Changes in Blood Electrolytes and Plasma Volume in National Football League Players During Preseason Training Camp

Sandra Fowkes Godek, PhD, ATC; and Arthur R. Bartolozzi, MD

ABSTRACT

Blood samples were drawn from 6 National Football League players for baseline measures and then prior to morning practice on days 3, 5, and 9. Mean blood sodium level was lower on days 3 (136.9±0.6 mmol·L^{-1}) and day 5 (138.1±0.6 mmol·L^{-1}) compared to baseline (140.4±0.4 mmol·L^{-1}) and day 9 (140.3±0.4 mmol·L^{-1}). Mean blood potassium level was higher on day 5 (4.16±0.13 mmol·L^{-1}) and day 9 (4.36±0.08 mmol·L^{-1}) compared to baseline (3.77±0.15 mmol·L^{-1}). Mean plasma volume was lower on day 3 (-4.9%±2.4%) compared to day 5 (4.5%±1.9%), and mean mass (days 2 through 9) was below baseline before and after practices. Blood sodium level declined by day 3 of preseason and was maintained at low normal levels at the expense of contracted plasma volume. Increased resting blood potassium levels on days 5 and 9 indicated rhabdomyolysis. Increased consumption of sodium is important for professional football players to maintain plasma volume during the first week of preseason.

Individual sweat rates vary and are dependent on environmental conditions such as ambient temperature, humidity, and airflow,[1,2] as well as metabolic rate and the insulating effects of equipment.[1,3,4] Additionally, the rate at which athletes sweat is related to body mass and body surface area.[5,6] We reported higher sweat rates in collegiate football players compared to smaller athletes,[7] which likely was due to both genetic and physical size factors that determine sweat gland number, diameter, and total glandular size.[5,8] Furthermore, football players have a large body mass and fat-free mass, particularly when compared to smaller athletes such as runners, which contribute to a high metabolic rate when exercising at the same absolute work rate such as running speed.[9,10] Finally, wearing protective equipment hinders heat dissipation via dry avenues, resulting in a greater reliance on the evaporation of sweat.[3,4]

Daily sweat losses of >9 L per day (range = 7.0 to >14.5 L per day) reported in collegiate players[7] caused us to question whether electrolyte balance might be important to study in American football players.[5,7,11,12] We recently documented sweat sodium losses in 3 groups of professional football players and reported average daily losses of 7.5±3.9 g per day in backs (n = 18), 9.9±5.3 g per day in linebackers and quarterbacks (n = 12), and 12.5±7.8 g per day in linemen (n = 14).[13] The potential for substantial sodium losses exists even in mild conditions, with mean sweat losses of ~4.5 L per day reported in professional players practicing in a thermoneutral environment (wet-bulb globe temperature = 15.5°-19°C).[14]

Preseason training for teams in the National Football League (NFL) consists of several weeks of twice-a-day practices (two-a-days) during July and August. Sodium losses ⩾12.5 g per day on consecutive days could make it difficult for these athletes to maintain normal serum sodium concentrations, particularly when players are instructed to drink large volumes of fluid to approximate sweat losses. The extremely low urine sodium excretion in 4 samples per day and decreased plasma volume on the morning of the second and third day of preseason report-

---

Dr Fowkes Godek is from the Heat Illness Evaluation Avoidance & Treatment Institute, West Chester University, West Chester, and Dr Bartolozzi is from 3B Orthopaedics, Pennsylvania Hospital, Philadelphia, Pa.

Originally submitted January 16, 2009.

Accepted for publication September 30, 2009.

The authors have no financial or proprietary interest in the materials presented herein.

The authors thank the athletic training staff and players from this NFL team for allowing them to conduct this study. This study was partially funded by a faculty development grant from West Chester University.

Address correspondence to Sandra Fowkes Godek, PhD, ATC, Sports Medicine Department, West Chester University, 755 South New Street, West Chester, PA 19383; e-mail: sfowkesgod@wcupa.edu.

doi:10.3928/19425864-20091019-03

TABLE 1

Physical Characteristics of the Players

CHARACTERISTIC	MEAN±SD
Age (y)	25.5±2.6
Height (cm)	186.3±5.5
Mass (kg)	104±17.6
BSA (m^2)	2.28±0.19
BSA·mass ($cm^2 \cdot kg^{-1}$)	222.2±11.9

BSA = body surface area.

