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ORIGINAL ARTICLE

The Effect of Volume of Consumed Water on Drinking-Induced Sweating and Plasma Levels of Arginine Vasopressin, Epinephrine and Norepinephrine

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The purpose of this study was to investigate the effect of the volume of consumed water on the sweating response and plasma levels of arginine vasopressin, epinephrine and norepinephrine in the first few minutes of drinking.

Materials and Methods: After 4 hours water deprivation, six healthy male medical students were exposed to heat and performed mild exercise under an ambient temperature (2 hours, 38-40°C, relative humidity<30%). Subjects were dehydrated by sweating. They were then allowed to drink water with volumes of 1, 3, and 5 ml/kg of body weight using three separate protocols. Sweat rate was measured by amount of sweat collected from the forehead area in grams during 3 minute periods before and after drinking. Blood samples were drawn before heat exposure, before drinking and then every 3 minutes up to the 15th minute after drinking.

Results: Dehydration increased mean serum sodium ($p<0.001$). Sweating increased markedly just after the onset of drinking ($p<0.01$) and was greater when consumed water was 5ml/kg of body weight. The more the water volume consumed, the greater was the reduction in plasma arginine vasopressin 3 minutes after drinking. The reverse was true for plasma norepinephrine ($p<0.01$), whereas plasma epinephrine was essentially unchanged by drinking.

Conclusion: These data suggest that oropharyngeal sensors that interfere with the activation of sweating response can also manipulate it by consumed water volume. Moreover, the amount of water received affected plasma arginine vasopressin and norepinephrine but not plasma epinephrine which suggests a drinking stimulated neural mechanism.

Key Words: Consumed water volume, Sweat rate, Arginine vasopressin, Epinephrine, Norepinephrine, Oropharyngeal receptors

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Introduction

When the ambient temperature is above body temperature, radiation, conduction and convention all transfer heat into the body rather than out. The only mechanisms left to regulate body temperature are the evaporation of sweating from the skin and the evaporative cooling from exhaled moisture. In hot climates, a substantial volume of body water may be lost via sweating to enable evaporative cooling. One study has shown that dehydrated humans in a warm environment begin to sweat within seconds to minutes after drinking.[1] Another study demonstrated that when dehydrated goats were allowed to drink

after 60 minutes of heat exposure, sweating began abruptly within 3 minutes of the start of drinking in every animal whether water or saline was drunk.[2]

A rapid inhibitory effect of fluid ingestion on thirst and vasopressin (VP) secretion has been documented in studies using water-deprived dogs as experimental subjects.[3] Inhibition of VP secretion occurred within minutes after drinking began, before substantial amounts of the ingested water had been absorbed. These findings suggest that the swallowing of fluid provides an early signal that inhibits VP secretion in dehydrated dogs.[4,5] A similar conclusion regarding the control of VP secretion has been drawn from studies of human[6,7] or nonhuman primates.[8,9] Investigators also observed an increase in plasma norepinephrine (NE), which occurred immediately after onset of drinking which may suggest, as for arginine vasopressin (AVP), a drinking-stimulated neural mechanism.[10]

The effects of volume of consumed water, following dehydration, on drinking induced sweating have not been yet studied. In the present study, we have tried to elucidate the effects of different volumes of water consumed following dehydration on the extent of sweating response and plasma levels of vasopressin, norepinephrine, and epinephrine

Materials and Methods

Subjects

Six healthy male medical students (22-26 (23.7±0.6) years old, weight: 80.7±5.7 kg, and height: 181±2 cm) participated in this study. They were physically active but did not routinely participate in sports or endurance exercise training, nor did they take frequent saunas. All volunteers were familiarized with all the experiment procedures and written informed consent was obtained

Procedure

Experiments started at 4 pm. Pretest instructions included eating a light lunch, refraining from drinking any beverage since 12 noon and abstaining from exercise on the day of an experiment. Before each experiment, subjects rested in the sitting position for 30 minutes at a thermoneutral temperature (28°C). After 8 ml of blood were drawn by venipuncture as the first control sample, subjects entered an environmental chamber (38-40°C, <30% relative humidity) and their body weights were measured. Subjects performed mild physical activity by alternating 10-minutes rest and 20-minutes exercise periods for 60-minutes, and then exercise continued for the last 30- minute period to induce a reduction in total body water through sweating. Air temperature inside the chamber was controlled at 39±1°C and relative humidity was measured at being between 20-28% during the experiment. Total heat exposure time was 120 minutes and subjects were under constant observation for indications of any inability to tolerate the experimental conditions (e.g. elevated heart rate, nausea or confusion).

