

Human Hydration Indices: Acute and Longitudinal Reference Values

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It is difficult to describe hydration status and hydration extremes because fluid intakes and excretion patterns of free-living individuals are poorly documented and regulation of human water balance is complex and dynamic. This investigation provided reference values for euhydration (i.e., body mass, daily fluid intake, serum osmolality; $M \pm SD$); it also compared urinary indices in initial morning samples and 24-hr collections. Five observations of 59 healthy, active men (age 22 ± 3 yr, body mass 75.1 ± 7.9 kg) occurred during a 12-d period. Participants maintained detailed records of daily food and fluid intake and exercise. Results indicated that the mean total fluid intake in beverages, pure water, and solid foods was >2.1 L/24 hr (range 1.382–3.261, 95% confidence interval 0.970–3.778 L/24 hr); mean urine volume was >1.3 L/24 hr (0.875–2.250 and 0.675–3.000 L/24 hr); mean urine specific gravity was >1.018 (1.011–1.027 and 1.009–1.030); and mean urine color was ≥ 4 (4–6 and 2–7). However, these men rarely (0–2% of measurements) achieved a urine specific gravity below 1.010 or color of 1. The first morning urine sample was more concentrated than the 24-h urine collection, likely because fluids were not consumed overnight. Furthermore, urine specific gravity and osmolality were strongly correlated ($r^2 = .81-.91$, $p < .001$) in both morning and 24-hr collections. These findings provide euhydration reference values and hydration extremes for 7 commonly used indices in free-living, healthy, active men who were not exercising in a hot environment or training strenuously.

Keywords: urine, plasma, specific gravity, osmolality, total body water, fluid intake

The human body constantly loses water from the lungs, skin, and kidneys. Because the thirst drive does not stimulate drinking until water loss reaches 1–2% of body mass (Adolph, 1947), athletes may train and compete in an unrecognized state of mild to moderate hypohydration (Armstrong et al., 1998). Such mild dehydration (i.e., –1 to –2.5% of body mass) reduces cognitive function, alertness (Edwards et al., 2007; Maughan, 2003; Wilson & Morley, 2003), endurance-exercise performance (Cheuvront, Carter, & Sawka, 2004), and high-intensity exercise performance lasting ~7 min (Nielsen et al., 1981); it also increases physiological strain (i.e., heart rate and core body temperature; Maughan, 2003). Furthermore, insufficient or excessive dietary intake of water changes cellular volume and affects a variety of cellular functions including metabolism, excitation, transport, hormone release, cell proliferation, and cell death (Lang et al., 1998). In

rare instances (1 in 1,000), athletes consume too much fluid, dilute body fluids abnormally, and experience the illness known as exertional hyponatremia (Noakes, 2003). These facts explain why the position statements of the American College of Sports Medicine (ACSM; ACSM et al., 2007) and the National Athletic Trainers' Association (NATA; Casa et al., 2000) acknowledge the detrimental effects of dehydration on health and performance and provide guidelines regarding the rate of fluid consumption and methods to evaluate hydration state. For example, the National Collegiate Athletic Association (NCAA; 2003) and the National Federation of High School Associations (2006) use urine specific gravity >1.020 – 1.025 to indicate dehydration. Wrestlers may not have their minimal competitive weight determined for competition unless an appropriate urine specific gravity is verified. This rule exists to deter acute dehydration-related weight loss and its potential health risks and to promote competitive equity among athletes (Oppliger & Bartok, 2002). The NATA also states that a urine specific gravity of >1.020 , a body-mass loss of $>3\%$, and a urine color >4 represent dehydration (Casa et al., 2000). However, our extensive review of print (Armstrong, 2007; Kavouras, 2002; Oppliger & Bartok, 2002; Shirreffs, 2003) and Internet publications indicates that studies of human hydration indices are in short supply. Thus, the recommendations

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of sports-medicine and sport-governing bodies are not strongly supported by normative values from adequate subject samples or research that describes variability across days.

It is difficult to assign a numerical value to euhydration, dehydration, or hyperhydration using any hydration index because human water turnover is complex and dynamic (Armstrong, 2007). Therefore, the current investigation was designed to provide reference values and 95% confidence limits for body mass, 24-hr fluid intake, serum osmolality, and seven urinary variables (i.e., volume and acute and chronic specific gravity, osmolality, and color) derived from 59 healthy men age 18–34 years. Observations were made on selected mornings over a period of 12 days. These data allow evaluation of the recommendations and regulations set forth by sports-medicine and sport-governing bodies, augment published review articles that describe hydration indices (Armstrong, 2007, Kavouras, 2002; Shirreffs, 2003), and provide reference values that can be used to counsel athletes and recreational enthusiasts. The data also allow a large-scale evaluation of the timing of urine collections. Previously, authors have questioned whether initial morning urine samples validly represent a daily average (Armstrong et al., 1994; Shirreffs & Maughan, 1998; Wemple, Lamb, & McKeever, 1997). Based on those previous observations, we hypothesized that initial morning urine samples would not represent a 24-hr collection.

