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Research Article

The Effect of Exercise Intensity on Sweat Rate and Sweat Sodium and Potassium Losses in Trained Endurance Athletes

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Abstract

This randomized crossover trial study was designed to investigate the relationship between exercise intensity, sweat rate and sweat sodium and potassium concentrations of trained endurance athletes in order to determine sodium and potassium losses and therefore requirements.

Eighteen male endurance athletes (age 37.9±9.7 y, weight 83.2±13.6 kg, VO_2 max 60.8±9.4 mL/kg.min^{-1}) were randomized into one of three groups for the experimental trials. Group L began with the low intensity trial (60%HR_{max}), group M with the moderate intensity trial (80%HR_{max}) and group H with the high intensity trial (time trial). Over three consecutive weeks, all participants performed each of the three trials.

There was a significant increase in average sweat sodium ($p<0.01$) but not potassium concentration between the L and H exercise trials (L=30.6 mmol/L±11.4, H = 49.4 mmol/L±22.9). Inter-individual coefficient of variance for average sodium concentrations ranged from 37-47%. There was a significant positive linear relationship ($p<0.001$) between sweat rate (L/h) and sweat sodium concentration (mmol/L) (r^2 = 0.229). These measurements computed to significant increases in both sodium and potassium losses (mg/h) with increasing exercise intensity. In conclusion, there was considerable individual variation in sweat rate and sodium loss in endurance athletes with losses up to 4.5 g sodium per hour at high intensity. Thus endurance athletes with high sweat rates are at risk for substantial sodium loss and should ensure they choose salty food as well as hydrate adequately after an event.

ABBREVIATIONS

H: High; HR: Heart Rate; L: Low; M: Medium; RH: Relative Humidity; Usg: Specific Gravity of Urine

INTRODUCTION

Endurance athletes often train and compete in harsh environmental conditions prompting high sweat losses. There is a body of literature to suggest that a loss of body weight between 2-7% due to dehydration, can significantly reduce exercise performance, particularly when exercise is performed in the heat (i.e. >30 ºC) [1-3]. In addition to this, dehydration will increase the physiologic strain associated with exercise and negate the thermoregulatory mechanisms that are known to result from high aerobic fitness [4,5]. If dehydration is prolonged or severe, the athlete is at risk of more serious medical consequences such as heat stroke [2].

The sodium and potassium losses that accompany water loss through sweat have received much less attention in the literature and have generally focused on team-based sports with their relatively short game times [6]. In contrast, endurance events can last 10-12 hours, often in hot and humid conditions, resulting in excessive sodium and not insignificant potassium losses.

Guidelines for the adequate replacement of the sodium and potassium lost through sweat are limited, often conflicting [6,7] and do not differ for athletes training and competing in different events [8]. Lack of specific recommendations for endurance athletes may lead to the inadequate replacement of sodium and potassium losses [6,7].

The sweat rate of an athlete can be calculated simply and practically by measuring weight loss over an exercise session. There are however, practical difficulties in determining wet sodium and potassium losses, as comprehensive sweat analysis in a laboratory is required for accurate assessment. Several studies have reported a linear relationship between increases in sweat rate and sweat sodium loss in untrained participants [9-11]. This information cannot be directly applied to athletes due to the sweat gland adaptations that are known to occur with physical training, including sweat gland hypertrophy and an increase in sweat output per gland [12]. Sweat rates have been shown to be higher in athletes resulting in an increase in inter-individual sweat rate variation [12]. Endurance athletes with high sweat losses and thus an increased risk of heat-related illness, need to be identified early so an appropriate fluid and electrolyte replacement strategy can be developed.

The aim of this study was to determine whether the linear relationship between sweat rate and sweat sodium concentration, previously demonstrated in untrained participants, persists in endurance athletes. Potassium losses were also investigated.

MATERIALS AND METHODS

Participants were recruited from triathlon and cycling clubs around Perth, Western Australia. Criteria for participation were: male 18-50 years; participation in at least 10 hours per week of moderate intensity cycling and/or running in the three months prior to the study; no known medical condition and not taking any regular medication.

