻¹·h⁻¹, P = 0.0198). There was a significant (P = 0.022, R = -0.674) inverse correlation between the rate of plasma sodium change and exercise time. A greater rate of plasma sodium change was correlated with a shorter exercise time.

One subject developed hyponatremia (plasma sodium 128 mmol/l) at 2 h 30 min in the W trial. This subject presented with a decrease in plasma sodium from 144 to 128 mmol/l in this time. He was exhausted and had difficulties with coordination. This was the same subject who vomited after 2 h 15 min in trial G.
Fluid balance and urinary sodium losses. In the pretrial, the mean rate of sweat loss was 1.27 ± 0.22 l/h. Although fluid intake during treatment trials was closely matched to the losses measured in each subject’s 1-h pretrial, a small net weight loss in experimental trials was observed in both treatments (G: 0.52 ± 0.32 kg, W: 0.60 ± 0.42 kg). The rate of fluid loss was not different between treatments (Table 1). Plasma volume decreased over time in both trials, but, similarly, there was no difference between treatments (Table 1). There was no significant correlation between sweat rate and rate of change in plasma sodium concentration.

There was a significant (P = 0.0447) inverse correlation (R = −0.478) between the rate of urine production and the rate of plasma sodium change. A lower rate of urine production correlated with a higher rate of plasma sodium change. Urinary losses were less than the mean in the hyponatremic subject (Table 1).

Plasma glucose and lactate. Plasma glucose concentration decreased significantly (P = 0.0086) over time in both trials, and there was a significant (P = 0.0446) difference between treatments, with a greater decrease with W (Fig. 2). Plasma lactate concentration did not significantly increase over time with exercise, nor was there a difference between treatments.

Plasma aldosterone. Plasma aldosterone concentration progressively increased over time with no difference between treatments. Mean aldosterone concentration increased from 126 ± 50 at rest to 493 ± 123 pg/ml at 3 h with G and from 140 ± 55 at rest to 564 ± 125 pg/ml at 3 h with W.

Heart rate, thermal responses, and RPE. Mean heart rate increased over time in both trials (P = 0.0001). No significant change was detected between G and W. Mean rectal temperature increased in both the G and W trials (P = 0.0001), although no significant treatment effect was observed. RPE increased over time in both trials with no treatment difference. A positive correlation between RPE and exercise time was observed (R = 0.492, P = 0.0276).

**DISCUSSION**

The objective of this study was to assess whether consumption of sodium-free fluid in amounts to match fluid loss, when sweat rates are high, can lower the plasma sodium concentration. Fluid balance and urinary sodium losses. In the pretrial, the mean rate of sweat loss was 1.27 ± 0.22 l/h. Although fluid intake during treatment trials was closely matched to the losses measured in each subject’s 1-h pretrial, a small net weight loss in experimental trials was observed in both treatments (G: 0.52 ± 0.32 kg, W: 0.60 ± 0.42 kg). The rate of fluid loss was not different between treatments (Table 1). Plasma volume decreased over time in both trials, but, similarly, there was no difference between treatments (Table 1). There was no significant correlation between sweat rate and rate of change in plasma sodium concentration.