After the cessation of exercise, subjects dried their body with a towel, were weighed, and then sat on chairs and dried their foreheads. An indwelling cannula was inserted into a large superficial vein in the forearm to collect free-flowing blood samples. Second control blood sample was drawn through the cannula. The first control blood sample comparest the plasma concentrations of sodium, arginine vasopressin (PAVP), epinephrine (PE) and, norepinephrine (PNE) pre and post heat exposure while the second control blood sample was considered as a control to compare values before and after drinking.

Sweat rate was measured before drinking for 3 minutes as a control, and then subjects were allowed to drink tap water at the volumes of 1, 3, and 5 ml/kg of body weight using three protocols. Blood samples (8 ml) were drawn through the indwelling cannula at the start of drinking (0 minute) and at 3, 6, 9, 12, and 15 minutes after drinking. Each sample was immediately divided, so that 6 ml were collected in 3 chilled tubes containing

dry heparin for determination of PAVP, PE, and PNE, which after centrifugation for 15 minutes at 1,000 g and 4°C, aliquots of plasma were frozen and stored at -70°C until the hormone assays were performed. The remainder of the blood sample (2 ml), which had been transferred to a simple tube, was used to determine the plasma concentration of sodium.

Measurements

Forehead sweat rate was chosen to represent a localized area of sweating and was measured by the weight gain of a covered filter paper disk (96 cm^2) placed on the skin over the forehead. The disks were enclosed in a waterproof tape to prevent evaporation. Each time, the disk was left on the skin for 3 minutes. The weight of a filter paper disk was obtained using EK-500 G beam balance, accurate to ±0.01 g. Body weight was measured using a Seca beam balance, accurate to ±100 g. Plasma sodium concentration was determined by eppendorf flame photometry (model EFOX 5054, Instrumentation Laboratory). Because sodium and its associated anions account for about 94 percent of the solute in the extracellular compartment, plasma osmolality could be roughly approximated as: P P_{osm} = 2.1 × Plasma sodium concentration. [PAVP], [PE], and [PNE] values were determined by radioimmunoassay (AVP-RIA Kit, Webster, Texas and Norepinephrine/ Epinephrine-RIA Kit, KatCombi), from the samples mentioned above.

Table 1. Effect of 2-hour heat exposure followed by water drinking with different volumes on plasma osmolality and plasma levels of arginine vasopressin, norepinephrine, and epinephrine

	Pre-heat exposure	Post-heat exposure	Start of drinking	After drinking				
	-120 min	-3 min	0 min	3 min	6 min	9 min	12 min	15 min
Drinking 1 ml/kg body weight								
P_{osm} (mosmol/kgH_2)	302±0.6	309±1.0	309.4±0.9	309±1.0	309±1.4	308.7±1.4	307.4±1.4	306.6±1.5
PAVP (pg/mL)	2.02±0.07	2.88±0.12	2.88±0.08	2.49±0.07†	2.40±0.09	2.02±0.07	2.01±0.07	1.99±0.07
PNE (pg/mL)	215±19	310±13	304±21	339±11	316±24	247±14	227±13	213±13
PE (pg/mL)	39.8±4.0	90.7±1.3	88±3.6	87.7±2.4	83.8±4.9	69.3±5.3	52±5.7	48.2±3.6
Drinking 3ml/kg body weight								
P_{osm} (mosmol / kg H_2O)	305±5±1.0	317.1±1.8	317.4±1.6	317.8±2.1	317.8±2.0	316.7±2.1	316.3±1.7	316.2±1.1
PAVP (pg/mL)	2.03±0.03	2.97±0.07	298±0.07	2.37±0.08†	2.34±0.09	2.03±0.09	2.04±0.07	1.98±0.08
PNE (pg/mL)	211±15	296±17	292±13	378±20‡	349±14	253±18	212±15	213=14
PE (pg/mL)	40.3±3.7	73.2±4.0	72.3±6.2	72.5±5.2	69.2±4.4	60.3±4.8	48.8±3.9	45.2±2.0
Drinking 5ml/kg body weight								
P_{osm} (mosmol /kg H2O)	308.3±0.6	312.9±0.8	313.2±1.4	312.9±0.8	311.8±1.0	311.5±1.5	311.2±1.7	310.5±1.8
PAVP (pg/mL)	1.90±0.07	2.98±0.09	3.01±0.07	2.13±0.08†	2.10±0.09	1.90±0.07	1.85±0.06	1.80±0.07
PNE (pg/mL)	209±13	324±17	319±16	468±18‡	388±19	273±19	227±13	222±18
PE (pg/mL)	37.2±3.0	78.2±2.7	78.2±1.8	76.8±2.3	72.5±3.2	68.3±4.3	54.2±4.8	48.5±2.1