TABLE 2

Ambient Temperature, Relative Humidity, and Wet-Bulb Temperatures

	AM PRACTICE	PM PRACTICE
Ambient temperature (°C)	20.6±0.4	26±1.8
Relative humidity (%)	87.3±8.1	68.0±19.2
Wet-bulb temperature (°C)	19.9±0.8	22.0±1.3

ed in collegiate football players would suggest this is the case.[12] The 1996 American College of Sports Medicine exercise and fluid replacement guidelines promoted the hydration doctrine of "consume the maximal amount that can be tolerated" during exercise[15] (this recently has been updated to include the need to be more individualized), and National Athletic Trainers' Association fluid replacement guidelines state athletes should "drink about 25% to 50% more than sweat losses to assure optimal hydration" after exercise.[16] However, substantial sweat sodium losses combined with aggressive hydration practices aimed at replacing copious sweat losses actually could cause blood sodium concentration to decline, particularly if players are not consuming a high enough quantity of salt in their diet.[17] Therefore, the purpose of this field study was to measure blood and urine electrolytes, and to assess changes in body mass and plasma volume in NFL players who were not consuming sodium in excess of their normal diet and who were participating in two-a-days in a warm and humid environment.

METHODS

Participants

Six football players from the same professional team who had a mean 3.8±2.5 years of playing experience in the NFL participated in the study. Seven players originally were recruited; however, one player sustained an injury and did not practice for several days, and therefore he was excluded from the study. The players represented a variety of positions: defensive back (2), receiver (1), special teams (1), and linemen (2). Physical characteristics of the participants are displayed in Table 1. All players were apprised of the risks involved with the study and signed consent forms. The study was approved by the lead author's (SFG) institutional review board for human subjects subcommittee.

Procedures

Venous blood samples were collected from participants for baseline measures on arrival to camp. Blood was drawn from an antecubital vein via a 20-gauge needle while participants were seated in a chair for 10 minutes. Subsequent blood samples were obtained using the same technique prior to the morning practice on the third, fifth, and ninth days of preseason training camp. Urine samples were also collected from the players when baseline blood samples were collected. Because urine electrolyte excretion can be quite variable, a second urine sample was collected before practice on the first morning; this sample was averaged with the baseline sample and used for baseline measures to provide a better indication of electrolyte excretion instead of using a single sample. Subsequent urine samples were collected before and after all practices on days 3, 5, and 9. Baseline mass was recorded with the players dressed in dry shorts the day they reported to camp; under the supervision of a research assistant, all players were weighed before and after all practices while dressed in dry shorts or a towel.

Blood and Urine Measurements

Blood samples were analyzed immediately for sodium (Na^+), potassium (K^+), magnesium (Mg^{++}), and ionized calcium (Ca^{++}) by ion-selective electrode (AVL 988; Roche Diagnostics, Roswell Ga). Additionally, blood was placed in capillary tubes and spun in triplicate for determination of hematocrit, and hemoglobin was determined by a portable hemoglobin analyzer (HemoCue, Mission Viejo, Calif). Percent change in plasma volume (%ΔPV) was calculated as described previously by Dill and Costill[18] using hematocrit and hemoglobin. Urine samples also were analyzed for Na^+ and K^+, and for urine specific gravity by refractometry. Daily urine

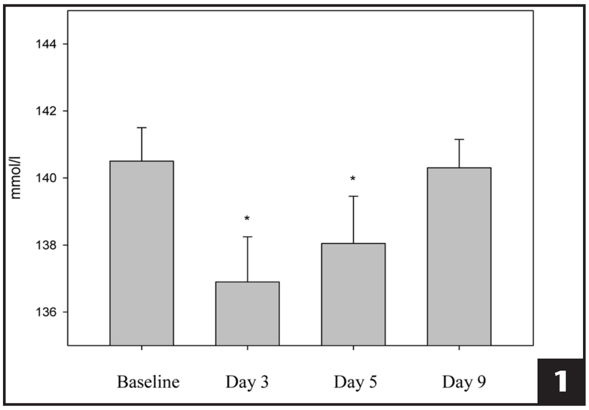

Figure 1. Mean blood sodium levels at baseline and on days 3, 5, and 9. *Significantly different from baseline ($P < .01$) and day 9 ($P < .05$). (Normal range for blood sodium is 135-144 mmol/L).

measures for Na^+ and K^+ concentration were the average of 3 to 4 samples per day.

The dependent variables (blood and urine electrolytes, urine specific gravity, %ΔPV, and change in body mass) were analyzed using 1-way ANOVA with repeated measures on the time factor (baseline and days 3, 5, and 9). Tukey's post hoc testing was used when a significant F value was obtained with the alpha level set a priori at $P < .05$.

Team's Hydration Protocol

The sports medicine staff for this professional team uses an aggressive hydration program, and the players are well educated about fluid replacement. Prior to each practice, cups of cold Gatorade® ($Na^+ = 19.1$ $mEq \cdot L^{-1}$, $K^+ = 3.4$ $mEq \cdot L^{-1}$, and sugar from sucrose and high fructose corn syrup = 58 g per day, Chicago, Ill) are offered to all players as they enter the practice field. During practice, squeeze bottles of cold water and cups of Gatorade® are offered to players between nearly every repetition, and players can request that additional electrolytes (Gatorlytes) be added to individual bottles of cold Gatorade®. After practice, bottles of water and Gatorade® with and without Gatorlytes are offered to players as they exit the field and are available in the locker rooms and athletic training room. Additionally, players have nearly constant access to fluids outside of the practice facility. Bottled water and Gatorade® are available in the dining hall, outside of the meeting rooms, in the lobby of the dorms, and in the players' refrigerators in their rooms.

