Plasma vasopressin and aldosterone responses to oral and intravenous saline rehydration

ROBERT W. KENEFICK,1 CARL M. MARESH,2–4 LAWRENCE E. ARMSTRONG,2–4 JOHN W. CASTELLANI,2 DEBORAH RIEBE,2 MARCOS E. ECHEGARAY,2 AND STAVROS A. KAVOROUS2

1Department of Kinesiology, The University of New Hampshire, Durham, New Hampshire 03824; and Departments of 2Kinesiology, 3Physiology and Neurobiology, and 4Nutritional Sciences, University of Connecticut, Storrs, Connecticut 06269-1110

Received 27 October 1999; accepted in final form 28 June 2000

Kenefick, Robert W., Carl M. Maresh, Lawrence E. Armstrong, John W. Castellani, Deborah Riebe, Marcos E. Echegaray, and Stavros A. Kavorous. Plasma vasopressin and aldosterone responses to oral and intravenous saline rehydration. J Appl Physiol 89: 2117–2122, 2000.—This investigation examined plasma arginine vasopressin (AVP) and aldosterone (Ald) responses to 1) oral and intravenous (IV) methods of rehydration (Rh) and 2) different IV Rh osmotic loads. We hypothesized that AVP and Ald responses would be similar between IV and oral Rh and that the greater osmolality and sodium concentration of a 0.9% IV saline treatment would stimulate a greater AVP response compared with a 0.45% IV saline treatment. On four occasions, eight men (age: 22.1 ± 0.8 yr; height: 179.6 ± 1.5 cm; weight: 73.6 ± 2.5 kg; maximum O2 consumption: 57.9 ± 1.6 ml·kg−1·min−1, body fat: 7.7 ± 0.9%) performed a dehydration (Dh) protocol (33°C) to establish a 4–5% reduction in body weight. After Dh, subjects underwent each of three randomly assigned Rh (back to −2% body wt) treatments (0.9 and 0.45% IV saline, 0.45% oral saline) and a no Rh treatment during the first 45 min of a 100-min rest period. Blood samples were obtained pre-Dh, immediately post-Dh, and at 15, 35, and 55 min post-Rh. Before Dh, plasma AVP and Ald were not different among treatments but were significantly elevated post-Dh. In general, at 15, 35, and 55 min post-Rh, AVP, Ald, osmolality, and plasma volume shifts did not differ between IV and oral fluid replacement. These results demonstrated that the manner in which plasma AVP and Ald responded to oral and IV Rh or to different sodium concentrations (0.9 vs. 0.45%) was not different given the degree of Dh (−4.5% body wt) and Rh and amount of time after Rh (55 min).

arginine vasopressin; oropharyngeal; osmotic load

PROLONGED EXERCISE HEAT STRESS without rehydration (Rh) has been shown to induce a state of hypovolemic hypovolemia (5, 11, 26, 28) and increase plasma arginine vasopressin (AVP) (3, 8) and aldosterone (Ald) (3, 10, 14) concentrations. The response of these fluid-regulating hormones has generally been shown to be lower when subjects were rehydrated, either during or after exercise (31), especially when electrolytes were also given (3, 15). However, to our knowledge, the response of AVP and Ald to various Rh methods, such as intravenous (IV) infusion and oral drinking, has not been fully investigated. Comparison of the responses of these fluid-regulating hormones to differing methods of Rh and, additionally, differing osmotic loads may help to identify which may provide a more effective means of Rh. These findings may have important applications regarding the most efficacious method for Rh for athletes, laborers, and military personnel during subsequent exercise heat stress.

Moses et al. (22, 23) used dehydration (Dh) and IV saline infusion to examine mediators of AVP release and suggested that expansion of plasma volume (PV) after infusion may serve to attenuate the osmotic stimulus for AVP secretion. Francesconi et al. (14) observed reduced Ald responses in subjects who received water or an electrolyte solution before or during exercise. However, the responses of fluid-regulating hormones to IV Rh remain unclear. We are unaware of any investigations that have specifically compared the effects of IV infusion and oral ingestion on AVP and Ald. Therefore, the primary purpose of the present study was to address the following question: After exercise-induced Dh (−4% body wt), what are the responses of plasma AVP and Ald after Rh via different routes (ingestion vs. infusion) of administration? In the present study, Rh occurred over a 45-min period, followed by 55 min of additional standing rest. Given the amount of time allowed for Rh and rest, we hypothesized that plasma AVP and Ald would be similar between these different routes of administration because PV could likely be restored to a similar degree. Use of the IV infusion methodology also permitted us to address a second question: After Dh, what are the responses of plasma AVP and Ald to Rh using different osmotic loads (0.45 vs. 0.9% IV saline)? In this regard, we hypothesized that the 0.9% IV saline treatment would lead to higher plasma AVP and Ald concentra-
tions because of a higher plasma sodium and osmolality (Osm) compared with the 0.45% IV saline treatment.

