Is Sodium Supplementation Necessary to Avoid Dehydration During Prolonged Exercise in the Heat?

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Abstract

Hoffman, MD and Stuempfle, KJ. Is sodium supplementation necessary to avoid dehydration during prolonged exercise in the heat? *J Strength Cond Res* 30(3): 615–620, 2016—The primary purpose of this work was to gain further insight into the need for sodium supplementation for maintenance of appropriate hydration during prolonged exercise under hot conditions. Participants of a 161-km ultramarathon (ambient temperature reaching 39° C) underwent body weight measurements immediately before, during, and after the race, and completed a postrace questionnaire about supplemental sodium intake and drinking strategies during 4 race segments. The postrace questionnaire was completed by 233 (78.7%) race finishers. Significant direct relationships were found for percentage weight change during the race with intake rate ($r = 0.18$, $p = 0.0058$) and total amount ($r = 0.24$, $p = 0.0002$) of sodium in supplements. Comparing those using no sodium supplements throughout the race ($n = 15$) with those using sodium supplements each race segment ($n = 138$), body weight change across the course showed significant group ($p = 0.022$), course location ($p < 0.0001$), and interaction ($p = 0.0098$) effects. Posttests revealed greater weight loss at 90 km ($p = 0.016$, $-3.2 \pm 1.6\%$ vs. $-2.2 \pm 1.5\%$, mean $\pm$ *SD*) and the finish ($p = 0.014$, $-3.2 \pm 1.5\%$ vs. $-1.9 \pm 1.9\%$) for those using no sodium supplements compared with those using sodium supplements each segment. Six runners who used no sodium supplements, drank to thirst, and only drank water or a mixture of mostly water with some electrolyte-containing drink finished with mean weight change of -3.4%. Although the use of supplemental sodium enhanced body weight maintenance, those not using sodium supplements maintained a more appropriate weight than those consistently using sodium supplements. Therefore, we conclude that the supplemental sodium is unnecessary to maintain appropriate hydration during prolonged exercise in the heat.

Key Words endurance exercise, running, water-electrolyte imbalance

Introduction

Fluids containing sodium have been shown to increase plasma volume greater at rest (22,26,31,32,37) and to maintain plasma volume better during exercise (3,4) than water alone. Given the concerns of some about performance impairment from weight loss during exercise of only 2% body weight, recent guidelines recommend ingestion of sodium with fluids during exercise (1,2,6,7). However, some studies have shown that the supplemental sodium during prolonged exercise has little or no effect on maintenance of body weight (8,9,14,33).

In our recent study during a 161-km ultramarathon with ambient temperatures reaching 39° C, runners who took no sodium supplements and drank to thirst finished with an average weight loss of 3.0% compared with their weight immediately before race start (14). Previous work has also demonstrated that total body water was maintained despite a loss in body weight of ~3.5% among runners participating in a 56-km ultramarathon (38) and a loss in body weight of ~2% among soldiers during a 14.6-km march (28). This mismatch between body weight loss and total body water loss can be attributed to the production of metabolic water during fuel oxidation and the release of water with the breakdown of muscle and liver glycogen (24). The expected weight loss for maintenance of euhydration during a 161-km ultramarathon has been suggested to be on the order of 3–4% owing to greater mobilization of fat stores than in shorter events (11,27). Thus, the finding that runners who drank to thirst and did not use sodium supplements finished a hot 161-km ultramarathon with an average weight loss of 3.0% suggests that sodium supplements are not necessary to maintain proper hydration during prolonged exercise.

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Besides the mounting evidence that sodium supplements are not necessary during prolonged exercise, excessive sodium intake during exercise may also carry some potential adverse consequences, including hypernatremia (11) and unnecessary weight gain (11,18,21). Excessive sodium intake during exercise may also increase the risk for development of pulmonary edema (23) and has even been seen associated with exercise-associated hyponatremia (13,18), effects possibly resulting from overhydration mediated by gastrointestinal or hepatic portal osmoreceptors that provide an early stimulus of thirst without elevation in blood osmolality (20,34,35). Therefore, sodium use during exercise should be with regard for some potential risks. In fact, avoiding excessive sodium supplementation has been recommended as an appropriate approach to maintaining hydration during endurance exercise (5,30).

