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# Heat acclimation causes a linear decrease in sweat sodium ion concentration

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ABSTRACT

The purpose of this study was to determine the time course for the previously reported reduction in sweat sodium ion concentration during heat acclimation. Four healthy volunteers completed 7 consecutive days of heat acclimation which included 2 h of treadmill walking in a 40 °C and 40% relative humidity environment. A modified constant hyperthermia protocol was used as workloads were increased each day to maintain a constant core temperature over the 7 days of heat acclimation. Forearm sweat was collected 3 times during each 2 h exercise bout on days 1, 3, 5, and 7 of heat acclimation. Forearm sweat rate and sweat sodium ion concentration were determined from each sample. The results showed that there was a significant ($p < 0.05$) downward shift in the mean sweat rate vs. sweat sodium ion concentration relationship on days 3, 5, and 7 of heat acclimation, as compared to the pre-heat acclimation (day 1) data. Thus, at any given sweat rate, heat acclimation resulted in a significantly lower sweat sodium ion concentration. The response was very rapid and occurred following only 2 consecutive days of heat exposure (i.e., day 3 vs. day 1 data). Furthermore, the calculated sweat sodium ion concentration, at a sweat rate of 1 μl/cm$^2$/min, decreased linearly ($r = -0.50$, $p < 0.05$) during the 7 days of heat acclimation. Such results suggest that heat acclimation rapidly improves sodium ion reabsorption from the eccrine sweat gland duct as evidenced by significant reductions in the sweat sodium ion concentration.

## 1. Introduction

Heat acclimation is known to result in a multitude of positive adaptations. These include increases in whole body sweat rate and plasma volume and reductions in core temperature and heart rate during exercise. However, the time course for the onset and progression of improvement during heat acclimation has been shown to be different for each physiological parameter (Armstrong and Maresh, 1991; Pandolf, 1998; Périard et al., 2016). For example, significant increases in sweat rate do not occur until approximately the fifth day of heat acclimation while decreases in heart rate occur almost immediately (Best et al., 2014; Weller et al., 2007).

It is well known that heat acclimation results in a significant reduction in the sweat sodium ion concentration (Allan and Wilson, 1971; Buono et al., 2007; Orenstein et al., 1984). For example, Kirby and Convertino (1986) reported a 50% reduction in sweat sodium ion concentration following 10 days of heat acclimation. Interestingly, a review of the literature reveals that no study has examined the time course of the decrease in sweat sodium ion concentration during heat acclimation.

It is generally believed that aldosterone is responsible for the reported reduction in sweat sodium ion concentration via increased expression and/or translocation of the epithelial sodium channel (ENaC) into the apical membrane of the eccrine sweat gland duct (Booth et al., 2002; Kirby and Convertino, 1986; Quinton, 2007). This is evidenced by the fact that a reduction in sweat sodium ion concentration during heat acclimation is not seen in patients with Addison's disease (i.e., decreased aldosterone production) (Collins, 1963). Furthermore, administration of spironolactone, a competitive antagonist of aldosterone, attenuates the reduction in sweat sodium ion concentration in subjects during heat acclimation (Robinson and Robinson, 1954).

The effect of aldosterone on ENaC expression and thus sodium reabsorption appears to occur quite rapidly. Specifically, it has previously been shown that administration of aldosterone in several different cell types increases the expression of ENaC within 2–6 h (Alvarez de la Rosa et al., 2002; Chen et al., 1999; Loffing et al., 2001). Furthermore, the sweat sodium ion concentration is significantly reduced by approximately 15–20% one day following an intradermal aldosterone injection (Sato and Dobson, 1970).

Since exercise in the heat is known to significantly increase plasma aldosterone concentration (Morgan et al., 2004; Sawka and Montain,

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2000; Yoshida et al., 2006), it seems plausible that reductions in the sweat sodium ion concentration might occur very rapidly during heat acclimation – possibly after only the first several days of exposure.

In light of the above, the purpose of this study was to determine how rapidly heat acclimation causes the well-known reduction in sweat sodium ion concentration. It was hypothesized that significant reductions in the sweat sodium ion concentration would occur following the first several days of heat acclimation.

## 2. Materials and methods

The subjects for this study were four healthy volunteers (3 males, 1 female). All were physically active but none were heat acclimated, as determined by questionnaire. The female subject completed the 7 days of the study during the follicular phase of her ovarian cycle as determined by diary records. They had a mean ± SD age, height, and weight of 26 ± 1 y, 175.2 ± 3.5 cm, and 72.27 ± 4.97 kg, respectively. The study was approved by the San Diego State Institutional Review Board and signed informed consent was obtained from each subject. Subjects were asked to report each day to the laboratory euhydrated which was confirmed by having a urinary specific gravity of < 1.020 (Cutrufello and Dixon, 2013). No restrictions were placed on the subjects' diets because it has been reported that electrolyte supplementation is not necessary during heat acclimation (Sawka and Montain, 2000). Furthermore, unless the subjects are on very low sodium intake diets, manipulations of dietary sodium do not appear to greatly affect sweat sodium ion secretion during heat acclimation (Allsopp et al., 1998; Armstrong et al., 1985).

Subjects performed two hours of continuous treadmill exercise in an environmental chamber, which was set to 40 °C and 40% relative humidity for seven consecutive days. Prior to exercise, subjects inserted a rectal temperature probe ten centimeters past the anal sphincter to measure core body temperature during the exercise bouts. Heart rate was measured during exercise using a photometric analyzer attached to the index finger (Nonin Medical, Plymouth, MN). Water was allowed ad-libitum during the exercise sessions.