Values are means±SE.

P_{osm}: plasma osmolalityY PAVP: plasma arginine vasopressin; PNE: plasma norepinephrine; PE: plasma epinephrine

* Values obtained in -120 minutes are baseline levels for the minute of -3 while 0 minute acts as baseline for the values coming afterwards; † P<0.0041 and ‡ P< 0.01 compared to baseline.

Plasma AVP (PAVP) was extracted using the Sep-Pack C18 cartridge. 1.0 ml plasma sample was acidified with 150 μl 1 N HCL which was then brought into the column. The column was washed with 20 ml 4% acetic acid. Elution was performed with 4 ml methanol. The methanol was then evaporated to dryness under air. Finally, the dried samples were made using 1.0 ml of assay buffer. The assay sensitivity was 0.5 pg/mL and the intra-assay variations were <10%.

Plasma norepinephrine (PNE) and epinephrine (PE) were extracted using extraction buffer and 0.05 N HCL. The intra-assay coefficients of variance were 4.7% and 4.6% and the detection limits were 10 pg/mL and 3 pg/mL for NE and E, respectively.

Statistical analysis

Data were analyzed by SPSS software, using one-way analysis of variance. The Paired-sample t Test was used for within-group comparisons between control values and the values obtained after drinking. The variations in data were expressed in terms of the estimated 95% confidence interval of the individual differences relative to the mean of the repeated measurements. Values of $p<0.05$ were considered statistically significant, and all data are presented as mean±SE.

Results

Effects of heat exposure and exercise on plasma osmolality

Heat exposure and the performance of exercise significantly raised P_{osm} in all subjects ($p<0.01$; Fig. 1). After heat exposure, just 3 minutes before the drinking, total mean P_{osm} was increased to 312.2±1.2 mosmol/kg H_2O from the baseline level of 304.8±1.0 mosmol/kg H_2O. As it is shown in the Table 1, this was also significant for each of the three protocols. All subjects showed similar dehydration with losing 2.37±0.08% (24.3±1.2 ml/kg water loss) of their respective preheat exposure body weight. There was significant difference between control and other conditions ($p<0.01$) but no significant difference after drinking at different times.