Methods

Fifty-nine healthy men participated in 12 days of testing. To be included in this investigation, participants had to exercise at least twice per week but could not regularly participate in prolonged or intense exercise. Exclusionary factors included body mass outside the range of 60–85 kg and self-reported tobacco smoking, lactose intolerance, and consuming more than eight cola beverages or four cups (150 ml) of brewed coffee per day. Data were recorded as part of a previous study (Armstrong et al., 2005), which evaluated the effects of controlled daily caffeine intake on hydration status during ordinary, free-living dietary consumption. During that previous study no evidence of disturbed hydration was observed when participants consumed 0, 3, and 6 mg · kg⁻¹ · day⁻¹ of caffeine (0, 226, and 452 mg/day, respectively). Because none of the participant personal characteristics, dietary components, or measured indices of hydration state were different between treatment groups, data were combined and all participants are considered as one group for the purposes of the current investigation. Participants completed a medical-history questionnaire to verify that they were healthy, not taking medications that would affect measured physiological variables, and free from cardiovascular, metabolic, or respiratory disease. The local institutional review board for human studies approved this protocol, and each participant provided written, informed consent to participate after attending a briefing.

The mean (\pm *SD*) physical characteristics for the 59 test subjects were age 22 \pm 3 years, height 178 \pm 6 cm, body mass 75.1 \pm 7.9 kg, and body-mass index (BMI) 23.9 \pm 2.4 kg/m². The activity questionnaire indicated that participants exercised an average of 4.1 \pm 2.1 sessions/week, for 1.1 \pm 0.7 hr/session. Based on these findings, participants were declared active but not highly trained. During an exit interview, all participants stated that their prestudy exercise habits were similar to exercise sessions conducted during this investigation. Their mean daily ad libitum macronutrient intake (Days 1–11) included 52% \pm 8% carbohydrate, 31% \pm 5% fat, 18% \pm 4% protein, and 2,782 \pm 699 kcal of energy.

Participants visited the human performance laboratory 2–4 days before any experimental data collection to receive information pertaining to study procedures. Height was measured to the nearest 1 cm, and body mass was measured on a platform scale (\pm 100 g; Ohaus DS44L, Florham Park, NJ). BMI was calculated from height (m) and body mass (kg) using the formula BMI = body mass/height². An activity questionnaire was administered to evaluate the duration, type, and frequency of exercise during the 30 days before data collection. Participants were instructed to maintain their usual exercise program throughout this investigation.

Participants met with a registered dietitian to receive instructions regarding standardized food- and fluid-recording procedures and a packet of dietary records. The dietitian met with participants each morning (Days 1–11) to optimize completeness and accuracy of food and fluid records. Dietary components were analyzed with commercial software (Nutritionist Pro, version 1.2, N-Squared Computing, Salem, OR) that computed carbohydrate, fat, and protein (%); caloric intake (kcal); sodium (total mEq); potassium (total mEq); and daily total fluid intake (ml). This latter variable was calculated from all beverages, soups, and water-dense foods (e.g., watermelon) consumed.

Experimental Design

Participants collected all urine produced over 24 hr on Days 1, 3, 6, 9, and 12. Technicians then measured urine volume, color (U_{Col} ; Armstrong et al., 1998; Armstrong et al., 1994), specific gravity (U_{SG}) using a handheld refractometer (Atago A 300CL, Japan), and osmolality (U_{Osm} ; mOsm/kg) via freezing-point-depression osmometer (Advanced Digimatic, Model 3DII, Needham Heights, MA). These samples also were analyzed for urine creatinine (Sigma Diagnostics, Procedure #555, St. Louis, MO) using a spectrophotometer calibrated at 500 nm (Spectronic 401, Spectronic Instruments, Rochester, NY). The initial morning urine specimen was collected when participants returned their 24-hr collections on Days 1, 3, 6, 9, and 12 between 7 and 8 a.m.; these were analyzed for U_{Col} , U_{SG} , and U_{Osm} , and the remaining volume was added to the 24-hr collection. Body mass was measured on Days 1, 3, 6, 9, and 12 using the platform scale described previously.

Plasma samples (collected on Days 1, 3, 6, 9, and 12) were stored at -80°C and later analyzed for blood urea nitrogen (Ortho Vitros 950 analyzer, Johnson & Johnson Co., Rochester, NY; 1.5% coefficient of variation) to evaluate renal function. Also on those days, blood was obtained from an antecubital arm vein while participants were seated. Serum osmolality (mOsm/kg) was measured with the osmometer described previously.

Statistical Analyses

The means, standard deviations, percentile values, skewness, kurtosis, and normalcy of variables ($N = 59$) were analyzed with SPSS Base 11.0 software (SPSS Inc., Chicago, IL). Statistical comparisons of means were analyzed with one-way repeated-measures analyses of variance with time as the only independent variable. To avoid violating the assumption of independence, means were compared separately across days, using post hoc paired-sample t tests and Holm's sequential Bonferroni correction. Significance was accepted at the .05 level. Statistical correlations, regression analyses, and figure designs were accomplished with Microsoft Office Excel software (version 11.0, 2003, Redmond, WA).

Results

Table 1 presents four hydration indices measured on Days 1, 3, 6, 9, and 12. Table 2 compares U_{SG} and U_{Col} from

single initial morning samples with 24-hr collections. No statistical differences occurred across days for any variable shown in Table 1 or 2. Tests for skewness and kurtosis were normal for all variables in Tables 1 and 2.