The need for sodium supplementation during exercise deserves further exploration given the disparity that sodium intake during exercise has been commonly recommended to maintain hydration; however, recent observations suggest that supplemental sodium is not necessary during prolonged exercise, coupled with concerns about potential adverse effects from excessive sodium intake. The present work examines the change in body weight associated with different hydration strategies during continuous exercise for 15–30 hours. Building on our previous work in which we found hydration status could be maintained without the use of sodium supplementation and by drinking to thirst during a hot 161-km ultramarathon (14), we quantify sodium intake in supplements in this study. Thus, a key purpose of this study was to examine the relationship between amount of sodium consumed in supplements and change in body weight. We also sought to further evaluate whether drinking to thirst without sodium supplementation would allow for appropriate maintenance of hydration during prolonged exercise. Such information is pertinent for generation of scientifically supported hydration guidelines for prolonged exercise.

Methods

Experimental Approach to the Problem

The study was performed at the 2014 Western States Endurance Run, a 161.3-km ultramarathon through the Sierra Nevada Mountains of Northern California with 5,500 m of cumulative climb and 7,000 m of cumulative descent. Other details of the race have been provided elsewhere (10,12,17,19,29). Nearby weather station ambient temperatures during the race ranged from a low of 0° C just after the start to a high of 31.7° C in the afternoon, which was close to the historical median high temperature for this event, although we measured (Vantage Vue Wireless Weather Station; Davis Instruments, Vernon Hills, IL) a maximum on-course air temperature of 39° C at which time the relative humidity was 13%.

Subjects

All race starters were invited to participate in the study. The research was approved by our institutional review boards. Electronic consent was obtained from those participating in a questionnaire.

Procedures

Body weight was measured on all race participants during registration on the day before the race, within 1.5 hours before the start of the race, when reaching 47.8, 89.6, and 125.5 km during the race, and again immediately after finishing the race. Weight measurements were made using calibrated scales (Sunbeam Products, Inc., Health o meter, model 349KLX; Boca Raton, FL, USA) placed on firm, level surfaces. During each measurement, the runner was wearing running clothes and shoes, but other items such as waist packs and hydration vests were removed, and nothing was permitted in the runner's hands. Because the design of the race course makes it impossible to weigh each runner with the same scale across course locations, it was necessary to assure that the sales were standardized. Therefore, before the event, the scales were examined for consistency, and although the maximum variation between scales was less than 0.5% across the weight range of our subjects, correction equations were developed to standardize all weight measurements to a single scale.

Prerace correspondence alerted runners that they would be requested to complete a postrace web-based questionnaire. All race starters were sent an electronic invitation to complete the questionnaire during the event. Reminder e-mails were sent to runners who had not completed the survey 7 and 12 days later, and the survey was closed 15 days after the race.

The questionnaire requested information about running background and training during the 3 months before the race and information about the main factors that were used to determine fluid intake (thirst, predetermined drinking schedule, maximum tolerated, change in body weight, urine color, and others) during each of the 4 race segments defined by the location of body weight measurements. The questionnaire also requested information about the fluid type consumed (only water, mostly water and some electrolyte drink, about equal water and electrolyte drink, mostly electrolyte drink, and only electrolyte drink), as well as the number and brand of sodium supplements used, if any, during each of the 4 race segments. The most commonly used commercially available products were listed, and the runner also had the opportunity to specify other forms of sodium supplementation they might have used. Sodium intake rate from supplements was then calculated using the known sodium content of each brand of sodium supplement and official split times.

For purposes of defining hydration status (i.e., overhydration, euhydration, and dehydration) of runners at the finish, we used body weight immediately before the start as the

Table 1. Comparison of selected runner characteristics between finishers using sodium supplements each race segment ($n = 138$) and finishers not using sodium supplements any race segment ($n = 15$) who completed the postrace questionnaire.*

Runner characteristics	Sodium supplementation use during each segment	No sodium supplementation use during any segment	p
Age (y)	41 ± 8	45 ± 6	0.14
Sex (% men)	86.2	73.3	0.24
Ultramarathon running experience (y)	5 (3–8)	5 (2–7)	0.53
Previous 161-km ultramarathon finishes (n)	2 (1–4)	2 (1–3)	0.75
Previous 161-km ultramarathon drops (n)	0 (0–1)	0 (0–1)	0.76
Average running distance ($km \cdot wk^{-1}$)†	97 (80–121)	89 (80–97)	0.21
Highest running distance in 1 wk (km)†	145 (122–169)	132 (121–169)	0.62
Longest single run (km)†	80 (74–100)	80 (80–100)	0.81
Finish time (h)	25.75 (22.64–28.24)	27.18 (26.00–28.47)	0.26