**Table 1.** Plasma volume changes, fluid intakes, fluid losses, and urinary sodium content

<table>
<thead>
<tr>
<th></th>
<th>Water (n = 10)</th>
<th>Gatorade (n = 10)</th>
<th>Hyponatremic Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma volume change, %</td>
<td>−8.0 ± 4.0</td>
<td>−9.7 ± 6.6</td>
<td>−7.7</td>
</tr>
<tr>
<td>Rate of plasma volume change, %/h</td>
<td>−3.5 ± 2.5</td>
<td>−3.7 ± 2.7</td>
<td>−3.1</td>
</tr>
<tr>
<td>Total fluid intake, liters</td>
<td>3.1 ± 0.9</td>
<td>3.4 ± 0.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Rate of fluid intake, l/h</td>
<td>1.25 ± 0.2</td>
<td>1.20 ± 0.2</td>
<td>1.00</td>
</tr>
<tr>
<td>Rate of urine production, l/h</td>
<td>0.119 ± 0.1</td>
<td>0.082 ± 0.085</td>
<td>0.048</td>
</tr>
<tr>
<td>Rate of estimated sweat loss (total fluid loss − urine loss), l/h</td>
<td>1.35 ± 0.2</td>
<td>1.38 ± 0.21</td>
<td>1.32</td>
</tr>
<tr>
<td>Urine [Na⁺], mmol/l</td>
<td>19 ± 14</td>
<td>49 ± 38</td>
<td>34</td>
</tr>
<tr>
<td>Rate of weight loss, kg/h</td>
<td>0.248 ± 0.151</td>
<td>0.187 ± 0.105</td>
<td>0.372</td>
</tr>
<tr>
<td>Rate of percent change in body weight, %/h</td>
<td>0.33 ± 0.02</td>
<td>0.25 ± 0.15</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Values for water and Gatorade are means ± SD for n subjects. [Na⁺], Na⁺ concentration.
plasma sodium concentration and thereby possibly precipitate the development of hyponatremia. Additionally, a comparison was made between fluid replacement with W and a sports drink (G), which contained 18 mmol/l sodium, in terms of plasma sodium concentration.

The results demonstrate a differential response of plasma sodium concentration with the two beverages. Plasma sodium concentrations decreased to a greater extent with W ingestion than with ingestion of the sports drink, and the rate of sodium change was also greater with W than with the sports drink. This can contribute to the development of hyponatremia. This contention is supported by the fact that one of our subjects actually did develop hyponatremia (plasma sodium 128 mmol/l) at the end of the W trial.

A number of other studies have not been able to demonstrate an effect of beverage sodium content on plasma sodium concentration (2, 4, 5, 9, 19). The study most comparable with the present study was one by Barr et al. (2). During 6 h of intermittent exercise, subjects received plain W or a sodium-containing (25 mmol/l) solution in amounts equal to the fluid loss. Plasma sodium concentration decreased, but there was no significant difference between the two fluid replacement conditions. The difference in results of this study compared with the present study may, in part, be explained by the fact that subjects exercised in an environmental chamber at 30°C and 50% relative humidity, whereas in our study the chamber was set at 34°C and 65% relative humidity. The sweat rate in the present study was 1.36 ± 0.20 l/h with W and 1.38 ± 0.21 l/h with sports drink replacement. In the study done by Barr et al., the sweat rate was considerably lower (0.79 l/h with W replacement and 0.81 l/h with the sodium solution). More fluid was thus lost and replaced with ingested fluids in the present study. Additionally, with an increasing sweat rate, the sodium content of sweat tends to increase (6). It is, therefore, likely that our subjects lost more sodium than did subjects in the study by Barr et al. (2). Furthermore, in the study by Barr et al. subjects excreted 363 ml/h with W ingestion and 323 ml/h with sodium-containing fluid ingestion. In the present study, only 119 ml/h was excreted with W and 82 ml/h with the sports drink. This may have contributed to the more precipitous drop in plasma sodium concentration and the significant difference between the two fluid regimens in the present study.

A few studies have shown a decrease in plasma sodium concentration when fluid was consumed in amounts equal to the fluid loss (2, 13). These studies were both done in the heat (30 and 21°C, respectively). Conversely, plasma sodium concentration is observed to increase when fluid loss is not completely replaced (9, 14, 19) or when subjects drink ad libitum (5). Galun et al. (8) found during a 24-h endurance march that the total amount of W consumed by the marchers correlated inversely with plasma sodium levels. Although they observed a decrease in the glomerular filtration rate (GFR), neither GFR nor free W clearance was significantly correlated with plasma sodium concentration. The fall in GFR was insufficient to account for the hyponatremia observed. Nevertheless, Galun et al. speculated that high levels of ADH because of a lowered plasma volume might be related to the electrolyte and fluid changes occurring during this type of prolonged exercise.