Table 3 was designed using percentiles for the normal distribution of 290 data points. The extreme categories (i.e., extremely hyperhydrated and extremely dehydrated) represent the 10 percentile units farthest from the mean. The categories slightly hyperhydrated, well hydrated, slightly dehydrated, and very dehydrated represent 15 percentile units each between the extremes. Euhydration, the central category, occupies the middle 20 percentile units of this distribution. Table 3 also includes the 95% confidence limits (see Row 9) for all variables in Tables 1 and 2 except body mass.

Virtually all measures presented in Tables 1 and 2 and Figures 1 and 2 fall within normal clinical ranges (Kratz, Ferraro, Sluss, & Lewandrowski, 2004). Renal function also was deemed normal in all participants because measurements of urine creatinine excretion and blood urea nitrogen (not shown; reported in Armstrong et al., 2005) were within the normal clinical range for healthy adult men (Kratz et al., 2004).

The mean ($\pm SD$) change in body mass between consecutive measurements (i.e., Day 1 to Day 3, or Day 6 to Day 9) was 0.57 kg, or 0.8%. The greatest change of body mass for participants across all days of this investigation (maximum – minimum) was 1.29 ± 0.56 kg, or 1.8% of body weight.

Table 1 Four Hydration Variables Measured on Days 1, 3, 6, 9, and 12, $M \pm SD$

Day	Morning body mass ^a (kg)	Morning serum osmolality (mOsm/kg)	24-hr fluid intake ^b (ml)	24-hr urine volume (ml)
1	75.4 \pm 8.0	290 \pm 4	2,149 \pm 724	1,513 \pm 603
3	74.9 \pm 8.0	290 \pm 4	2,249 \pm 711	1,541 \pm 565
6	75.1 \pm 8.1	290 \pm 5	2,108 \pm 708	1,533 \pm 611
9	74.8 \pm 8.1	290 \pm 6	2,147 \pm 682	1,459 \pm 539
12	75.0 \pm 7.9	290 \pm 5	2,183 \pm 659 ^c	1,377 \pm 544

Note. $N = 56$ –59. There were no statistical differences across days for any variable.

^aInitial, single morning measurement. ^bFrom daily dietary records; includes beverages plus fluid in solid food. ^cMeasured on the morning of Day 11.

Table 2 Three Urinary Hydration Indices: Comparison of Initial Morning Samples and 24-hr Collections, $M \pm SD$

Day	Morning U_{SG} of the initial single sample ^a	24-hr U_{SG} ^b	Morning U_{Osm} of the initial single sample ^a (mOsm/kg)	24-hr U_{Osm} ^b (mOsm/kg)	Morning U_{Col} ^c of the initial single sample ^a	24-hr U_{Col} ^{b,c}
1	1.024 \pm 0.005	1.020 \pm 0.006 ^d	859 \pm 183	717 \pm 233 ^d	5 \pm 1	5 \pm 1
3	1.025 \pm 0.006	1.019 \pm 0.006 ^d	858 \pm 230	668 \pm 249 ^d	5 \pm 1	5 \pm 1
6	1.023 \pm 0.006	1.018 \pm 0.006 ^d	805 \pm 225	637 \pm 233 ^d	4 \pm 1	4 \pm 1
9	1.024 \pm 0.005	1.019 \pm 0.006 ^d	843 \pm 218	667 \pm 252 ^d	5 \pm 1	4 \pm 1
12	1.024 \pm 0.005	1.020 \pm 0.007 ^d	867 \pm 210	720 \pm 246 ^d	5 \pm 1	5 \pm 1

Note. $N = 58$. U_{SG} = urine specific gravity; U_{Osm} = urine osmolality; U_{Col} = urine color. There was no statistical difference across days for any variable.

^aMeasured in the initial urine sample of the day. ^bMeasured in a 24-hr urine collection. ^cRef. 4, 5. ^dThe mean U_{SG} and U_{Osm} values for 24-h collections on all days were significantly different ($p < .005$ to $.001$) from initial morning samples.

Table 3 Categories of Hydration Status for 75.1-kg Men

Hydration category	Percentile range (percentile)	Morning serum osmolality (mOsm/kg)	24-hr total fluid intake (ml) ^a	24-hr urine volume (ml)	Morning U _{SG} of the initial sample	24-hr U _{SG}	Morning U _{Osm} of the initial sample (mOsm/kg)	24-hr U _{Osm} (mOsm/kg)	Morning U _{Col} of the initial sample	24-hr U _{Col}
Extremely hyperhydrated	1–10	<285	>3,261	>2,250	<1.017	<1.012	<545	<377	<4	<4
Slightly hyperhydrated	11–25	285–286	2,615–3,261	1,898–2,250	1.017–1.021	1.012–1.014	545–713	377–475	4	4
Well hydrated	26–40	287–288	2,454–2,614	1,526–1,897	1.022–1.023	1.015–1.017	714–817	476–586	5	5
Euhydrated	41–60	289–291	2,049–2,453	1,226–1,525	1.024–1.026	1.018–1.020	818–924	587–766	5	5
Slightly dehydrated	61–75	292	2,009–2,048	1,075–1,225	1.027–1.028	1.021–1.024	925–999	767–880	5	6
Very dehydrated	76–90	293–296	1,382–2,008	875–1,074	1.029–1.031	1.025–1.027	1,000–1,129	881–1,013	6	6
Extremely dehydrated	91–100	>296	<1,382	<875	>1.031	>1.027	>1,129	>1,013	>6	>6
95% confidence intervals	2.5–97.5	274–301	970–3,778	675–3,000	1.011–1.033	1.009–1.030	377–1,194	281–1,114	3–7	2–7

Note. Percentiles were used to determine numerical values for each category (290 data points, 59 test subjects). U_{SG} = urine specific gravity; U_{Osm} = urine osmolality; U_{Col} = urine color.