Each two-hour exercise bout was split into three 40-min intervals with exercise intensity increasing with each successive interval. This was done to induce three different sweat rates so the sweat rate vs. sweat sodium ion concentration relationship could be determined for each subject. The exercise intensity was adjusted to maintain a consistent core temperature at the end of each of the three intervals over the seven days of heat acclimation. Constant hyperthermia was achieved in the current study, as the mean rectal temperature over the seven days of heat acclimation at the end of the three exercise intervals was 37.8, 38.1, and 38.3 °C, respectively. Forearm sweat was collected during the last 30 min of each of the three intervals using macroduct sweat collectors (Wescor, Logan, UT). The collectors were held in place on the proximal third of the left forearm by Velcro straps, which prevented leakage and sample contamination. The skin was cleaned with deionized water and dried immediately before securing each collector. Collected sweat was expelled into air tight test tubes and frozen until the end of the study. Sweat rate was calculated using a volumetric procedure (Buono et al., 2007) and sweat sodium ion concentration was measured in duplicate using a flame photometer (Cole-Palmer Chicago, Illinois).

Mean sweat rate vs. sweat sodium ion concentration for the three intervals during heat acclimation were compared using a 3 (time) × 4 (day) repeated measures ANOVA and post-hoc comparisons. Individual plots of sweat rate vs. sweat sodium ion concentration were determined for each subject on days 1, 3, 5, and 7 of heat acclimation. From these plots, the sweat sodium ion concentration at a sweat rate of 1 μl/cm$^2$/min was calculated. A Spearman rank order correlation was calculated comparing the sweat sodium ion concentration at 1 μl/cm$^2$/min vs. heat acclimation day.

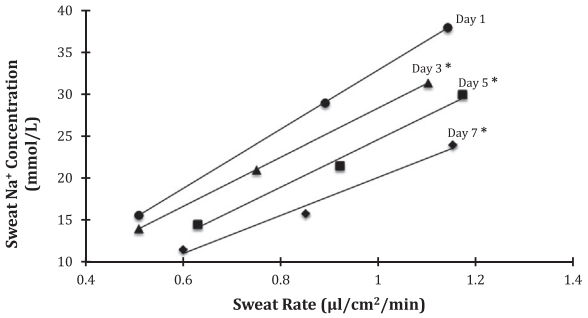


**Fig. 1.** Mean forearm sweat rate vs. mean sweat sodium ion concentration on day 1, 3, 5, and 7 of heat acclimation. * indicates that day was significantly ($P < 0.05$) different from the pre heat acclimation data (i.e., day 1).

## 3. Results

The mean sweat rate vs. sweat sodium ion concentration relationship for days 1, 3, 5, and 7 are depicted in Fig. 1. There was a significant ($p < 0.05$) main effect for time (i.e., sweat rate) and a significant ($p < 0.05$) main effect for heat acclimation (i.e., day), but there was a non-significant interaction. Post-hoc comparisons revealed that the sweat rate vs. sweat sodium ion concentration relationship on days 3, 5, and 7 were all significantly ($p < 0.05$) different than day 1. From individual graphs, the mean sweat sodium ion concentration was calculated at a sweat rate of 1 μl/cm$^2$/min for each subject on days 1, 3, 5, and 7 of heat acclimation. These results are shown in Fig. 2. As can be seen, there was a significant ($p < 0.05$) negative correlation of − 0.50 between sweat sodium ion concentration and the day of heat acclimation (i.e., 1, 3, 5, and 7).

## 4. Discussion

The results of the current study agree with, and extend, past findings concerning the effect of heat acclimation on sweat sodium ion concentration. First, as can be seen in Fig. 1, seven consecutive days of heat acclimation caused a significant downward shift in the sweat sodium ion concentration vs. sweat rate relationship. This resulted in a significant 45% reduction in the sweat sodium ion concentration at any given sweat rate following seven days of heat acclimation. This agrees quite favorably in magnitude with past studies. Specifically, following heat acclimation Allan and Wilson (1971) and Buono et al. (2007) reported significant 49% and 40% reductions in the sweat sodium ion concentration at any given sweat rate, respectively.

The most interesting new finding of the current study involves determining the time course of changes in sweat sodium ion concentration during heat acclimation. As can be seen in Fig. 1, the sweat sodium ion concentration was significantly reduced by day 3 of heat acclimation vs.

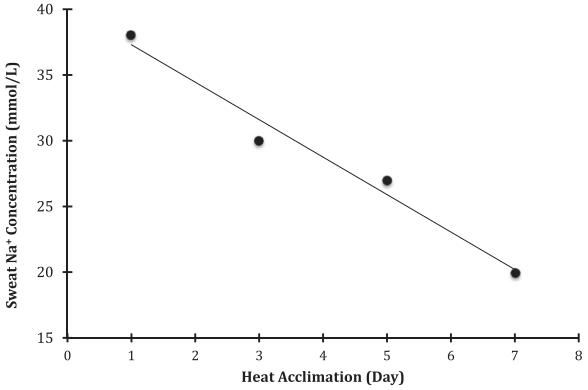


**Fig. 2.** Mean sweat sodium ion concentration at a sweat rate of 1 μl/cm$^2$/min on days 1, 3, 5, and 7 of heat acclimation. r = − 0.50.