METHODS

Subjects. Eight men, unacclimatized to heat, volunteered to participate in this investigation. Physical characteristics were as follows: age, 22.1 ± 0.8 (SE) yr; height, 179.6 ± 1.5 cm; weight, 73.6 ± 2.4 kg; maximal O2 consumption (\(\dot{V}O_2\)max), 57.9 ± 1.6 ml·kg\(^{-1}\)·min\(^{-1}\); percent body fat, 7.7 ± 0.9%. Each subject completed a written, informed consent document and a medical history questionnaire after being informed of the purpose of the experiment and possible risks. The Committee on the Use of Human Subjects in Research at the university approved all procedures. Subjects were given a stipend for their participation.

Preliminary measures. \(\dot{V}O_2\)max was determined by using a continuous treadmill running test as previously described (6). The hydrostatic weighing technique described by Katch and Katch (20) was utilized to determine body density. Body fat was calculated from the formula of Brozek et al. (4). Measurement of residual lung volume was made by using a nitrogen washout technique (32) on a pulmonary analysis system (model 1070, Medical Graphics, St. Paul, MN).

Experimental design. Testing involved four treatments, each consisting of two stages: 1) exercise-induced Dh and 2) Rh. The Rh treatment protocols were randomly assigned and separated by at least 14 days. The treatments were as follows: 0.9% IV infusion (0.9% IV); 0.45% IV infusion (0.45% IV); 0.45% saline oral ingestion (0.45% Oral); and no fluid (NF). Subjects were asked to maintain similar diets during the 3 days before each experimental trial and to maintain a 3-day dietary record. These foods diaries were then analyzed for kilocalorie, carbohydrate, fat, protein, sodium, and potassium content (Food Processor II, ESHA Research, Salem, OR). Subjects were asked to refrain from any recreational or exercise training for 24 h before experimental testing. They were also instructed to drink 450 ml of water the night before testing and 450 ml of water the morning of testing and to abstain from eating for 12 h before each experimental treatment.

Experimental treatments. On arrival at the laboratory (0700), subjects provided a urine sample for determination of urine specific gravity (USG) (model A 300 CL, Spartan Refractometer). A USG of 1.023 ± 0.006 (1) was used to verify that the subject was adequately hydrated before each trial. Hydration status was additionally verified by a pre-Dh placement of a butterfly catheter (1.5 in., 16 gauge; Abbott Laboratories, North Chicago, IL), administered the IV infusions in the arm opposite to the indwelling venous cannula. During the 0.45% Oral and NF trials, a cannula was not placed in the opposite arm during the Rh period. The rate of IV infusion was 0.56 ml·kg\(^{-1}\)·min\(^{-1}\). 0.45% Oral consisted of 4 g of a commercial sugar-free flavored beverage (Kool-Aid) dissolved in 889 ml of 0.45% NaCl and 111 ml of distilled deionized water. 0.45% Oral was chilled to 4°C for palatability and was consumed in equal volumes every 5 min over the 45-min period. The composition of 0.45% Oral was 78.6 ± 1.0 meq Na\(^+\)/l, 0.96 ± 0.02 meq K\(^+\)/l, and 2.54 ± 0.07 meq Ca\(^2+\)/l and 145.6 ± 1.1 mosmol/kgH₂O. Fluid intake was 25 ml/kg of pre-Dh body weight. This volume has been shown to be the upper range for fluids orally ingested after exercise-induced Dh (24). Immediately after Rh, subjects assumed a standing posture for 5 min post-Rh.

Physiological measures. During all Dh bouts, the subject’s heart rate and T re were measured every 15 min to monitor physiological strain. Heart rates that exceeded 180 beats/min for fluids orally ingested after exercise-induced Dh (24).

Analysis of blood samples. Blood was transferred to tubes containing EDTA, lithium heparin, or SST gel and clot activator for serum separation, depending on the specifications for each blood variable. Serum or plasma was separated from each sample and stored at −80°C for later analysis. Samples of whole blood were taken for analysis of Hb and hematocrit (Hct). After centrifugation, plasma was separated and analyzed for Osm, sodium (Na\(^+\)), and potassium (K\(^+\)).