^aBeverages account for approximately 80% of total fluid intake (liquid + solid foods).

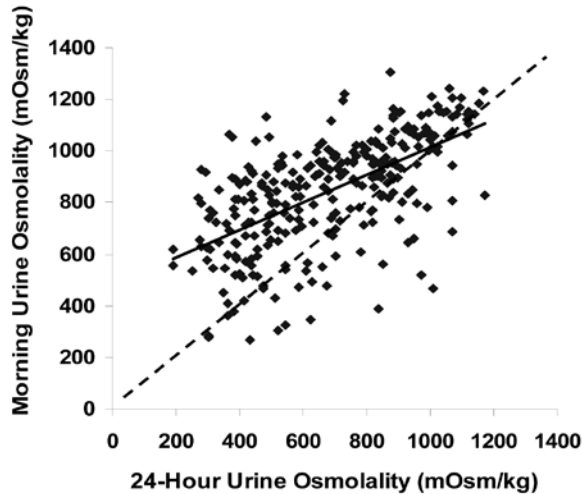
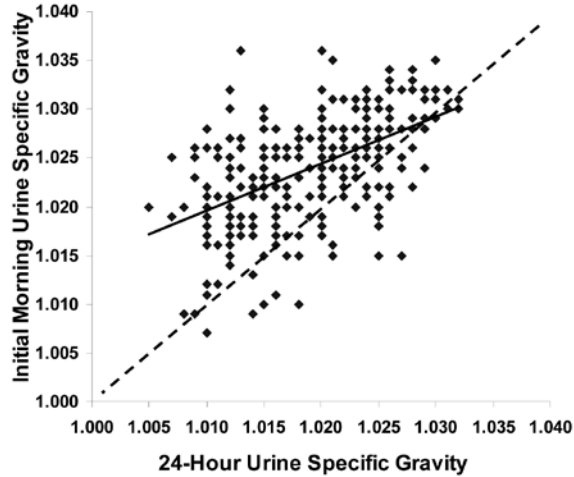


Figure 1 — Urine specific gravity (top panel: $r^2 = .29$, $p < .001$, $N = 290$; $y = 0.49x + 0.53$) and urine osmolality (bottom panel: $r^2 = .37$, $p < .001$, $N = 290$; $y = 0.53x + 482.36$) as measured in 24-hr collections and initial morning urine samples. The solid regression lines of best fit appear above the dashed lines representing unity.

Figure 1 presents U_{SG} (top panel) and U_{Osm} (bottom panel) as measured in 24-hr collections (x axis) in initial morning urine samples (y axis). Data points represent 59 participants observed on all experimental days.

Figure 2 illustrates the strong statistical correlations between U_{SG} and U_{Osm} . The top panel depicts this relationship in initial morning urine samples (acute), and the bottom panel focuses on 24-hr collections ($N = 59$ men on Days 1, 3, 6, 9, and 12). Figure 3 presents a frequency histogram for all U_{Col} measurements. Both 24-hr collections and initial morning samples are depicted; means of these values were statistically similar. In addition, no test subject presented with a urine color of either 1 or 8.

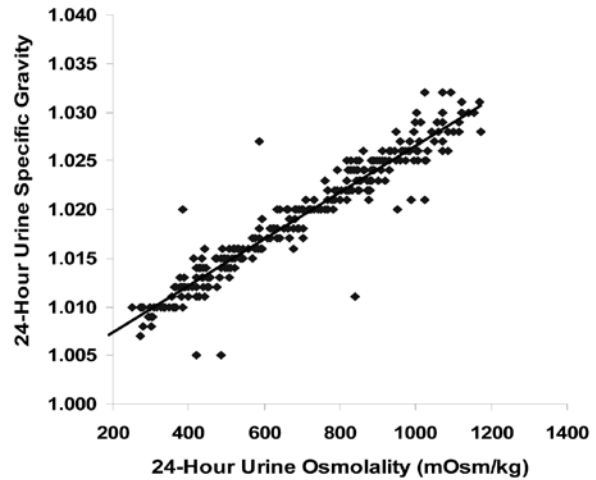
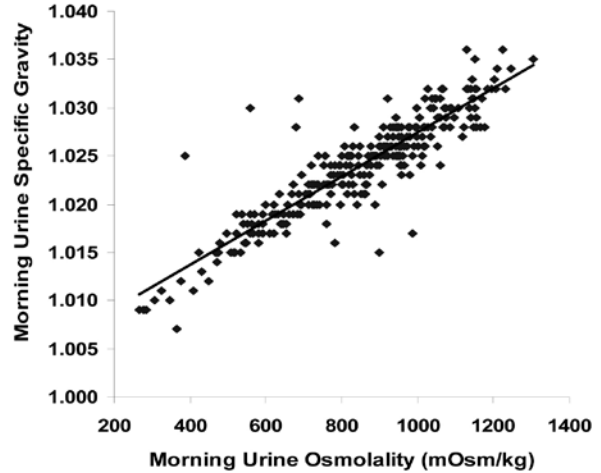