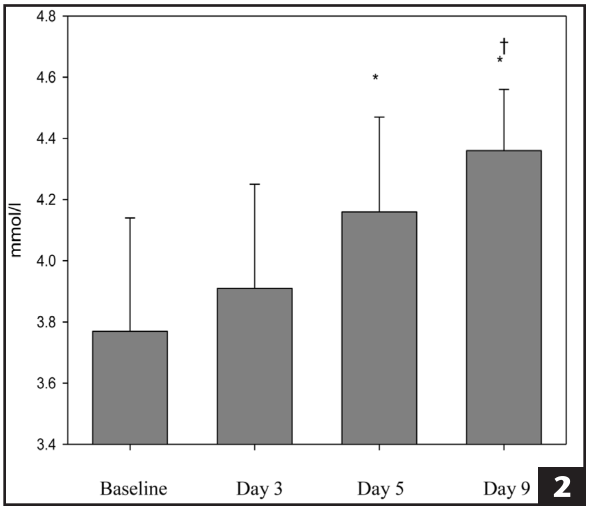

Figure 2. Mean blood potassium levels at baseline and on days 3, 5, and 9. *Significantly different from baseline ($P < .01$) and †significantly different from day 3 ($P < .01$). (Normal range for blood potassium is 3.5-5.0 mmol/L).

There were no other electrolyte-containing fluids available to the players except for pickle juice that was kept in the athletic training room and provided on request in 2-oz portions before practice. Participants were instructed not to consume pickle juice, but other than that, there was no intervention for participants as they were told not to alter their preseason dietary and fluid replacement habits in anyway.

Preseason Schedule

Players participated in physical testing on the morning of day 1 and then practiced in shorts and helmets in the afternoon. All of the players practiced 2 times per day on days 2, 3, and 4. They wore full pads (helmet, shoulder pads, football pants with pads and jersey) for the morning practices and shorts and shells (lighter weight foam shoulder pads without the plastic outer shell) with a jersey for the afternoon practices. On days 5, 7, and 9, the entire team practiced in full pads in the morning and then there was special teams only practice (shorts and shells) in the afternoon. On Days 6 and 8, all of the players practiced twice, full pads in the morning and then shorts and shells in the afternoon. Three of the 6 participants were special team players and therefore practiced a total of 17 times from day 1 through day 9, whereas the other 3 players practiced a total of 14 times.

RESULTS

Environmental Conditions

Wet-bulb measures (Table 2) were calculated from ambient temperature and humidity readings recorded at the beginning, middle, and end of each practice from

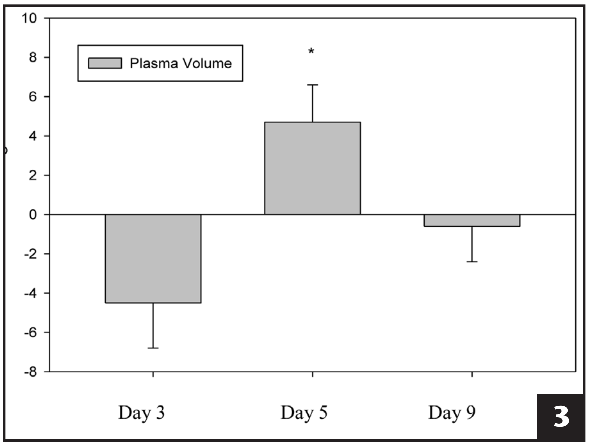

Figure 3. Percent change in plasma volume from baseline on days 3, 5, and 9. *Significantly different from day 3 ($P < .01$).

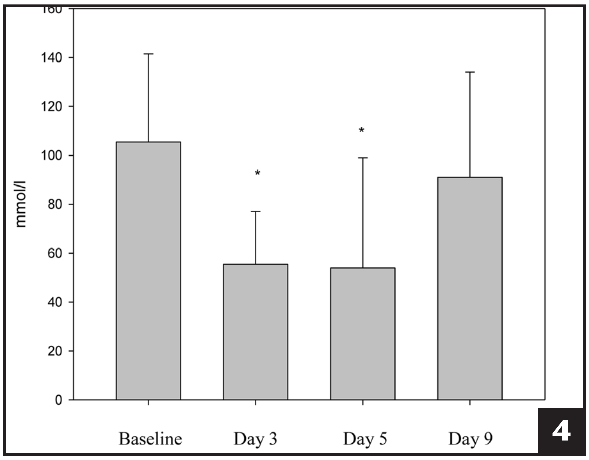

Figure 4. Urine sodium excretion at baseline and on days 3, 5, and 9. *Significantly different from baseline and day 9 ($P < .05$).

day 1 through day 9.