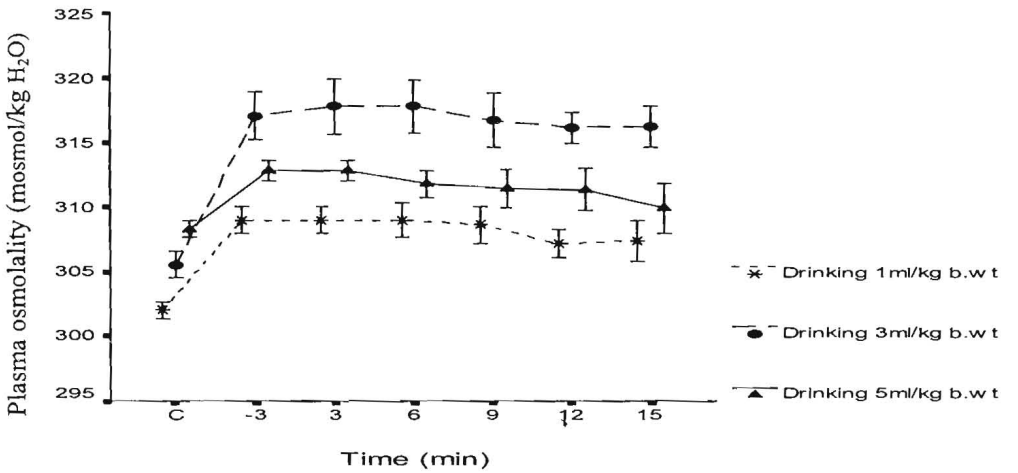

Fig. 1. Changes in plasma osmolality pre and post heat exposure and after drinking. Significant differences were observed for dehydrated (-3 minutes) and rehydrated conditions (3, 6, 9, 12, and 15 minutes) with that of control ($p<0.01$). Values are mean±SE in six subjects.

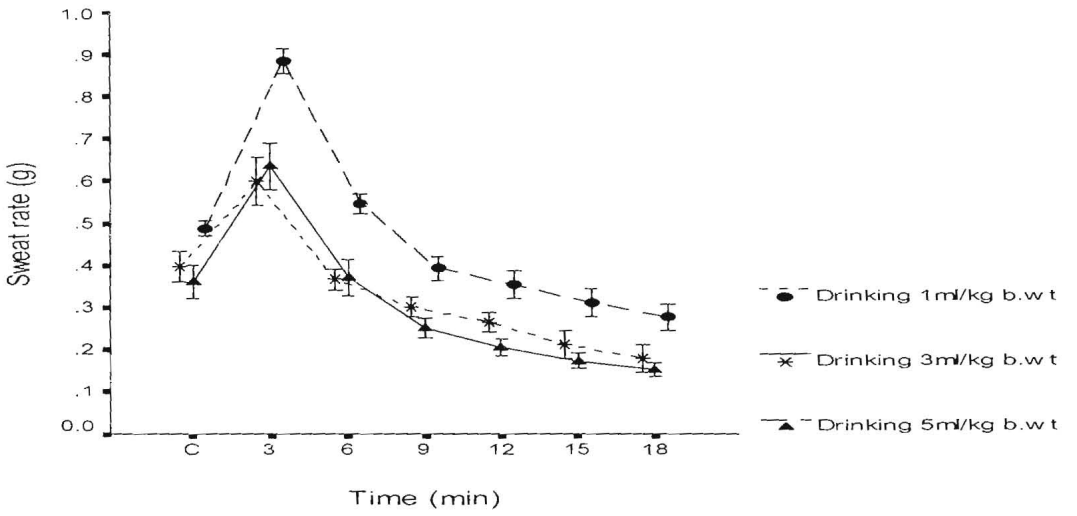

Fig. 2. Effect of drinking water volume on sweat rate. Subjects started drinking at 0 minute. Significant differences were observed for all protocols just after drinking ($p<0.01$). This difference was greatest in water volume of 5ml/kg body weight. Values are mean±SE of six subjects.

Effects of drinking water volumes on sweating

Table 2 and Fig. 2 show mean sweat rates (M_{sw}) in three water volumes (1, 3, and 5 ml/kg body weight). The increase in sweating response became evident immediately after drinking started and reached a maximum within 3 minutes ($p<0.01$). It then fell gradually, becoming significant below baseline in the final stages ($p<0.001$). The extra sweat just after drinking high volume water (5 ml/kg body weight) was the greatest. Elevated percentages of Msw, 3 minutes after the onset of drinking were 51.6±3.7, 75.5±3.9, and 79.7±3.1% regarding the consumed order of the water volume, mentioned above. Comparing Msw within 3 minutes after drinking in the different consumed water volumes showed a significant difference between 1 and 5 ml/kg body weight ($p<0.02$), but there was no significant difference between 3 ml/kg body weight and others.