Eighteen eligible athletes (age 37.9±9.7 y, weight 83.2±13.6 kg,VO_2 max 60.8±9.4 mL/kg.min^{-1}) volunteered for the study and gave their written informed consent to participate. This study was approved by the Curtin University Human Ethics Committee.

In the week before the experimental trials all participants were required to undergo a familiarization trial. The cardiovascular fitness (mean VO_2max) was assessed using the Astrand and Rodahl protocol. Participants then completed one trial per week over three consecutive weeks, during which sweat was collected. Participants were randomized into one of three groups for the intensity of the first experimental trial (L, M, H). Groups were then crossed over twice so that all participants completed one trial at each of three exercise intensities.

All trials were conducted in an environmental chamber during summer. Before entering the chamber, all participants were required to provide a urine sample for specific gravity analysis to verify that they were adequately hydrated (Usg <1.015) [13].

The trials were performed at 35ºC and 50% relative humidity (RH), similar day-time conditions to those encountered in Perth at the height of summer. All trials were conducted between 0600-0900 hours. The exercise trials were: low (L) intensity (60% HR_{max}), moderate (M) intensity (80% HR_{max}) and high (H) intensity – maximal intensity time trial.

All participants performed an incremental protocol of exercise using a cycle ergometer in the environmental chamber. The protocol consisted of a 15-minute warm up at a workload estimated to be approximately 50% of maximal HR (220 minus age) followed by 15 minutes at one of the three intensities. The 15-minute time frame was chosen as it allows sufficient time for the sweat collecting coils to be filled with sweat [14]. The subjects were fitted with four sweat collecting devices (one per limb) after the 15-minute warm up period which allowed for initiation of sweating. Wescor sweat collection capsules (Wescor Environmental, Utah, USA) were secured to the shaved, sterilized skin using custom-made adjustable strapping. Sweat was collected from the lateral aspects of both upper arms and at the midpoint on both thighs. At the end of the exercise session the sweat collecting devices were removed and placed individually in sealed plastic bags.

The subjects were then instructed to shower without wetting their hair, to abstain from drinking, eating, or urinating, and to ensure they were completely dry before putting on the clothes in which they were originally weighed. After re-weighing, the sweat rate (ml/min) was calculated from the weight loss of the subject over time. The collected sweat was evacuated with compressed air into small weighing trays. The sweat samples were weighed from each site for sweat rate comparisons, and then diluted in volumetric flasks with deionized water. The concentrations of sodium and potassium were then determined by atomic absorption spectrophotometry.

For each participant, left and right sweat sodium and potassium concentrations were averaged for arms and for legs as a previous study from our group has shown no significant bilateral differences [14]. Unless otherwise indicated, a participant's sweat sodium or potassium concentration was the average of the values from the four sites. Data were tested for normality and summarized as mean (± standard deviation). A one-way repeated measures analysis of variance (ANOVA) was then used to detect differences in study outcomes (sweat rate and sweat sodium and potassium concentrations) amongst the three exercise intensity levels. Post hoc Bonferroni adjusted t-tests were used for pair wise comparisons. Pearson product-moment correlation was used to assess the relationships between sweat rates and sweat sodium or potassium concentrations. For all analyses the 0.05 level of significance was used. All statistical analysis was performed using SPSS for Windows (version 18.0, SPSS Inc., Chicago, IL, USA).

RESULTS AND DISCUSSION

No significant differences in sodium and potassium sweat concentrations between arm and leg collection sites were observed (Table 1). The coefficients of variation for the inter-individual variation in average sweat sodium and potassium concentrations across the three trials ranged from 37-47% and 22-32%, respectively, indicating a high degree of between-subject variability at all exercise intensities.

The increase in exercise intensity achieved a near doubling of mean sweat rate from low to high intensity trials with each increment resulting in a significant increase (Table 1). A significant effect of exercise on mean sweat sodium concentration occurred between the low and high exercise intensity trials only ($p<0.01$) (Table 1). The mean values of average sweat potassium concentrations remained stable.