Blood and Urine Measures

Significant differences existed over time in both blood Na^+ ($F_{3,23} = 12.1$, $P = .0003$) and K^+ ($F_{3,23} = 13.7$, $P = .0001$). Blood Na^+ on day 3 was significantly lower than baseline and day 9 ($P < .01$) but was not different from day 5, which also was different from both baseline and day 9 ($P < .05$) (Figure 1). Compared to baseline, blood K^+ was higher on days 5 and 9, and day 9 was higher than day 3 ($P < .01$ for all) (Figure 2). No differences existed for either ionized Ca^{++} or blood Mg^{++}. There was a significant difference for %ΔPV over time ($F_{3,23} = 4.98$, $P = .013$) as plasma volume was below baseline (~5%) on day 3 and significantly different from day 5 (4.5%±1.9% above baseline, $P < .01$) (Figure 3).

Urine Na^+ concentration also differed over time ($F_{3,23} = 4.5$, $P = .019$) and was lower on days 3 and 5 compared to baseline ($P < .05$), whereas urine K^+ ($F_{3,23} = 4.2$, $P = .024$) was elevated above baseline (30±16 $mmol \cdot L^{-1}$) by day 9 (69±28 $mmol \cdot L^{-1}$) (Figures 4 and 5). Urine specific gravity across days (baseline = 1.012, day 3 = 1.0233, day 5 = 1.0213 and day 9 = 1.0252) approached but did not reach significance ($P = .06$).

Changes in Mass

Body mass recorded pre-morning (pre-AM) and post-morning (post-AM) practice, and pre-afternoon (pre-PM) and post-afternoon (post-PM) practice on days 2 through 9 were analyzed as the percent change from baseline and were collapsed across days ($F_{4,239} = 41.1$, $P < .0001$) (Figure 6). Mass changed significantly from baseline at pre-AM ($P < .05$), and at post-AM, pre-PM, and post-PM ($P < .01$ for all). Change in mass also was greater post-AM and post-PM compared to both pre-AM and pre-PM ($P < .01$).

DISCUSSION

In response to the hypovolemia and extremely low urinary sodium concentrations reported in college football players,[12] we hypothesized blood sodium levels would decline in NFL players during the first week of two-a-days. These players likely incur substantial sodium losses from consecutive days of heavy sweating but may not be attentive to increasing dietary sodium intake while consuming hypotonic fluids. Therefore, we were not surprised blood sodium was significantly lower on days 3 and 5 compared to baseline levels in these professional players who practiced in the heat 2 times per day on consecutive days. We recently found a mean sweat (Na^+) of 50.3±21.0 $mmol \cdot L^{-1}$ (range = 15 to 99 $mmol \cdot L^{-1}$) in 44 professional football players during preseason training camp,[13] which was similar (20 to 80 $mmol \cdot L^{-1}$) to that reported in young, healthy men and women using total body washdown technique.[19] During two-a-days, the average sodium loss in the linemen was 12.5 g, with one player losing >30 g in 1 day. Replacing 30 g of sodium (15 tsp of table salt) in the diet would be extremely difficult and clearly impossible to consume in a sports drink as it would require the consumption of 65 L of Gatorade® (adding 13,742 kcal to the diet).[13] Sodium losses of this magnitude without adequate replacement would help to explain the lower blood sodium concentrations on days 3 and 5 compared to baseline in these NFL players.

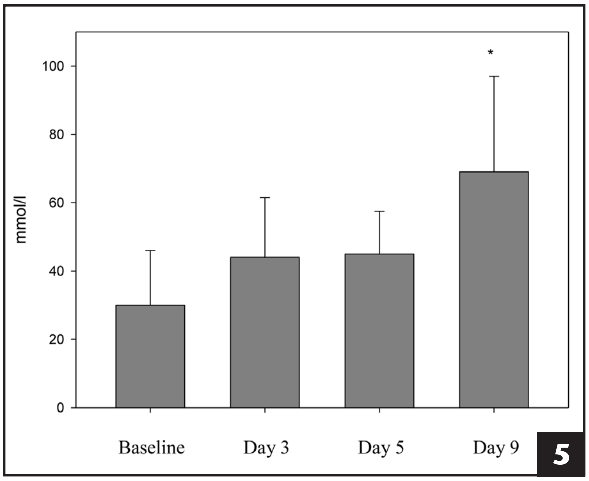

Figure 5. Urine potassium excretion at baseline and on days 3, 5, and 9. *Significantly different from baseline ($P < .05$).