Hct was determined in triplicate by the microcapillary technique after centrifugation for 4 min at 9,500 g. Values were not corrected for trapped plasma. Hb was determined in triplicate by the cyanomethemoglobin method (kit 525, Sigma Chemical, St. Louis, MO). Percent change in PV (%ΔPV) was calculated by using the equation of Dill and Costill (13) from appropriate Hct and Hb values. All %ΔPV values were calculated by using post-Dh as the initial time point. Plasma Osm was measured in triplicate via freezing-point depression (microosmometer model 3MO, Advanced Instruments, Needham Heights, MA). Plasma and urine Na\(^+\) and K\(^+\) concentrations were determined in duplicate by se-
Endocrine measures. After extraction on silica columns (DiaSorin, Stillwater, MN), plasma AVP was determined in duplicate by a commercially available radioimmunoassay kit (DiaSorin). AVP values were not corrected for extraction recovery, which was 91.3%. Assay sensitivity was 7.042 x 10^{-7} pg/ml. Serum levels of Ald were determined in duplicate by radioimmunoassay (Diagnostics Products, Los Angeles, CA). Assay sensitivity was 11.0 pg/ml. Within- and between-assay coefficients of variability for both assays were <5%. Concentrations of AVP and Ald were not corrected for %PV.

Statistical analysis. Analysis of variance (treatment × time) with repeated measures was used to compare differences among trials. A Newman-Keuls post hoc analysis was employed to determine significant differences within and between conditions. For the purpose of observing changes in variables measured after Rh, all comparisons were made as an absolute change (Δ) from the post-Dh values and analyzed by using a two-way (treatment × time) analysis of variance with repeated measures. The 0.05 level of significance was selected. All data are presented as means ± SE.

RESULTS

Pre-Dh. Pre-Dh dietary carbohydrate, sodium, and total kilocalorie intakes were similar over the 3 days before each experimental treatment. Pre-Dh body weights were not different (P > 0.05) and were 75 ± 2, 74 ± 3, 74 ± 3, and 74 ± 3 kg for the 0.45% IV, 0.45% Oral, 0.9% IV, and NF treatments, respectively. Pre-Dh plasma and urine Osm, Na⁺, and K⁺ were not different (P > 0.05) among treatments (Table 1).

Table 1. Selected plasma and urine variables pre- and post-Dh

<table>
<thead>
<tr>
<th></th>
<th>Pre-Dh</th>
<th>Post-Dh</th>
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<tr>
<td></td>
<td>0.45% IV</td>
<td>0.45% Oral</td>
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<tr>
<td></td>
<td>0.9% IV</td>
<td>NF</td>
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<td></td>
<td>0.45% IV</td>
<td>0.45% Oral</td>
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<tr>
<td></td>
<td>0.9% IV</td>
<td>NF</td>
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<tr>
<td>Plasma</td>
<td></td>
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<tr>
<td>AVP, pg/ml</td>
<td>5.5 ± 0.8</td>
<td>20.0 ± 1.9*</td>
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<tr>
<td>Ald, pg/ml</td>
<td>410 ± 69</td>
<td>1,551 ± 226*</td>
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<tr>
<td>Osm, mosmol/kgH₂O</td>
<td>284 ± 1</td>
<td>294 ± 2*</td>
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<tr>
<td>Na⁺, meq/l</td>
<td>146 ± 0.4</td>
<td>153 ± 1.0*</td>
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<tr>
<td>K⁺, meq/l</td>
<td>4.3 ± 0.2</td>
<td>4.9 ± 0.1*</td>
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<tr>
<td>Urine</td>
<td></td>
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<tr>
<td>Osm, mosmol/kgH₂O</td>
<td>607 ± 108</td>
<td>499 ± 117</td>
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<tr>
<td>Na⁺, meq/l</td>
<td>61 ± 9</td>
<td>44 ± 6</td>
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<tr>
<td>K⁺, meq/l</td>
<td>83 ± 27</td>
<td>108 ± 33</td>
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Values are means ± SE; n = 8 subjects. Pre- and Post-Dh, pre- and postdehydration; AVP, arginine vasopressin; Ald, aldosterone; Osm, osmolality. Treatment groups are as follows: 0.9 and 0.45% intravenous saline infusion (0.9% IV and 0.45% IV, respectively), 0.45% saline oral, 0.9% IV, and NF treatments, respectively. All data are presented as means with repeated measures. The 0.05 level of significance was employed to determine significant differences within and between trials. A Newman-Keuls post hoc analysis was employed to determine significant differences within and between conditions. For the purpose of observing changes in variables measured after Rh, all comparisons were made as an absolute change (Δ) from the post-Dh values and analyzed by using a two-way (treatment × time) analysis of variance with repeated measures. The 0.05 level of significance was selected. All data are presented as means ± SE.