A significant effect of exercise intensity on sweat rate was observed (repeated measures ANOVA, $p<0.01$), and a significant positive linear relationship ($p<0.001$) existed between sweat rate (L/h) and sweat sodium concentration (mmol/L) (Figure

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Table 1: Sweating rate, sweat sodium and potassium concentrations (mean±SD) in each of the exercise trials of varying intensity.

Variable*	Low	Moderate	High
Sweat rate (L/h)[b]	1.0±0.3[c e]	1.5 ± 0.3[d]	1.9±0.3
Sweat [Na^+] arms (mmol/L)[a]	32.7 ± 15.1[e]	42.3±18.2	51.7±27.7
Sweat [Na^+] legs (mmol/L)	28.5 ± 10.1[e]	39.7 ± 16.7	46.8 ± 20.4
Sweat [Na^+] average (mmol/L)	30.6 ± 11.4[e]	41.0 ± 17.1	49.3 ± 22.9
Sweat [K^+] arms (mmol/L)	8.4±2.4	7.3 ± 2.0	7.1±2.6
Sweat [K^+] legs (mmol/L)	10.3 ± 3.0	9.6 ± 3.8	8.7 ± 3.6
Sweat [K^+] average (mmol/L)	9.4 ± 2.1	9.1 ± 2.6	7.9 ± 2.5

*Repeated measures ANOVA analysis completed for sweat rate and sweat sodium concentrations for arms and legs and the average of arms and legs for all participants (n=18).
[a]Significantly different using repeated measures ANOVA (p<0.05); [b]Significantly different using repeated measures ANOVA (p<0.01); [c]Significantly different between low and moderate intensity trial using *post hoc* pairwise comparisons (p<0.01); [d]Significantly different between moderate and high intensity trial using *post hoc* pairwise comparisons (p<0.01); [e]Significantly different between low and high intensity trial using *post hoc* pairwise comparisons (p<0.01)

1). Approximately 23% of the variability in sweat sodium concentration could be explained by changes in sweat rate.

The statistically significant increase in sweat sodium concentration with increasing sweat rates shown in this study supports previous work conducted in untrained participants [10,11,15]. These studies, however, have demonstrated a much stronger relationship (r=0.73) than was displayed in the results of the present study (r=0.48). This may be explained by the large inter-individual variation in both sweat rate and sweat sodium concentrations in the 18 athletes tested. Sweat rates ranged from 0.6 to 2.6 L/h and sweat sodium concentrations from 13 to 103 mmol/L, much wider variations than those previously reported in untrained participants. These large variations are similar to those reported by Maughan et al [16] and Shirreffs et al [17] in male professional football players.

The physiological mechanism responsible for the increase in sodium concentration with increases in sweat rate is currently unknown. However, there are several possible explanations for these findings. The human eccrine sweat gland consists of two distinct regions involved in both the production and reabsorption of sodium and chloride ions. The secretory coil produces an isoosmotic precursor sweat, while the sweat duct actively reabsorbs sodium from the precursor sweat throughout the passage of sweat to the skin [18]. This reabsorption depends on the active transport of sodium into the interstitial fluid via Na^+ - K^+ ATPase which is localized on the basolateral membrane of the ductal cells. At low levels of sweat production there is ample time for active sodium reabsorption to occur. At higher levels of sweat loss there is insufficient time for complete reabsorption [19]. This mechanism is supported by the results of the present study. At higher rates of sweat loss there was a significantly greater concentration of sodium in sweat. The in vivo study by Buono et al [10] provides further support for this mechanism. This study demonstrated that with higher sweat rates, the rate at which sodium is secreted from the secretory coil is greater, while the proportion reabsorbed is decreased, leading to an overall increase in the sodium concentration of the sweat on the skin surface.

As expected from Figure 1, increased intensity of exercise resulted in significantly greater sodium losses (Table 2). The mean estimated sodium loss in the high intensity trial was three times higher than that of the low intensity trial. The difference in mean estimated potassium losses between the low and high intensity trials (150%) was also significantly higher (p<0.05).