Figure 2 — Relationship between urine osmolality and urine specific gravity in initial morning samples (top panel: $r^2 = .81$, $p < .001$; $y = 0.00002x + 1.0046$) and 24-hr collections (bottom panel: $r^2 = .91$, $p < .001$, $n = 290$; $y = 0.00002x + 1.0026$).

Discussion

The neuroendocrine regulation of human water balance is complex and dynamic because of the influences of dietary water-salt intake, exercise, sweat loss, kidney function, and osmotic fluid movements between the intracellular and extracellular compartments. Thus, the elusive state of euhydration is best described as a sinusoidal wave that fluctuates around an average total body water that varies constantly (Oppliger & Bartok, 2002). This dynamic complexity underlies the perplexing question, “Which body-fluid measurement best represents whole-body hydration status?” The answer remains elusive today because the fluid intake and excretion patterns of free-

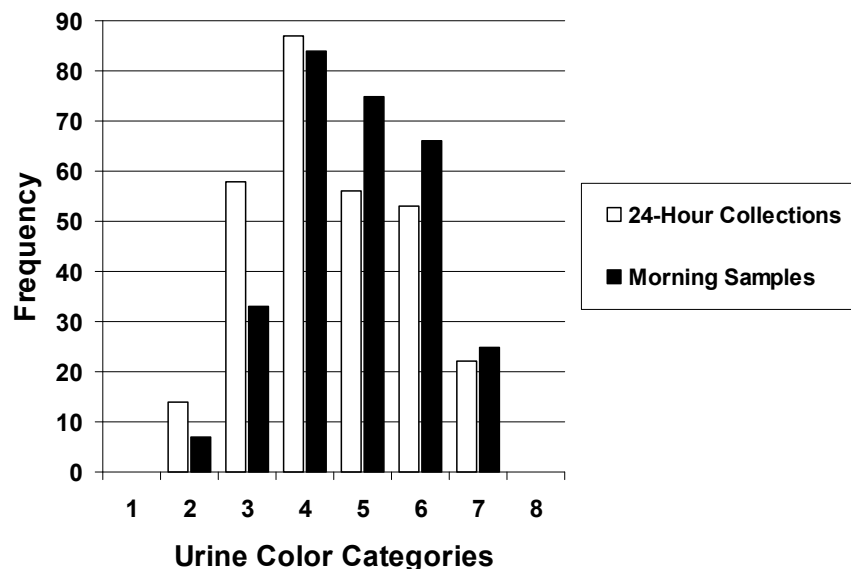


Figure 3 — Frequency histogram of urine color categories, measured in 24-hr collections and initial morning samples ($N = 290$; experimental Days 1, 3, 6, 9, 12).

living individuals are poorly documented (Raman et al., 2004), despite the publication of numerous research studies involving more than a dozen hydration-assessment techniques during the previous 3 decades (Armstrong, 2007; Maughan & Griffin, 2003). Even if one hydration-assessment technique were superior in a given situation (i.e., a reference standard), a second question arises: “What numerical values represent hypohydration, euhydration, and hyperhydration?” The current investigation provides an initial attempt to answer this question for healthy men under free-living conditions.

Reference Values

The current data build on four previous publications, each with a unique approach to hydration assessment. First, the NATA position statement regarding fluid replacement categorized hydration indices as guidance for athletes during training and competition (Casa et al., 2000). In terms of U_{SG} , the NATA defined well hydrated as a value less than 1.010 and dehydrated as a value over 1.020. However, these values were based on expert consensus opinion, not a systematic evaluation of a large database representing multiple daily observations. Second, a previous publication from our laboratory (Armstrong et al., 1994) defined normal hydration in terms of a U_{Osm} of 442–1052 mOsm/kg, U_{SG} of 1.013–1.029, and U_{Col} of 3–7; that publication also defined hypohydration as $U_{Osm} > 1,052$ mOsm/kg, $U_{SG} > 1.029$, and $U_{Col} > 7$. These ranges, published in 1994, are considerably broader than those in Table 3, likely because they were derived from a smaller sample. Third, Popowski et al. (2001) represented euhydration as the range of U_{SG} from 1.006 to 1.020. Their approach matches our categories in Tables 2 and 3 well,

although only 4 of the 290 U_{SG} measurements were less than 1.010 in initial morning samples (Figure 1). Fourth, the NCAA requires wrestlers to achieve a euhydrated U_{SG} (defined as 1.020 or less) to compete in a desired weight class (NCAA, 2003). This supports the U_{SG} data in Tables 3 well, in that all dehydration categories (i.e., slightly, very, extremely) exceed a U_{SG} of 1.020. Thus, the results of the current investigation refine these four publications with additional categories and a statistical approach to the problem based on percentiles. As such, these new categories (Table 3) provide a framework within which sports-medicine personnel can assess the hydration state of any individual, using one of nine hydration indices.