Effects of water drinking on plasma vasopressin, epinephrine, and norepinephrine

The 2-hour period of heat exposure and exercise induced significant increases in plasma levels of AVP, epinephrine, and norepinephrine ($p<0.001$). These were 1.0±0.1, 41.6±2.2, and 98.6±6.7 pg/mL, respectively (Figs. 3, 4, and 5). Within 3 minutes following drinking, plasma AVP faced a significant decrease ($p<0.001$) being greater in 5 ml/kg body weight consumed water. PAVP continued to fall and reached preheat exposure levels by 9 minutes in all three protocols (Table 1). Comparing plasma levels of AVP just 3 minutes after drinking in the different water volumes consumed showed a significant difference between volumes of 1 and 5 ml/kg body weight ($p<0.03$). There was no significant difference, however, between 1 and 3 or between 3 and 5 ml/kg body weight.

Plasma levels of epinephrine increased significantly after heat exposure ($p<0.001$) and remained approximately unchanged after drinking (Fig. 5). There was a significant in-

Table 2. Effects of water volumes consumed on mean sweat rate

Water volume	Msw before drinking (g)	Msw After drinking (g)					
	-3 min	3 min	6 min	9 min	12 min	15 min	18 min
1ml/kg b.wt	0.40±0.04	0.60±0.05*	0.37±0.02	0.30±0.02	0.26±0.02	0.21±0.03	0.18±0.03
3ml/kg b.wt	0.36±0.04	0.63±0.05*	0.37±0.04	0.25±0.02	0.20±0.02	0.17±0.02	0.15±0.02
5ml/kg b.wt	0.48±0.02	0.88±0.03*	0.55±0.02	0.39±0.03	0.35±0.03	0.31±0.03	0.28±0.03

Values are means±SE.
Msw: Mean sweat rate; b.wt: body weight
* Significantly different from baseline ($p<0.01$)

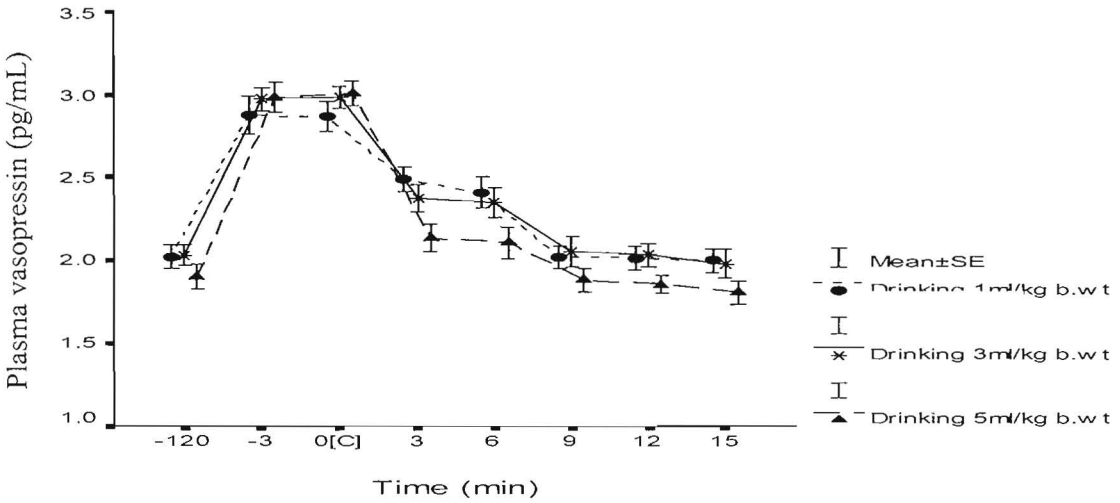

Fig. 3. Effect of consumed water volume on plasma levels of AVP following dehydration. Subjects started to drink at 0 time which is considered as control. There was a significant increase between before (-120 minutes) and after (-3 minutes) heat exposure for all protocols ($p<0.001$). Values are mean±SE of six subjects.