*Values are reported as mean ± *SD* if normally distributed, median and interquartile range if not normally distributed, or percentage.
†During the 3 months before the event.

baseline weight. We have consistently observed that weight is approximately 1% greater at the start than during registration on the day before the start (14,16). Therefore, to be consistent with previous work (11,27), we used weight change from that immediately before the start of ≥ -1 as overhydration, < -1 to -4% as euhydration, and $< -4\%$ as dehydration. This is justified by an estimation that there is ~1% body weight loss from fat utilization during a 161-km ultramarathon (36).

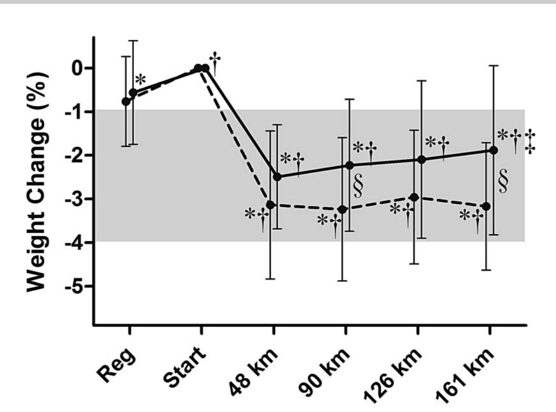

Figure 1. Mean percentage weight change relative to start weight for the finishers completing the postrace questionnaire who reported using sodium supplements each race segment (solid line, $n = 138$) and no sodium supplements any race segment (dashed line, $n = 15$). The shaded zone demarcates the weight change range of −1 to −4%. Error brackets represent 1 *SD*. Data points are offset slightly along the horizontal axis for clarify of the error brackets. *$p < 0.005$ compared with start weight, †$p < 0.005$ compared with registration (Reg) weight, ‡$p \leq 0.05$ compared with 48 km for the indicated group, and §$p \leq 0.05$ compared with other group at indicated course location.

Statistical Analyses

Between group comparisons of categorical data were made with the Fisher's exact test or Chi-square test. Continuous data underwent normality testing with the D'Agostino-Pearson test. When continuous data for 2 groups were compared, the unpaired t-test or Mann Whitney test was used depending on whether the data passed normality testing. Three group comparisons were made with the Kruskal-Wallis test and Dunn's multiple comparison test because the data did not pass normality testing. Examination of body weight change across course locations and between groups based on sodium supplement use was accomplished with two-way repeated-measures analysis of variance and the Scheffe posttest. Correlations between 2 variables were determined with Pearson correlation analyses. Statistical significance was set at $p \leq 0.05$.

Results

There were 376 race starters and 296 (78.7%) finishers. The study population consisted of the 233 (78.7%) finishers who completed the postrace questionnaire. Of those finishers completing the questionnaire, 56.7% did so within 7 days after the race and 88.4% did so within 10 days. Age range was 19 to 64 years.

Among the study sample, 25.3% were overhydrated, 57.5% were euhydrated, and 17.2% were dehydrated at the finish. Overall, 93.6% of finishers reported using sodium supplements with frequencies being 100% among the overhydrated, 91.8% among the euhydrated, and 90.0% among the dehydrated finishers. The proportion using sodium supplements was not statistically different ($p = 0.061$) when comparing across all 3 groups, but a difference was present ($p = 0.014$) when the overhydrated group was compared with the combined euhydrated and dehydrated group (91.4%). Median (interquartile range) intake rates of sodium in supplements