When interpreting Tables 1 and 2, we assumed that the statistical means of all variables represented a state of euhydration and that the 59 male test subjects validly represented all men. Thus, in this sample of 59 healthy, active men (75.1 kg body mass) euhydration was represented by the following mean values (some are presented as a range because the mean varied from day to day): serum osmolality 290 mOsm/kg, fluid intake 2,108–2,249 ml/24 hr, urine volume 1,377–1,533 ml/24 hr, initial morning single-sample U_{SG} 1.023–1.025, 24-hr U_{SG} 1.018–1.020, initial morning single-sample U_{Osm} 805–867 mOsm/kg, 24-hr U_{Osm} 637–720 mOsm/kg, initial morning single-sample U_{Col} 4–5, and 24-hr U_{Col} 4–5. As noted previously, we believe that euhydration is best described as a sinusoidal wave that constantly fluctuates around a changing mean (Oppliger & Bartok, 2002), and these values represent that mean.

Body mass is a reliable, accurate method of evaluating change in body water within a day (Cheuvront, Carter, Montain, & Sawka, 2004). As a guide for sports-medicine professionals, we evaluated the repeated mea-

tures of body mass for each participant to determine the magnitude of day-to-day changes. The mean difference between consecutive measurements (i.e., Day 1 to Day 3, Day 6 to Day 9, or Day 9 to Day 12) was 0.57 ± 0.45 kg, or $0.75\% \pm 0.60\%$ of total body mass. The maximal morning body-mass difference across 12 days (i.e., the maximum minus the minimum value) was 1.28 ± 0.56 kg; expressed as a mean percentage, this maximal difference was $1.8\% \pm 0.7\%$ within subjects. However, the reader should note that our test subjects were active but not highly trained; as such, these values do not represent athletes who undertake intense physical training or exercise in a hot environment.

Extremes of Hydration

Table 3 is unique in the scientific and clinical literatures in that it provides the 95% confidence intervals for young, healthy, active men. Any participant who exhibits a value outside these limits can be considered an extreme case of either hypohydration or hyperhydration (i.e., at risk for hyponatremia). These numerical values quantify the outer boundaries of normal hydration that sports-medicine personnel, health care providers, physiologists, and dietitians use when advising athletes and clients.

Table 3 also illustrates the body's regulation of fluid-electrolyte balance. Although the labels in Column 1 provide cognitive anchors, deciles typically elude precise physiological definitions and meanings (i.e., as 1/10th of a continuous spectrum of hydration states). This is true in Table 3 because statistical categories (Column 2) do not translate easily to defined hydration levels. Although we did not measure neuroendocrine responses in the current investigation, widely accepted physiological principles of fluid-electrolyte homeostasis indicate that the body continuously modifies extreme hydration states (e.g., extremely hyperhydrated and extremely dehydrated in Column 1) by hormonally altering urine electrolyte concentration (Columns 6–9 in Table 3), as well as thirst, urine water content, and urine volume (Columns 4–5 in Table 3). These neuroendocrine and sensory responses in turn regulate the critical variable serum osmolality (Column 3). Furthermore, because the regulation of total body water is dynamic and complex (Armstrong, 2007), all hydration states in Table 3 should be viewed as temporary. When there is either excess or inadequate total body water, the brain alters thirst and renal function in an effort to bring body-water balance toward the homeostatic set point (i.e., the central hydration point, labeled euhydration in Column 1). In our experience, the lowest U_{SG} values in Table 3 are surprising, when considering that athletes and recreational enthusiasts are advised that a U_{SG} below 1.010 represents a well-hydrated state (Casa et al., 2000). However, in our initial morning urine samples, any value less than 1.012 represented a state of extreme hyperhydration and lay outside the 95% confidence intervals (Table 3). We interpret this to mean that a U_{SG} below 1.012 is difficult to achieve in an initial morning sample, because little or no fluid is consumed

overnight and because glomerular filtration decreases during sleep. Furthermore, the data in Table 3 suggest that single morning samples with a $U_{SG} < 1.017$ are quite acceptable (comprising the first to tenth percentiles). In contrast, when assessing 24-hr collections, when fluids were consumed ad libitum during daily activities, the 95% confidence interval of U_{SG} was 1.009 at the 2.5 percentile. These values suggest that advice regarding hydration should discriminate between the initial morning urine sample and urine collected throughout the day, because these variables are not equivalent (see Footnote d in Table 2). Initial morning samples tend to be more concentrated than 24-hr collections.