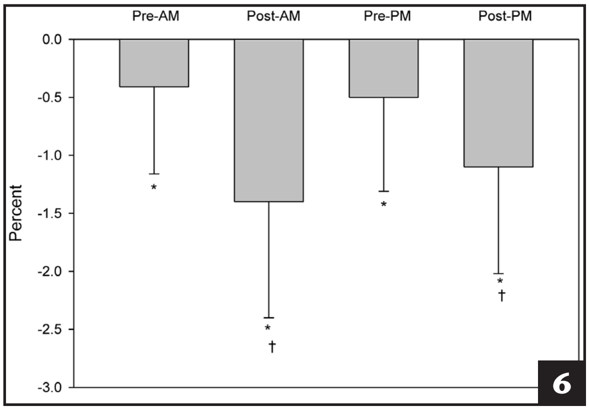

Figure 6. Change in body mass (in percent) from baseline measures. *Significantly different from baseline ($P < .05$) and †significantly different from pre-AM and pre-PM ($P < .01$). (Abbreviations: pre-AM, before morning practice; post-AM, after morning practice; pre-PM, before afternoon practice; post-PM, after afternoon practice.)

Importantly, to preserve a state of fluid and electrolyte homeostasis, the body will maintain blood sodium levels within a normal range (135 to 145 $\text{mmol}\cdot\text{L}^{-1}$) by reducing (or expanding as in the case of fluid overload) the volume of solvent (plasma) in which the sodium is dissolved.[20] This was shown by Romero et al[21] who sodium deprived subjects (dietary Na^+ <5 mEq per day) for a 6-day period and measured plasma renin activity, aldosterone, sodium, and potassium well as blood volume and urine sodium excretion. Although renin activity and aldosterone were both higher after sodium deprivation, blood volume (-6%) and urine sodium excretion were both significantly lower. Plasma sodium showed a tendency to decline but not significantly and was likely maintained by the drop in blood volume.[21] Although the football players in our study were not sodium restricted, our data support this as blood sodium concentration appeared to be maintained (>135 $\text{mmol}\cdot\text{L}^{-1}$) on the morning of the third day at the expense of plasma volume, which was ~5% below baseline. Notably, if plasma volume had actually been maintained in our NFL players, their blood sodium likely would have been even lower on day 3.

Low dietary sodium intake has also been shown by Armstrong et al[22,23] to affect plasma volume expansion during exercise and heat acclimatization compared to high sodium intake. When participants ingested a high-sodium diet (9 g per day) during 9 days of exercise and heat exposure, plasma volume increased >16 % by day 4 and was different from when they consumed a low-sodium diet (2.25 g per day) and showed no significant expansion of plasma volume. Additionally, blood Na^+ was significantly higher on day 4 when participants consumed a high-sodium diet compared to a low-sodium diet (138.8 $\text{mmol}\cdot\text{L}^{-1}$ versus 136.8 $\text{mmol}\cdot\text{L}^{-1}$, respectively).[24] Interestingly, our blood sodium data on day 3 (136.9 $\text{mmol}\cdot\text{L}^{-1}$) was identical to that reported by Armstrong et al[22] on the 4th day in their low-sodium group; however, the critical dissimilarity between our present investigation and this acclimatization study was the unlikelihood that our football players were consuming a diet low in sodium content (< 3 g per day).

Alternatively, if sodium consumption had matched sodium losses, plasma volume may have expanded by the third day as expected.[22-26] Of note is that participants in previous acclimatization studies exhibited plasma volume expansion beginning on the first day of exercise in the heat.[24-26] Average-sized males clad in minimal clothing did not experience an initial decline in plasma volume prior to subsequent expansion as documented in our NFL players.[22-26] Similar to previously studied collegiate players, our NFL subjects began intensive 2-hour bouts of exercise in the heat on the 3rd morning of preseason mildly hypovolemic.[12] We believe this is due to large daily sweat and therefore sodium losses replaced with hypotonic fluids without adequate salt intake. Although some authors suggest sodium supplementation is unnecessary due to large body reserves and excess salt consumption in the average American diet, our data indicate large professional football players who engage in consecutive days of strenuous exercise for ~4 hours in the heat may be an exception to this thinking.[27,28]

Sodium supplementation during prolonged exercise has been investigated.[29,30,31] However, the hypovolemia observed in our participants and in other football players, which could be due to low blood sodium (hyponatremia), might be different from the hyponatremia that ultra-endurance athletes occasionally develop. This later phenomenon is well-documented in marathoners, triathletes, and military personnel; however, hypervolemic hyponatremia is almost always associated with weight gain.[32-37] It is clearly not advantageous for the ultra-distance athlete to consume too much of any sodium-poor fluid prior to or during an event.[32-37] This advice also may be true for American football players who represent a unique population with respect to fluid and electrolyte homeostasis, particularly during preseason when they practice and play in the heat.[7,12,13]