In the present study, a high rate of change in plasma sodium concentration during exercise was observed to be correlated with a decreased time to exhaustion. One could conclude that total fluid loss replacement in the heat with plain W has a negative influence on performance because of decreasing plasma sodium concentration.

In the recent literature, one other case of exercise-induced hyponatremia in a laboratory setting has been reported (1). A male volunteer unexpectedly developed hyponatremia during a research investigation that involved controlled sodium intake and exercise heat acclimation. The subject performed intermittent moderate exercise and was allowed to drink ad libitum, which amounted to 10.3 liters of sodium-free fluid in 7 h. This subject did not sweat more or lose more sodium than the other nine subjects who did not develop hyponatremia, but he did consume more sodium-free fluid. The authors concluded that a large intake and retention of W and a low initial plasma sodium concentration (134 mmol/l) are primary factors in the development of hyponatremia. Furthermore, it was speculated that sodium losses in sweat and urine could exacerbate the situation. This interpretation is not entirely supported by our findings. Our hyponatremic subject was clearly not fluid overloaded and did not have a low initial plasma sodium concentration (144 mmol/l). The finding of reduced plasma sodium concentration (and in 1 instance, hyponatremia) without fluid overload is supported by Speedy et al. (21), who also observed mild hyponatremia (plasma sodium 135 mmol/l) without fluid overload in ultraendurance, multisport triathletes.

However, the question remains why some subjects develop hyponatremia or decreased plasma sodium concentration to a greater extent than do others. Noakes (16) speculates that fluid retention plays a role in the development of hyponatremia. In support of this is a difference in urinary output between subjects in the study by Barr et al. (2) and the present study.

In the present study, the hyponatremic subject produced very little urine, and a low rate of urine production was found to be correlated with a high rate of sodium change. The fact that our hyponatremic subject vomited in one of the two trials is also an indication that this subject may have altered gastric emptying and intestinal absorption. Irving et al. (12) also observed a reduced plasma volume (as was found in the present study), indicating that the fluid gained would be retained in either the gastrointestinal tract or intracellular space. Particularly with pure W ingestion and retention, the gut may act as a “third space” into which some sodium may be temporarily lost, as has been suggested by Noakes (16).
The reduced plasma volume would act as a nonosmotic stimulus for increased fluid intake and increased ADH release, thereby inhibiting free W clearance and exacerbating the decrease in plasma sodium concentration. The plasma volume change in the study by Barr et al. (2), however, was not substantially different from that in the present study. In the present study, however, the warmer and more humid conditions would have resulted in an increased peripheral circulation. The increased peripheral circulation may decrease blood pressure and atrial volume receptor stimulation to a greater extent, thereby increasing ADH and, hence, fluid conservation.

Whatever the initial factors that lower plasma sodium, as Noakes (16) noted, it is the maintenance of a disproportionately large extracellular fluid volume, relative to sodium content, that allows for the development of hyponatremia. It should be borne in mind, however, that, in general, during exercise that induces large sweat losses, fluid deficit and relative hypernatremia occur more frequently than does hyponatremia. Nevertheless, the severity of the health risks associated with hyponatremia makes it worthy of note and consideration when collapsed or otherwise compromised athletes are evaluated.

Even low concentrations of sodium in a beverage can have a large effect on plasma sodium concentration when consumed in amounts to replace large sweat losses incurred during exercise. In the present study, in 2 h, 2.4 liters of G (containing 18 mmol/l) were consumed, which provided 43.2 mmol of sodium. Distributed in ~11 liters of extracellular fluid, this would theoretically provide an increase of 3.9 mmol/l of sodium. The measured difference in plasma sodium concentration between G and W at 2 h was 4 mmol/l (140–136 mmol/l).

It is concluded that, even with lack of fluid overload, a decreased plasma sodium concentration and increased risk of hyponatremia can occur with long-lasting exercise in the heat when only sodium-free fluids are consumed to replace sweat losses. If a sodium-containing beverage is consumed in this situation rather than plain W, the relative sodium deficit can be minimized.

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