Table 2. Selected Dh and Rh variables

<table>
<thead>
<tr>
<th></th>
<th>0.45% IV</th>
<th>0.45% Oral</th>
<th>0.9% IV</th>
<th>NF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dh %VO₂max, ml·kg⁻¹·min⁻¹</td>
<td>51 ± 2</td>
<td>50 ± 2</td>
<td>50 ± 3</td>
<td>51 ± 2</td>
</tr>
<tr>
<td>Exercise time, min</td>
<td>190 ± 12</td>
<td>182 ± 8</td>
<td>179 ± 12</td>
<td>180 ± 10</td>
</tr>
<tr>
<td>Post-Dh urine volume, liter</td>
<td>0.34 ± 0.12</td>
<td>0.45 ± 0.15</td>
<td>0.44 ± 0.11</td>
<td>0.48 ± 0.09</td>
</tr>
<tr>
<td>Rh fluid volume, ml</td>
<td>1,880 ± 45</td>
<td>1,856 ± 65</td>
<td>1,889 ± 62</td>
<td></td>
</tr>
<tr>
<td>Post-Dh weight loss, %</td>
<td>4.4 ± 0.07</td>
<td>5.1 ± 0.14</td>
<td>4.5 ± 0.07</td>
<td>4.6 ± 0.07</td>
</tr>
<tr>
<td>Post-Rh weight loss, %</td>
<td>2.1 ± 0.10</td>
<td>2.3 ± 0.07</td>
<td>2.1 ± 0.10</td>
<td>4.3 ± 0.04*</td>
</tr>
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Values are means ± SE; n = 8 subjects. %VO₂max, percentage of maximum O₂ consumption; Rh, rehydration. *Significant difference (P < 0.05) from 0.9% IV, 0.45% IV, and 0.45% Oral treatments.
In the present study, a 4 to 5% exercise-induced Dh caused subjects to become hyperosmotic and hypovolemic, because of hypotonic sweat production. This, in turn, enhanced circulating concentrations of vasopressin and Ald observed post-Dh. Additionally, as is evident from PV and Osm data in the “no fluid” trial, this state of hyperosmotic hypovolemia was maintained when body fluids were not restored. Consequently, concentrations of vasopressin and Ald remained elevated throughout the NF trial. These responses are in agreement with other investigations that have shown that Dh stimulates an increase in these fluid regulatory factors (7, 10). However, it is unknown how different Rh modes (oral vs. IV) or different IV fluids (osmotic stimulus) affect circulating vasopressin or Ald concentrations after exercise-induced Dh. Our findings demonstrate that the manner in which plasma AVP and Ald respond to different Rh modes or sodium concentration (0.9 or 0.45%) was not different, given the period of time allowed for Rh.

**Infusion vs. drinking.** The post-Rh ΔAVP was not different between the 0.45% IV and 0.45% Oral conditions. Additionally, there was no difference observed in plasma Osm between these two treatments, which has been demonstrated to be the major stimulus for AVP release (19). PV has also been shown to be another factor influencing AVP (19). In the present study, %ΔPV was different at 15 min post-Rh between the 0.45% Oral and 0.45% IV treatments. Given the greater time required for fluid to empty the gut, it might be expected that the ΔAVP might not be as great in drinking compared with infusion. Although not statistically significant, however, ΔAVP at 15 min post-Rh fell to a greater extent in 0.45% Oral compared with infusions, despite the lower %ΔPV. One mechanism might be the residual effects of the oropharyngeal reflex, which exerts its influence on plasma AVP concentrations almost immediately (18, 27). During oral ingestion of fluid in animals and humans, the reduction in AVP release seems to be an anticipatory response to the absorption of water and the decrease in plasma Osm after water intake (2, 18, 25, 27, 29, 30). Collectively, these studies suggest that oropharyngeal receptors may initiate a more rapid inhibition of AVP before a decline in plasma Osm or PV is detectable.
humans, oropharyngeal receptors have been implicated in the rapid, transient fall in plasma AVP due to drinking (18, 27). A comparable decrease in plasma AVP may have occurred in 0.45% Oral; however, the 15-min post-Rh measure may have been too late to observe this well-documented response.