The sodium losses that these players can incur due to several consecutive days of heavy sweating suggests it is possible for sodium stores to become depleted and mild hyponatremia to develop without necessarily overdrinking.[38] This may question the belief that the normal diet, even when it includes the increased number of calories necessary for large athletes, contains adequate sodium for football players.[28] We believe when sodium losses are considerable, with or without excessive fluid intake, substantial sodium consumption is likely necessary so that fluid and electrolyte balance can be maintained in these athletes. This not only will allow plasma volume to be maintained but should also promote expansion as expected during heat acclimatization.[22-25] Additionally, this may prevent the onset of symptoms such as nausea, headache, fatigue, and weight loss that often are associated with hypovolemic hyponatremia.[7]

Sodium replacement should be in the form of both sodium-rich fluids and increased dietary consumption of salt in amounts adequate enough to offset the individual players' sodium losses.[13,17] Some researchers believe beverages may need to contain a sodium content of 50 to 100 $\text{mmol}\cdot\text{L}^{-1}$, which is notably higher than commercial sports drinks (Na^+ ~20 $\text{mmol}\cdot\text{L}^{-1}$).[17] Importantly, Ray et al[39] showed restoration of plasma volume after dehydration was significantly better when fluid consumption occurred in combination with either chicken broth or chicken noodle soup compared to a carbohydrate and electrolyte drink or water.[39] Plasma volume returned to baseline by 2 hours postexercise in both the chicken broth and soup trials but remained below baseline in the carbohydrate and electrolyte drink (-4.1 %) and water (-5.6%) trials.

In addition to the important finding of low blood sodium and hypovolemia was the discovery of elevated blood K^+ after several consecutive days of two-a-days. We previously reported high urinary excretion of K^+ (>120 $\text{mmol}\cdot\text{L}^{-1}$) in football players, particularly at the end of the day so the slow rise in blood K^+ over the 9-day period was not unforeseen. Elevated blood potassium on days 5 and 9 was likely a consequence of rhabdomyolysis associated with the rigors of playing football in the heat. Ehlers et al[41] reported a significant rise in creatine kinase, which peaked at 5125 $\text{U}\cdot\text{L}^{-1}$ on the 4th day of two-a-days, indicating muscle cell damage does occur in football players during preseason training. Furthermore, we have reported proteinuria in collegiate and NFL players particularly after practices and games played in hot and humid conditions,[40,42,43] which would explain both the rise in blood K^+ and high urinary K^+ excretion in players after consecutive days of two-a-days.[11,12,40,42,43]

Urinary excretion of both sodium and potassium in our professional players parallels and therefore supports the blood electrolyte data. Urinary excretion of Na^+ was lower on days 3 and 5 compared to baseline and day 9, indicating sodium conservation during the first week of preseason, which is partially explained by acclimatization, and is normal and expected.[11,12,21-23] Conversely, urine K^+ excretion slowly increased from baseline, reaching a significantly higher level on day 9 likely due to rhabdomyolysis as previously discussed. Increased urinary excretion of potassium would also be partially explained by greater renal secretion by the proximal tubule subsequent to aldosterone-mediated sodium reabsorption. Extremely low urine sodium concentrations were reported in participants who were sodium deprived[21] and those consuming a low-sodium diet during acclimatization,[23] as well as collegiate football players during the first several days of consecutive two-a-day practices in preseason training camp.[13] In several of the collegiate football participants, urine sodium was undetectable (<1.0 $\text{mmol}^{\cdot\text{L}-1}$) in all 4 urine samples provided and the urine was extremely concentrated (mean specific gravity range = 1.022 to 1.032).[12] Low urine sodium excretion on days 3 and 5 in our NFL players was predictable; however, unlike the college players, urinary sodium was undetectable on only a couple of occasions. This may be due to dietary differences and the fact that the professional players on this team had 24-hour access to unlimited volumes of Gatorade® with and without added electrolytes, whereas the college players did not.[12]

The body mass data is an interesting and relevant clinical finding that further supports the argument that professional football players struggle to replace fluid and electrolyte losses during preseason as seen in collegiate players.[12] The inability of our NFL participants to return to baseline body mass prior to practices during the 9-day period supports the premise that they were not in sodium balance. We were somewhat surprised by this finding because the players were provided 4 meals per day and had unlimited access to water, Gatorade®, and Gatorade® with added Gatorlytes, which is an indication that accessibility alone will not ensure appropriate fluid restoration. The physiological responses of the NFL players were strikingly similar to those of college players who did not have unlimited access to electrolyte drinks but were chronically hypohydrated during preseason.[12] In addition, the urine specific gravity data appear to support the body mass findings as the mean daily urine specific gravity was clinically elevated (>1.020) on all days except baseline.