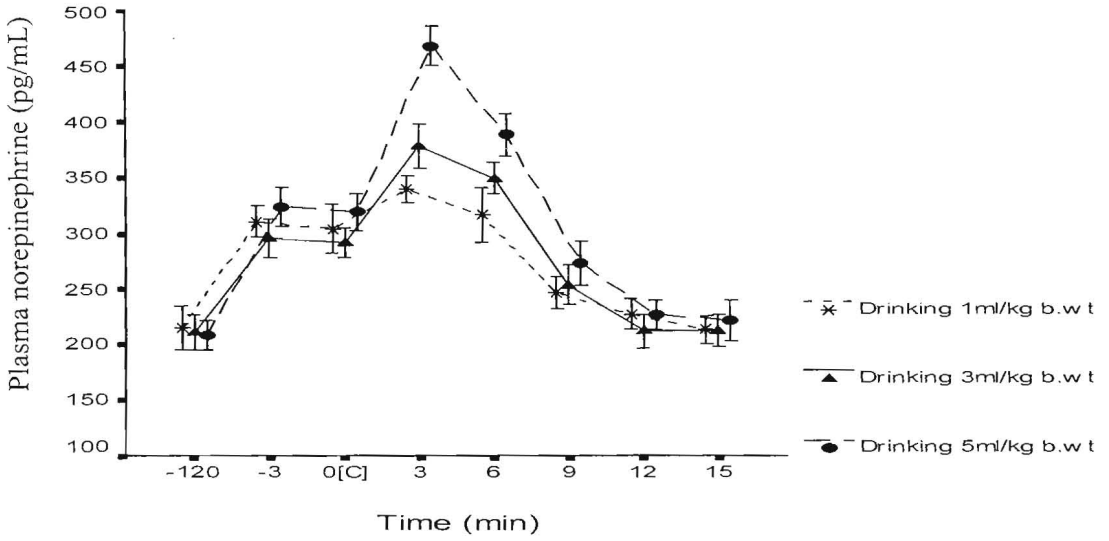

Fig. 4. Effect of consumed water volume on plasma levels of norepinephrine. Subjects started to drink at 0 time which is considered as control. Plasma NE increased significantly 3 minutes after drinking in consumed water volumes of 3 and 5ml/kg b.wt ($p<0.01$) but this increase was not significant in volume of 1ml/kg b.wt. Values are mean±SE of six subjects.

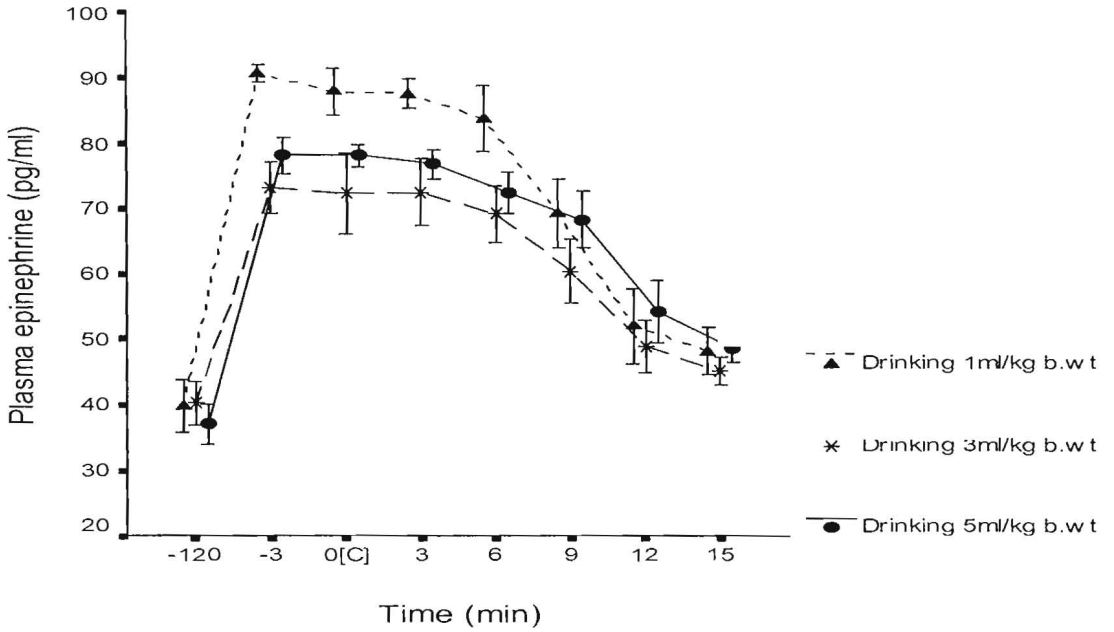

Fig. 5. Effect of consumed water volume on plasma levels of epinephrine. Subjects started to drink at 0 time which is considered as control. Significant differences were observed between before (-120 minutes) and after (-3 minutes) heat exposure for three protocols ($p<0.001$) and remained about unchanged after drinking, then it fell to baseline levels. Values are mean±SE of six subjects.