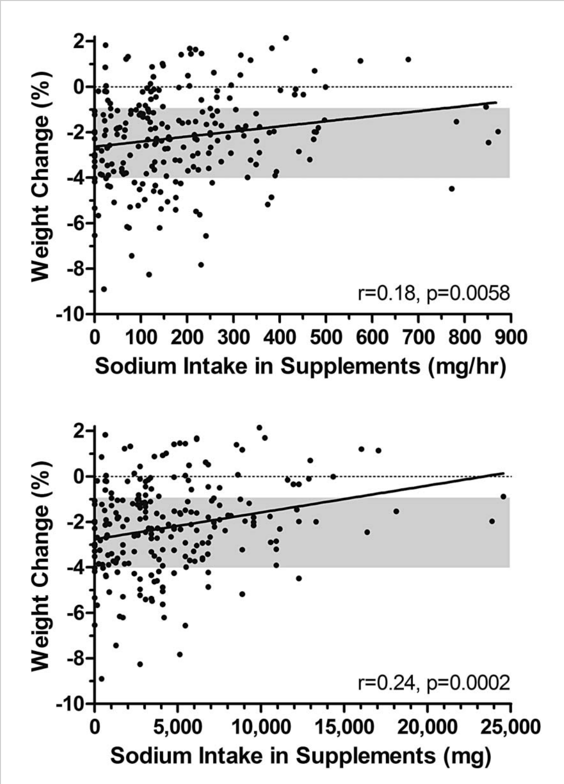

Figure 2. Relationship of percentage change in body weight from immediately before the start to the finish with rate (top) and total (bottom) intake of sodium in supplements for finishers completing the postrace questionnaire. The shaded zone demarcates the weight change range of −1 to −4%.

was 182 (110–295), 145 (57–256), and 106 (42–176) $mg \cdot h^{-1}$ among the overhydrated, euhydrated, and dehydrated finishers, respectively. Intake rate of sodium in supplements was different among groups ($p = 0.023$) with posttest showing greater ($p \leq 0.05$) intake for those who were overhydrated than those who were dehydrated.

Sodium supplement use varied across race segments, being reported by 74.0%, 88.9%, 82.1%, and 72.3% during race segments 1–4, respectively. Statistical differences ($p \leq 0.05$) in proportions were present between each pair of race segments except the first and last segments.

Comparisons were made between finishers who used sodium supplements each race segment ($n = 138$) and those who used no sodium supplements any race segment ($n = 15$). No differences between the 2 groups in age, sex, running history and training, and finish time were identified (Table 1). However, the comparison of body weight change across the course (Figure 1) showed significant group ($p = 0.022$), course location ($p < 0.0001$), and interaction ($p = 0.0098$) effects. Posttests revealed significant ($p < 0.0001$) weight loss throughout the course for both groups, but greater loss at 90 km ($p = 0.016$) and the finish ($p = 0.014$) for those using no sodium supplements compared with those using sodium supplements each segment. Furthermore, the group using sodium supplements had significantly less ($p = 0.0003$) weight loss at the finish than at 48 km.

Median (interquartile range) sodium intake in supplements among the finishers using sodium supplements each race segment was 219 (126–332) $mg \cdot h^{-1}$ over the entire race, and 187 (104–302), 275 (145–392), 243 (150–379), and 174 (89–279) $mg \cdot h^{-1}$ during race segments 1–4, respectively. The rate of sodium intake in supplements was greater ($p \leq 0.05$) during the middle 2 race segments than during the first and last segments.

Among the finishers using no sodium supplements during any race segment, 11 of 15 (73.3%) reported drinking to thirst across all race segments, and of those 11 runners, 1 reported drinking only water during all race segments and another 5 reported drinking either water or mostly water with some electrolyte-containing drink across all race segments. Those 6 runners who used no sodium supplements, drank to thirst, and only drank water or a mixture of mostly water with some electrolyte-containing drink finished with mean (range) weight change from immediately before the start of −3.4% (−1.2 to −6.5%).

Figure 2 shows the significant direct relationships found between percentage weight change at the finish from immediately before the start with rate ($r = 0.18$, $p = 0.0058$) and total ($r = 0.24$, $p = 0.0002$) intake of sodium in supplements for finishers completing the postrace questionnaire.

Discussion

A key finding of this study is that there was a significant relationship between percentage body weight change and amount of sodium intake in supplements such that those taking in more sodium in supplements maintained higher proportions of their initial body weights. We also found that those runners using sodium supplements during each race segment maintained a greater weight than those using no sodium supplements during any race segment. These findings provide support for sodium intake as a means for maintaining weight during prolonged exercise.