Recognizing that our test subjects did not undertake intense physical training or exercise in a hot environment, it is interesting to note that no test subject presented with a U_{Col} of either 1 or 8 at any time during this 12-day investigation (Figure 3), supporting strongly the findings published by our research group in 1994 (Armstrong et al., 1994). Considering the absence of severe overhydration values in 24-hr urine collections (i.e., no U_{SG} values < 1.007 , no U_{Col} of 1, no U_{Osm} values < 200 mOsm/kg; see Figures 2 and 3), we believe that athletes should not be expected to achieve such a severe hydration state constantly. With the exception of renal dysfunction (e.g., nephron hypofiltration), a $U_{SG} < 1.010$, a $U_{Col} < 3$, and a $U_{Osm} < 300$ mOsm/kg will be observed in a single morning sample only after an athlete has consumed a large bolus of water or hypotonic fluid. Therefore, we strongly recommend that dietitians, physiologists, athletic trainers, coaches, and athletes not interpret the extremely hyperhydrated category (Table 3) as desirable. We believe that a $U_{SG} < 1.007$ (see Figure 2) and a U_{Col} of 1 (see Figure 3) are not appropriate goals for a 24-hr hydration regimen because individuals who are categorized as extremely hyperhydrated (Table 3) and who believe that overdrinking is desirable are predisposed to fluid overload. In support of this concept, a previous publication (Armstrong et al., 1993) reported that a healthy young man developed symptomatic hyponatremia (122 mEq Na⁺/L) during moderate-intensity exercise after consuming 10.3 L water ad libitum in 7 hr. He was predisposed to hyponatremia by a low-normal preexercise plasma sodium concentration (134 mEq Na⁺/L) because of overdrinking on the previous day and a strong belief that he could avoid heat illness if he consumed as much water as possible. In contrast to overdrinking, if an athlete is preparing for intense exercise in the heat and anticipates a large sweat loss with significant dehydration (i.e., 3–5% body-weight loss), it would be reasonable to begin exercise in a slightly hyperhydrated or well-hydrated state (Table 3).

Time of Samples

Previously, physiologists questioned whether initial morning urine samples were different from 24-hr urine collections (Armstrong et al., 1994; Shirreffs & Maughan, 1998; Wemple et al., 1997). This matter remains unresolved. For example, Shirreffs and Maughan stated that

an initial morning sample can be useful when athletes evaluate their own hydration state in field settings. They also observed that nonathletes had lower U_{Osm} values than wrestlers who attempted to lose body weight by dehydrating. In contrast, other investigators have cautioned that the initial morning urine sample represented the urine that accumulated overnight and may not represent the total urine output during a 24-hr period (Armstrong et al., 1994). This concept is supported by the data in Table 2, in that initial morning urine samples were significantly more concentrated than 24-hr collections on all days. Figure 1 expresses this relationship between U_{SG} and U_{Osm} graphically. For both variables, approximately 85% of all initial morning urine samples were greater than unity. This indicates that sports-medicine professionals should refine their recommendations to athletes by considering the time of day and the duration of each collection (i.e., single sample vs. 24-hr collection). Initial morning samples tend to be more concentrated than 24-hr collections.

This relationship was not true for U_{Col} , however. Single, initial morning samples were statistically similar to 24-hr collections. This finding is consistent with our initial publication regarding U_{Col} (Armstrong et al., 1994), which described U_{Col} as a field-expedient technique that approximates hydration state but lacks precision. For example, the U_{Col} chart is scaled using integers and cannot differentiate between a minor difference such as 4.7 versus 5.0. As such, the visual assessment of U_{Col} did not discriminate between initial morning and 24-hr urine samples (Columns 6 and 7, Table 2).

Practical Applications and Conclusions

Despite the obvious importance of monitoring hydration state, it is difficult to interpret hydration state or identify hydration extremes because the water intake and excretion patterns of free-living individuals are poorly documented (Raman et al., 2004) and the regulation of human water balance is complex and dynamic (Armstrong, 2007). The current investigation enables sports-medicine personnel, health care providers, physiologists, and dietitians to objectively evaluate the hydration states and fluid intakes of athletes by providing numerical values for categories in seven commonly used hydration indices. We have assumed that the statistical means of all variables represent a state of euhydration and the 59 healthy active male test subjects validly represented all young men, including healthy young athletes. Based on these data, a normally hydrated 75-kg man consumes more than 2.0 L of fluid per day and produces more than 1.5 L of urine per day. He also exhibits a U_{SG} less than 1.024 and a U_{Col} of 4 or less in the initial morning sample. If active individuals or athletes anticipate a large sweat loss or fluid deficit, these numerical values can serve as hydration goals each morning or for the beginning of prolonged exercise. However, it is rare (<2% of all samples) for healthy, active

men (i.e., who are not exercising in a hot environment or training strenuously) to achieve a U_{SG} below 1.010 and a U_{Col} of 1. It also is prudent to remember that the first morning urine sample is more concentrated than a 24-hr urine collection in 85% of all cases, likely because fluids are not consumed during sleep and because glomerular filtration decreases during sleep. Finally, U_{SG} and U_{Osm} may be used interchangeably to assess hydration status.