Several factors may account for the wide variation in both fluid and electrolyte losses including, the state of heat acclimatization, habitual salt intake and aerobic fitness level [20,21]. Physical training has been shown to result in significant increases in the rate of sweat loss due to increases in both the size and density of sweat glands as well as an increase in the output per gland [12,22,23]. Hamouti et al. [24] investigated sweat sodium concentrations during exercise in the heat in a group of aerobically trained compared to untrained participants. Results showed that when normalized for sweat rate, high aerobic fitness does not reduce sweat sodium secretion or enhance sodium reabsorption.

Absolute electrolyte loss in sweat is dependent on sweat electrolyte concentration and the volume of sweat lost and a large coefficient of variation was observed in both variables. In the present study there was a 300% increase in mean total sodium loss (mg/h) from the low to the high intensity trial. There was however substantial individual variation in estimated sodium losses ranging from 600 mg/h in the low intensity up to over 6000 mg/h in one athlete in the high intensity trial.

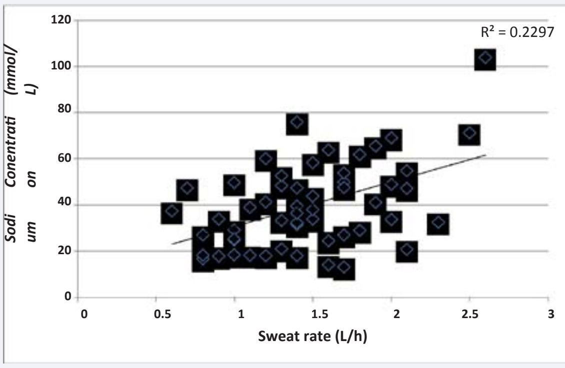

Figure 1 Scatter plot illustrating a statistically significant (p<0.001) positive linear association between sodium concentration (mmol/L) and sweat rate (L/h).

Table 2: Estimated (mean±SD) sweat sodium and potassium losses (mg/h).

		Sodium		Potassium	
Estimated sweat	Low Intensity	705.9±333.4[a]		358.5± 94.1[a]	
losses^ (mg/h)	Moderate Intensity	1389.2	±646.2[b]	484.9	±166.5[b]
	High Intensity	2196.3	± 1305.5[c]	580.6	±220.5

^Estimated mean sweat sodium loss (mg/h) calculated based on the sodium concentration and the sweat rate recorded at each intensity level for each individual.
[a]Low intensity trial is significantly different to the moderate intensity trial.
[b]Moderate intensity trial is significantly different to the high intensity trial.
[c]Low intensity trial is significantly different to the high intensity trial. P<0.05.

This highlights the difficulties associated with developing guidelines for fluid and electrolyte intake for all athletes and further supports the need for advice to be specific to the needs of the individual. While it is not practical for every athlete to have sweat analysis, athletes know whether or not they are heavy sweaters. This study has shown that those with high sweat rates have high sodium losses, therefore a practical outcome of this study is that those with high sweat rates lose additional sodium, independent of exercise intensity. Potassium losses also increase but not to the same extent. Replacement of these electrolytes is necessary during and after training and competition to reduce the possibility of electrolyte imbalances. The consumption of both foods known to have high salt content and electrolyte replacement beverages can be used to achieve sodium replacement. The lower potassium losses can be readily replaced via the intake of key foods, for example fruit, and electrolyte replacement drinks.

CONCLUSION

To the best of our knowledge this study is the first to document the sweat rate and sweat sodium and potassium relationships in an endurance athlete group with average sweat rates in excess of 1L/h. The current American College of Sports Medicine recommendations [25] state the importance of replacing the sodium lost in sweat to ensure euhydration. A comprehensive laboratory assessment of electrolyte losses is the ideal scenario in developing a fluid and electrolyte regime, but this is obviously not practical for all athletes. Therefore it would be useful to advise endurance athletes with high sweat rates that they are at risk of high sodium losses.

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