Interpretation of these findings must consider the extent of observed weight change for those who did and did not use sodium supplements. As a group, those consistently using sodium supplements never lost more than an average of 2.5% body weight and finished with mean (±*SD*) weight loss of 1.9 ± 1.9% relative to their weight immediately before the start. This weight loss is less than the 4% loss from starting weight that should be anticipated to maintain euhydration in an event of this duration (11). In contrast, those not using sodium supplements had lost 3.2 ± 1.5% by the finish. Therefore, weight was actually maintained at a more appropriate level by those not using sodium supplements.

Although the relationship between percentage weight change and sodium intake in supplements was statistically significant, it is important to note that supplemental sodium intake accounted for only 3–6% of the variability in weight change. Examination of Figure 2 makes it evident that there is considerable scatter of data points within each hydration status group. In fact, virtually the entire range of supplemental sodium intake rates was spanned by individuals in each hydration status group. Clearly, other runner characteristics and behaviors have a greater effect on weight change than supplemental sodium intake.

The use of sodium supplementation is common during 161-km ultramarathons. Our previous work at this same event has demonstrated that 90–96% of runners use sodium supplements (14,40), which is comparable with the overall use by 94% of finishers in the present work. Besides the use of sodium supplements being common, several runners reported taking in 15–25 g (~650–1,170 mmol) of sodium just in supplements during the race, which is likely more than the total sodium lost in sweat during the race (25,39). Interestingly, we have shown that supplemental sodium has minimal or no effect on postrace serum sodium concentration (15,40), and the data have been accumulating that excessive use of sodium supplements may be associated with unnecessary weight gain or inadequate weight loss during the race (11,21). The present work offers further support that the use of sodium supplements tends to be associated with inadequate weight loss but also that the intake of supplemental sodium is not a key determinant of hydration status nor is sodium supplementation necessary to maintain proper hydration during prolonged continuous exercise in a hot environment.

We acknowledge some study limitations that are largely due of the restraints of performing research at a competitive event. Such settings often require an observational design rather than allowing for a randomized controlled trial. Furthermore, given the current beliefs among most participants in the present event about the importance of sodium supplementation, we were required to accept that most runners would be using sodium supplements. As a result, the sample size of subjects not using sodium supplements was small. The study was also limited by an inability to quantify total sodium intake, which requires a full dietary analysis and is not feasible with a large sample in a race setting. We also note that the study depended on subject recall and response to a questionnaire, although runners were alerted in advance that they would be asked to provide information about hydration strategies, most completed the survey within a few days of the race, and significant memory distortion relative to sodium supplementation and hydration strategies was not likely because most runners avoid adopting new hydration approaches for an event of this nature.

From this work, we conclude that while supplemental sodium has a statistical effect on hydration status, the effect is weak, and those not using sodium supplements and drinking to thirst maintained a more appropriate weight than those consistently using sodium supplements. Therefore, we continue to recommend avoiding excessive sodium supplementation and to use thirst as the stimulus for fluid intake to maintain appropriate hydration during prolonged endurance exercise, even under high ambient temperatures.

Practical Applications

This work provides further support that appropriate hydration status can be maintained during prolonged endurance exercise under hot conditions without the use of sodium supplements and by drinking to thirst. Therefore, it seems that endurance athletes can be safely advised to drink to thirst and avoid sodium supplements during continuous exercise for 15–30 hours.

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References

1. American College of Sports Medicine, Sawka, MN, Burke, LM, Eichner, ER, Maughan, RJ, Montain, SJ, and Stachenfeld, NS. American College of Sports Medicine position stand. Exercise and fluid replacement. *Med Sci Sports Exerc* 39: 377–390, 2007.
2. American Dietetic Association; Dietitians of Canada; American College of Sports Medicine, Rodriguez, NR, Di Marco, NM, and Langley, S. American College of Sports Medicine position stand. Nutrition and athletic performance. *Med Sci Sports Exerc* 41: 709–731, 2009.
3. Anastasiou, CA, Kavouras, SA, Arnaoutis, G, Gioxari, A, Kollia, M, Botoula, E, and Sidossis, LS. Sodium replacement and plasma sodium drop during exercise in the heat when fluid intake matches fluid loss. *J Athl Train* 44: 117–123, 2009.
4. Barr, SI, Costill, DL, and Fink, WJ. Fluid replacement during prolonged exercise: Effects of water, saline, or no fluid. *Med Sci Sports Exerc* 23: 811–817, 1991.
5. Bennett, BL, Hew-Butler, T, Hoffman, MD, Rogers, IR, and Rosner, MH. Wilderness Medical Society practice guidelines for treatment of exercise-associated hyponatremia: 2014 update. *Wilderness Environ Med* 25(4 suppl): S30–S42, 2014.
6. Casa, DJ, Armstrong, LE, Hillman, SK, Montain, SJ, Reiff, RV, Rich, BS, Roberts, WO, and Stone, JA. National Athletic Trainers' Association position statement: Fluid replacement for athletes. *J Athl Train* 35: 212–224, 2000.
7. Casa, DJ, Clarkson, PM, and Roberts, WO. American College of Sports Medicine roundtable on hydration and physical activity: Consensus statements. *Curr Sports Med Rep* 4: 115–127, 2005.
8. Cosgrove, SD and Black, KE. Sodium supplementation has no effect on endurance performance during a cycling time-trial in cool conditions: A randomised cross-over trial. *J Int Soc Sports Nutr*, 2013 10: 30.