crease in plasma NE within 3 minutes after drinking, in consumed water volumes of 3 and 5 ml/kg body weight ($p<0.01$) but this accretion was not significant in volume of 1 ml/kg body weight. Three minutes after the onset of drinking, PNE increased by 12.1±5.1, 29.6±5.2, and 49.2±3.9% in consumed water volumes of 1, 3, and 5 ml/kg body weight, respectively. The difference between 1 and 5 ml/kg of body weight was significant ($p<0.02$), but there was no significant difference between 1 and 3 or between 3 and 5 ml/kg body weight.

Discussion

Previous studies have established what is called drinking-induced sweating in dehydrated humans[1] and animals.[2] In the present study we tested the effect of consumed water volume on the local sweating response following heat exposure and mild exercise.

Salata et al (1987) have demonstrated that a water temperature of 25°C has no significant effect on PAVP.[6] Hence, by using water at room temperature we tried to avoid the effect of water temperature on PAVP and to investigate the effect of volume per se.

The results indicated that in the first 3 minutes after drinking, local sweating is aggravated significantly for all three water volumes. This was transient and later on sweating was gradually decreased. As for sweating response, it was more or less proportional to consumed water volume and became greater when water volume increased. These results elucidate that not only does the passing of water through the oropharynx and upper gastrointestinal tract, but also its amount affect the post dehydration sweating response.

Secretion of AVP has close association with P_{osm}. Four hours of water deprivation increased P_{osm} and PAVP; both effects were then intensified by 2 hours of heat exposure. PAVP concentration started to fall significantly within 3 minutes of water intake for all volumes and reached pre-heat exposure levels by the 9th minute after drinking (Table 2 and Fig. 3). Although similar results have been reported by other researchers,[3,11,12] our results showed that the immediate changes in PAVP concentration were more prominent in higher volumes ($p<0.03$ when 5 ml/kg was compared with 1 ml/kg body weight). At the same time, plasma osmolality was almost unchanged. This response, also reported by others,[5,13] can be attributed to the delay in water absorption occurring simultaneously with the continuation of perspiration.

PE and PNE were increased by dehydration but a clear dissociation in the relevant profiles of changes occurred following drinking. PE was initially almost unchanged and then faced a gradual decrease, while PNE had an abrupt increase in the first 3 minutes followed by a sharp decrease. Similar results were also reported by Ghislaine et al (1996).[13] Changes in consumed water volume affected PNE changes proportionally, while no clear effect was evident in the case of PE.

The increase in PNE, which occurs immediately after drinking, considering AVP, may suggest, a drinking stimulated neural mechanism. However, this increase may be related to stomach distension. A reflex increase in sympathetic tone in response to stomach distension has been shown repeatedly in controlled laboratory animal experiments.[14-19]

In summary, we have shown that changing the volume of water alters the sweating response to drinking in dehydrated hyperthermic men. Drinking water volume had a positive effect on sweating response, i.e the more water volume consumed, the more was sweating response. PAVP, PNE and PE all of which increase by dehydration respond differently to drinking; PAVP decreases, PNE initially increases and then decreases, while PE shows no significant change for 6 minutes and then starts to decrease. Results also demonstrated that drinking increased volumes of water caused a greater decrease in PAVP and a greater increase in PNE, whereas PE was not affected.

It is concluded that the oropharynx and upper GI appear to have a receptor system that can discriminate between the volumes of consumed water. This factor in turn takes part in the integrated response of sweating following drinking.

In order to determine the location of receptor which trigger a neuronal reflex, leading to alterations in sweating and relevant hormonal secretion, we suggest the use of nasoesophageal and nasogastric tubes to introduce water selectively and the study of these changes in dehydrated men. The central locations and neurotransmitters involved in this reflex can be further clarified by designing invasive animal studies involving dialysis of interstitial fluid in different nuclei of the brain. If tolerated by subjects, the effect of water with different osmolalities on sweating response is also worth studying in detail.

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