CLINICAL IMPLICATIONS AND CONCLUSION

Professional NFL players may be challenged to maintain fluid and electrolyte homeostasis and normal body mass during preseason training due to large sweat sodium losses. Low blood sodium and below baseline plasma volume during the first few days of preseason training may be of clinical importance. Mild signs and symptoms related to hypovolemic hyponatremia might go unnoticed or the illness might be misdiagnosed as viral or gastrointestinal in nature.[7] Consequently, we contend that a diet high in sodium content is likely necessary for the average professional football player during the first several days of two-a-days to assure blood sodium is maintained, allowing for appropriate plasma volume expansion. Sodium intake should be with fluids that contain considerably higher concentrations of sodium than found in common fluid replacement drinks, players must ingest substantial amounts of extra salt in their diet, or both.[17,39] Importantly, the rise in resting levels of blood K^+ and subsequent elevation in urinary K^+ excretion in players are likely a consequence of muscle cell damage due to the physical stresses of practicing football twice a day in the heat and warrants further study.

Proper maintenance of plasma volume requires a correct balance between Na^+ and water in the body. Football players participating in twice-a-day practice sessions in hot weather can lose large amounts of Na^+, which can be difficult to replace via normal dietary intake and the consumption of hypotonic fluids, including commercial sports drinks. The Na^+ needs in these athletes are best determined on an individual basis, thus allowing for indicated increases in dietary sodium intake, Na^+ supplementation, or both. Reported increases in blood K^+ associated with consecutive days of twice-a-day football practice sessions may indicate the need for caution regarding the consumption of products containing K^+.

Low blood Na^+ concentrations can cause an athlete to feel ill. Clinicians should exclude any athlete exhibiting signs or symptoms of illness from strenuous activity in hot weather until the cause is ascertained, correctly treated, and eliminated. ■

REFERENCES

1. Montain SJ, Sawka MN, Cadarette BS, Quigley MD, McKay JM. Physiological tolerance to uncompensable heat stress: Effects of exercise intensity, protective clothing, and climate. *J Appl Physiol.* 1994;77:216-222.
2. Adams WC, Mack GW, Langhans GW, Nadel ER. Effects of varied air velocity on sweating and evaporative rates during exercise. *J Appl Physiol.* 1992;73:2668-2674.
3. Kenney WL, Lewis DA, Hyde DE, et al. Physiologically derived critical evaporative coefficients for protective clothing ensembles. *J Appl Physiol.* 1987;63:1095-1099.
4. Kulka TJ, Kenney W. Heat balance limits in football uniforms: How different uniform ensembles alter the equation. *The Physician and Sportsmedicine.* 2002;30(7):27-39.
5. Fowkes Godek S, Bartolozzi AR, Burkholder R, Sugarman E, Peduzzi C. Sweat rates and fluid turnover in professional football players: A comparison of National Football League linemen and backs. *J Athl Train.* 2008;4:184-189.
6. Havenith G, van Middendorp H. The relative influence of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress. *Eur J Appl Physiol Occup Physiol.* 1990;61:419-427.
7. Fowkes Godek S, Bartolozzi AR, Godek JJ. Sweat rate and fluid turnover in American football players compared with runners in a hot and humid environment. *Br J Sports Med.* 2005;39:205-211.
8. Sato K, Sato F. Individual variations in structure and function of human eccrine sweat gland. *Am J Physiol.* 1983;245:R203-R208.
9. Prior BM, Modlesky CM, Evans EM, et al. Muscularity and the density of the fat-free mass in athletes. *J Appl Physiol.* 2001;90:1523-1531.
10. Marino FE, Mbambo Z, Kortekaas E, et al. Advantages of smaller body mass during distance running in warm, humid environments. *Pflugers Arch.* 2000;441:359-367.
11. Fowkes Godek S, Bartolozzi AR. Hydration and core temperature in a football player during preseason: A case study. *Athletic Therapy Today.* 2004;9(4):64-70.
12. Fowkes Godek S, Godek JJ, Bartolozzi AR. Hydration status in college football players during consecutive days of twice-a-day preseason practices. *Am J Sports Med.* 2005;33:843-851.
13. Fowkes Godek S, Peduzzi C, Burkholder R, Condon S, Dorshimer G, Bartolozzi A. Sweat rates, sweat sodium concentration and sodium losses in three groups of professional football players. *J Athl Train.* 2009. In press.