9. Hew-Butler, TD, Sharwood, K, Collins, M, Speedy, D, and Noakes, T. Sodium supplementation is not required to maintain serum sodium concentrations during an Ironman triathlon. *Br J Sports Med* 40: 255–259, 2006.
10. Hoffman, MD and Fogard, K. Factors related to successful completion of a 161-km ultramarathon. *Int J Sports Physiol Perform* 6: 25–37, 2011.
11. Hoffman, MD, Hew-Butler, T, and Stuempfle, KJ. Exercise-associated hyponatremia and hydration status in 161-km ultramarathoners. *Med Sci Sports Exerc* 45: 784–791, 2013.
12. Hoffman, MD, Ingwerson, JL, Rogers, IR, Stuempfle, KJ, and Hew-Butler, T. Increasing creatine phosphokinase concentration at the 161-km Western States Endurance Run. *Wilderness Environ Med* 23: 56–60, 2012.
13. Hoffman, MD and Myers, TM. Symptomatic exercise-associated hyponatremia in an endurance runner despite sodium supplementation. *Int J Sport Nutr Exerc Metab*, 2015 Jun 9 [Epub ahead of print].
14. Hoffman, MD and Stuempfle, KJ. Hydration strategies, weight change and performance in a 161 km ultramarathon. *Res Sports Med* 22: 213–225, 2014.
15. Hoffman, MD and Stuempfle, KJ. Sodium supplementation and exercise-associated hyponatremia during prolonged exercise. *Med Sci Sports Exerc* 47: 1781–1787, 2015.
16. Hoffman, MD, Stuempfle, KJ, Fogard, K, Hew-Butler, T, Winger, J, and Weiss, RH. Urine dipstick analysis for identification of runners at risk for acute kidney injury following an ultramarathon. *J Sports Sci* 31: 20–31, 2013.
17. Hoffman, MD, Stuempfle, KJ, Rogers, IR, Weschler, LB, and Hew-Butler, T. Hyponatremia in the 2009 161-km Western States Endurance Run. *Int J Sports Physiol Perform* 7: 6–10, 2011.
18. Hoffman, MD, Stuempfle, KJ, Sullivan, K, and Weiss, RH. Exercise-associated hyponatremia with exertional rhabdomyolysis: Importance of proper treatment. *Clin Nephrol* 83: 235–242, 2015.
19. Hoffman, MD and Wegelin, JA. The Western States 100-Mile Endurance Run: Participation and performance trends. *Med Sci Sports Exerc* 41: 2191–2198, 2009.
20. Kraly, FS, Kim, YM, Dunham, LM, and Tribuzio, RA. Drinking after intragastric NaCl without increase in systemic plasma osmolality in rats. *Am J Physiol* 269: R1085–R1092, 1995.
21. Lebus, DK, Casazza, GA, Hoffman, MD, and Van Loan, MD. Can changes in body mass and total body water accurately predict hyponatremia after a 161-km running race? *Clin J Sport Med* 20: 193–199, 2010.
22. Luetkemeier, MJ, Coles, MG, and Askew, EW. Dietary sodium and plasma volume levels with exercise. *Sports Med* 23: 279–286, 1997.
23. Luks, AM, Robertson, HT, and Swenson, ER. An ultracyclist with pulmonary edema during the Bicycle Race Across America. *Med Sci Sports Exerc* 39: 8–12, 2007.
24. Maughan, RJ, Shirreffs, SM, and Leiper, JB. Errors in the estimation of hydration status from changes in body mass. *J Sports Sci* 25: 797–804, 2007.
25. Montain, SJ, Cheuvront, SN, and Sawka, MN. Exercise associated hyponatraemia: Quantitative analysis to understand the aetiology. *Br J Sports Med* 40: 98–105, 2006.