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References

- Adolph, E.F. (1947). *Physiology of man in the desert*. New York, NY: Interscience.
- American College of Sports Medicine, Sawka, M.N., Burke, L.M., Eichner, E.R., Maughan, R.J., Montain, S.J., & Stachenfeld, N.S. (2007). Position stand: Exercise and fluid replacement. *Medicine and Science in Sports and Exercise*, 39, 377–390.
- Armstrong, L.E. (2007). Assessing hydration status: The elusive gold standard. *Journal of the American College of Nutrition*, 26, 575S–584S.
- Armstrong, L.E., Curtis, W.C., Hubbard, R.W., Francesconi, R.P., Moore, R., & Askew, E.W. (1993). Symptomatic hyponatremia during prolonged exercise in heat. *Medicine and Science in Sports and Exercise*, 25, 543–549.
- Armstrong, L.E., Herrera Soto, J.A., Hacker, F.T., Casa, D.J., Kavouras, S.A., & Maresh, C.M. (1998). Urinary indices during dehydration, exercise, and rehydration. *International Journal of Sport Nutrition*, 8, 345–355.
- Armstrong, L.E., Maresh, C.M., Castellani, J., Bergeron, M., Kenefick, R.W., LaGasse, K.E., & Riebe, D. (1994). Urinary indices of hydration status. *International Journal of Sport Nutrition*, 4, 265–279.
- Armstrong, L.E., Pumerantz, A.C., Roti, M.W., Judelson, D.A., Watson, G., Dias, J.C., . . . Kellogg, M. (2005). Fluid, electrolyte, and renal indices of hydration during 11 days of controlled caffeine consumption. *International Journal of Sport Nutrition and Exercise Metabolism*, 15, 252–265.
- Casa, D.J., Armstrong, L.E., Hillman, S.K., Montain, S.J., Reiff, R.V., Rich, B.S., . . . Stone, J.A. (2000). National Athletic Trainers' Association position statement: Fluid replacement for athletes. *Journal of Athletic Training*, 35, 212–224.
- Cheuvront, S.N., Carter, R., Montain, S.J., & Sawka, M.N. (2004). Daily body mass variability and stability in active men undergoing exercise-heat stress. *International Journal of Sport Nutrition and Exercise Metabolism*, 14, 532–540.

- Chevront, S.N., Carter, R., & Sawka, M.N. (2003). Fluid balance and endurance exercise performance. *Current Sports Medicine Reports*, 2, 202–208.
- Edwards, A.M., Mann, M.E., Marfell-Jones, M.J., Rankin, D.M., Noakes, T.D., & Shillington, D.P. (2007). The influence of moderate dehydration on soccer performance: Physiological responses to 45-min of performance of sport-specific and mental concentration tests. *British Journal of Sports Medicine*, 41, 385–391.
- Kavouras, S.A. (2002). Assessing hydration status. *Current Opinion in Clinical Nutrition and Metabolic Care*, 5, 519–524.
- Kratz, A., Ferraro, M., Sluss, P.M., & Lewandowski, K.B. (2004). Laboratory reference values. *The New England Journal of Medicine*, 351, 1548–1563.
- Lang, F., Busch, G.L., Ritter, M., Völk, H., Waldegger, S., Gulbins, E., & Häussinger, D. (1998). Functional significance of cell volume regulatory mechanisms. *Physiological Reviews*, 78, 247–306.
- Maughan, R.J. (2003). Impact of mild dehydration on wellness and on exercise performance. *European Journal of Clinical Nutrition*, 57, S19–S23.
- Maughan, R.J., & Griffin, J. (2003). Caffeine ingestion and fluid balance: a review. *Journal of Human Nutrition and Dietetics*, 16, 411–420.
- National Collegiate Athletic Association. Wrestling Rules Committee. (2003). *National Collegiate Athletic Association wrestling rules*. Indianapolis, IN: Author.
- National Federation of State High School Associations. (2006). *Wrestling rules book 2006–07* (Pub. No. WRRB07). Indianapolis, IN: Author.
- Nielsen, B., Kubica, R., Bonnesen, A., Rasmussen, I.B., Stoklosa, J., & Wilk, B. (1981). Physical work capacity after dehydration and hyperthermia. *Scandinavian Journal of Sport Sciences*, 3, 2–10.
- Noakes, T.D. (2003). Overconsumption of fluids by athletes. *British Medical Journal*, 327, 113–114.
- Oppliger, R., & Bartok, C. (2002). Hydration testing of athletes. *Sports Medicine (Auckland, N.Z.)*, 32, 959–971.
- Popowski, L.A., Oppliger, R.A., Patrick, L.G., Johnson, R.F., Kim, J.A., & Gisolfi, C.V. (2001). Blood and urinary measures of hydration status during progressive acute dehydration. *Medicine and Science in Sports and Exercise*, 33, 747–753.
- Raman, A., Schoeller, D.A., Subar, A.F., Troiano, R.P., Schatzkin, A., Harris, T., . . . Tyllavsky, F.A. (2004). Water turnover in 458 American adults 40–79 yr of age. *American Journal of Physiology. Renal Physiology*, 286, F394–F401.
- Shirreffs, S.M. (2003). Markers of hydration status. *European Journal of Clinical Nutrition*, 57, S6–S9.
- Shirreffs, S.M., & Maughan, R.J. (1998). Urine osmolality and conductivity as indices of hydration status in athletes in the heat. *Medicine and Science in Sports and Exercise*, 30, 1598–1602.
- Wemple, R.D., Lamb, D.R., & McKeever, K.H. (1997). Caffeine vs caffeine-free sports drinks: Effects on urine production at rest and during prolonged exercise. *International Journal of Sports Medicine*, 18, 40–46.
- Wilson, M.M.G., & Morley, J.E. (2003). Impaired cognitive function and mental performance in mild dehydration. *European Journal of Clinical Nutrition*, 57, S24–S29.