The ΔAld was not different among any of the Rh treatments at 15 min post-Rh. However, ΔAld was different between the infusion and ingestion treatments and NF at 35 and 55 min post-Rh (Fig. 3). Changes in blood volume have been shown to be one of the primary influences on Ald secretion (16). Additionally, plasma Ald concentrations have been demonstrated to be affected by circadian variation and dietary sodium and potassium intake (8, 17, 21, 31). The Ald response in this study was primarily determined by factors related to the maintenance of PV for the following reasons. First, experimental testing occurred at the same time of day for each trial. Second, dietary sodium and potassium intake was similar for 3 days before each treatment, and pre-Dh measures of plasma sodium and potassium were not different (Table 1). Third, with the exception of 15 min post-Rh, %ΔPV was not different between infusion and ingestion, and the amount of fluid restored during Rh was not different among these treatments (Table 2).

We also hypothesized that PV shifts would not be different among the Rh treatments because of the consistent volume infused or orally ingested. Costill and Sparks (12) reported that Rh with a glucose-electrolyte solution resulted in a better recovery of PV than did tap water after thermal Dh. Nose et al. (24) reported a greater restoration of PV with a sodium-chloride solution compared with water after exercise-induced Dh. In the present study, both the infused and ingested solutions contained sodium chloride. Because of the similar composition of the oral and IV fluids, post-Rh %ΔPV tended not to be different. The only difference in %ΔPV found among Rh treatments was at 15 min post-Rh. At this time point, the PV recovered to a greater extent in both the 0.9% IV and 0.45% IV trials compared with the 0.45% Oral treatment. By 35 min post-Rh, however, no differences in %ΔPV existed among Rh treatments. The difference observed at 15 min post-Rh was likely due to limitations imposed by gastric emptying (9) and transit compared with IV administration. By 35 min post-Rh, the %ΔPV in 0.45% Oral was not different compared with the IV treatments, and a greater amount of fluid had emptied from the gut and entered the circulation.

0.9% IV vs. 0.45% IV. In the present study, Rh with both 0.9% and 0.45% saline concentrations equally blunted AVP and Ald responses. In previous studies in which subjects received water or an electrolyte solution before or during exercise in a warm environment, plasma AVP and Ald were also reduced (3, 14, 15). We reasoned that the 0.9% saline infusion used in this study would increase the plasma sodium concentration above that of the 0.45% saline treatment and subsequently continue to elevate plasma PV after Rh and stimulate AVP secretion. Although the sodium concentration in the 0.9% IV treatment was significantly greater at 15, 35, and 55 min post-Rh, compared with that in 0.45% IV, plasma Osm was not different post-Rh between treatments, and ΔAVP values were not different. Plasma Osm in the present study did parallel plasma sodium at each of the recovery time points, as previously observed by Nose et al. (24). It is possible that, whereas the volume or concentration of IV saline infused was large enough to cause differences in plasma sodium in the 0.9% IV treatment, it may not have been large enough to cause differences in plasma Osm between the 0.9% IV and 0.45% IV treatments. It is also possible that the addition of 0.9% saline did, in fact, temporarily raise plasma Osm. Because osmotic forces cause water to move between intravascular and interstitial compartments (24), this temporary increase might have caused a fluid shift from the interstitium into the vasculature, thereby reducing plasma Osm and plasma AVP.

In brief, the results of the present investigation demonstrated that the manner in which fluid regulatory hormones responded to different methods of Rh (IV or oral) or sodium concentration (0.9 or 0.45%) was not different between infusion and ingestion, and the amount of fluid restored during Rh was not different among these treatments (Table 2).
different. Clearly, the use of IV reinfusion offers no advantage over oral Rh and is equally effective in restoring fluid volume, given the degree of Dh (−4% body wt) and time permitted for Rh (100 min). This finding is important for individuals who exercise multiple times in 1 day, and our laboratory has shown (6) that there is no performance or thermoregulatory advantage to rehydrating by using IV infusion before the performance of subsequent exercise.

The authors thank Marie Kenefick, Mike Whittlesey, Stavros Kavouras, Dane McFarland, and Dean Aresco for technical support. We also thank the subjects for their participation. Additionally, the authors thank Deborah A. Podolin for editorial assistance.

This work was supported in part by a grant from the Proctor and Gamble Company and a grant from the University of Connecticut Research Foundation.

Present addresses: J. W. Castellani, Thermal and Mountain Medicine Division, US Army Research Institute of Environmental Medicine, Natick, MA 01760–5007; D.Wiebe, Dept. of Physical Education, University of Rhode Island, Kingston, RI 02881; M. E. Echegaray, Dept. of Physiology, University of Puerto Rico, Rio, PR 00927.

REFERENCES