26. Nelson, MD, Stuart-Hill, LA, and Sleivert, GG. Hypervolemia and blood alkalinity: Effect on physiological strain in a warm environment. *Int J Sports Physiol Perform* 3: 501–515, 2008.
27. Noakes, TD, Sharwood, K, Speedy, D, Hew, T, Reid, S, Dugas, J, Almond, C, Wharam, P, and Weschler, L. Three independent biological mechanisms cause exercise-associated hyponatremia: Evidence from 2,135 weighed competitive athletic performances. *Proc Natl Acad Sci U S A* 102: 18550–18555, 2005.
28. Nolte, HW, Noakes, TD, and van Vuuren, B. Protection of total body water content and absence of hyperthermia despite 2% body mass loss ("voluntary dehydration") in soldiers drinking ad libitum during prolonged exercise in cool environmental conditions. *Br J Sports Med* 45: 1106–1112, 2011.
29. Parise, C and Hoffman, MD. Influence of temperature and performance level on pacing a 161-km trail ultramarathon. *Int J Sports Physiol Perform* 6: 243–251, 2011.
30. Rosner, MH, Bennett, B, Hew-Butler, T, and Hoffman, MD. Exercise induced hyponatremia. In: *Hyponatremia: Evaluation and Treatment.* E. E. Simon, ed. New York, NY: Springer, 2013. pp. 175–192.
31. Sims, ST, Rehrer, NJ, Bell, ML, and Cotter, JD. Preexercise sodium loading aids fluid balance and endurance for women exercising in the heat. *J Appl Physiol (1985)* 103: 534–541, 2007.
32. Sims, ST, van Vliet, L, Cotter, JD, and Rehrer, NJ. Sodium loading aids fluid balance and reduces physiological strain of trained men exercising in the heat. *Med Sci Sports Exerc* 39: 123–130, 2007.
33. Speedy, DB, Thompson, JM, Rodgers, I, Collins, M, Sharwood, K, and Noakes, TD. Oral salt supplementation during ultradistance exercise. *Clin J Sport Med* 12: 279–284, 2002.
34. Stricker, EM, Callahan, JB, Huang, W, and Sved, AF. Early osmoregulatory stimulation of neurohypophyseal hormone secretion and thirst after gastric NaCl loads. *Am J Physiol Regul Integr Comp Physiol* 282: R1710–R1717, 2002.
35. Stricker, EM, Hoffmann, ML, Riccardi, CJ, and Smith, JC. Increased water intake by rats maintained on high NaCl diet: Analysis of ingestive behavior. *Physiol Behav* 79: 621–631, 2003.
36. Stuempfle, KJ, Hoffman, MD, Weschler, LB, Rogers, IR, and Hew-Butler, T. Race diet of finishers and non-finishers in a 100 mile (161 km) mountain footrace. *J Am Coll Nutr* 30: 529–535, 2011.
37. Sugihara, A, Fujii, N, Tsuji, B, Watanabe, K, Niwa, T, and Nishiyasu, T. Hypervolemia induced by fluid ingestion at rest: Effect of sodium concentration. *Eur J Appl Physiol* 114: 2139–2145, 2014.
38. Tam, N, Nolte, HW, and Noakes, TD. Changes in total body water content during running races of 21.1 km and 56 km in athletes drinking ad libitum. *Clin J Sport Med* 21: 218–225, 2011.
39. Weschler, LB. Exercise-associated hyponatraemia: A mathematical review. *Sports Med* 35: 899–922, 2005.
40. Winger, JM, Hoffman, MD, Hew-Butler, TD, Stuempfle, KJ, Dugas, JP, Fogard, K, and Dugas, LR. Physiology and hydration beliefs affect race behavior but not post-race sodium in 161-km ultramarathon finishers. *Int J Sports Physiol Perform* 8: 536–541, 2013.