14. Dorshimer G, Fowkes Godek S, Burkholder R, Fowkes B, Sugarman E. Sweat rates and fluid turnover in professional football players during practices in hot versus cool conditions [abstract]. *J Athl Train*. 2005;40(suppl 2):S40.
15. Convertino VA, Armstrong LE, Coyle EF, et al. American College of Sports Medicine position stand: Exercise and fluid replacement. *Med Sci Sports Exerc*. 1996;28:i-vii.
16. Casa DJ, Armstrong LE, Hillman SK, et al. National Athletic Trainers' Association position statement: Fluid replacement for athletes. *J Athl Train*. 2000;35:212-224.
17. Sharp RL. Role of sodium in fluid homeostasis with exercise. *J Am Coll Nutr*. 2006;25(suppl):231S-239S.
18. Dill DB, Costill DL. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J Appl Physiol*. 1974;37:247-248.
19. Shirreffs SM, Maughan RJ. Whole body sweat collection in humans: An improved method with preliminary data on electrolyte content. *J Appl Physiol*. 1997;82:336-341.
20. Noakes TD. The hyponatremia of exercise. *Int J Sport Nutr*. 1992;2:205-228.
21. Romero JC, Staneloni RJ, Dufau ML, et al. Changes in fluid compartments, renal hemodynamics, plasma renin and aldosterone secretion induced by low sodium intake. *Metabolism*. 1968;17(1):10-19.
22. Armstrong LE, Costill DL, Fink WJ. Changes in body water and electrolytes during heat acclimation: Effects of dietary sodium. *Aviat Space Environ Med*. 1987;58:143-148.
23. Armstrong LE, Costill DL, Fink WJ, et al. Effects of dietary sodium on body and muscle potassium content during heat acclimation. *Eur J Appl Physiol Occup Physiol*. 1985;54:391-397.
24. Harrison MH, Edwards RJ, Graveney MJ, Cochrane LA, Davies JA. Blood volume and plasma protein responses to heat acclimatization in humans. *J Appl Physiol*. 1981;50:597-604.
25. Senay LC, Mitchell D, Wyndham CH. Acclimatization in a hot, humid environment: Body fluid adjustments. *J Appl Physiol*. 1976;40:786-796.
26. Shapiro Y, Hubbard RW, Kimbrough CM, Pandolf KB. Physiological and hematologic responses to summer and winter dry-heat acclimation. *J Appl Physiol*. 1981;50:792-798.
27. Latzka WA, Montain SJ. Water and electrolyte requirements for exercise. *Clin Sports Med*. 1999;18:513-524.
28. Sawka MN, Montain SJ. Fluid and electrolyte supplementation for exercise heat stress. *Am J Clin Nutr*. 2000;72(suppl):564S-572S.
29. Hew-Butler TD, Sharwood K, Collins M, Speedy D, Noakes T. Sodium supplementation is not required to maintain serum sodium concentrations during an Ironman triathlon. *Br J Sports Med*. 2006;40:255-259.
30. Speedy DB, Thompson JM, Rodgers I, Collins M, Sharwood K, Noakes TD. Oral salt supplementation during ultradistance exercise [published correction appears in Clin J Sport Med. 2003;13:67]. *Clin J Sport Med*. 2002;12:279-284.
31. Twerenbold R, Knechtle B, Kakebeeke TH, et al. Effects of different sodium concentrations in replacement fluids during prolonged exercise in women. *Br J Sports Med*. 2003;37:300-303.
32. Hew-Butler T, Verbalis JG, Noakes TD. Updated fluid recommendations: Position statement from the International Marathon medical Directors Association (IMMDA). Clin J Sport Med. 2006;16(45):283-292.
33. Almond CS, Shin AY, Fortescue EB, et al. Hyponatremia among runners in the Boston Marathon. *N Engl J Med*. 2005;352:1550-1556.
34. Gardner JW. Death by water intoxication. *Mil Med*. 2002;167:432-434.
35. Hew-Butler T, Almond C, Ayus JC, et al. Consensus statement of the 1st International Exercise-Associated Hyponatremia Consensus Development Conference, Cape Town, South Africa 2005. *Clin J Sport Med*. 2005;15:208-213.
36. Noakes T. Hyponatremia in distance runners: Fluid and sodium balance during exercise. *Curr Sports Med Rep*. 2002;1:197-207.
37. Noakes TD. Overconsumption of fluids by athletes. *BMJ*. 2003;327(7407):113-114.
38. Noakes TD, Sharwood K, Speedy D, et al. Three independent biological mechanisms cause exercise-associated hyponatremia: Evidence from 2,135 weighed competitive athletic performances. *Proc Natl Acad Sci USA*. 20 2005;102:18550-18555.
39. Ray ML, Bryan MW, Ruden TM, Baier SM, Sharp RL, King DS. Effect of sodium in a rehydration beverage when consumed as a fluid or meal. *J Appl Physiol*. 1998;85:1329-1336.
40. Sugarman E, Fowkes Godek S, Peduzzi C, Burkholder R, Garvin G, Bartolozzi AR. Protein, creatinine and electrolyte excretion in sodium supplemented NFL players during pre-season [abstract]. *J Athl Train*. 2006;41(suppl 2):S59.
41. Ehlers GG, Ball TE, Liston L. Creatine kinase levels are elevated during 2-a-day practices in collegiate football players. *J Athl Train*. 2002;37:151-156.
42. Bartolozzi AR, Fowkes Godek S. Core temperature in college football players during a game played in hot conditions. *Med Sci Sports Exerc*. 2006;38(suppl 5):S58.
43. Fowkes Godek S, Bartolozzi AR, Burkholter R, Sugarman E. Core temperature in a symptomatic NFL running back during a full padded pre-season practice with post practice urine indicies of rhabdomyolysis. *Med Sci Sports Exerc*. 2006;38(suppl 5):S159.