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HYDRATION STATUS MONITORING

*Robert Carter III, Samuel N. Cheuvront, Margaret A. Kolka, Michael N. Sawka,
U.S. Army Research Institute of Environmental Medicine*

DEFINITION AND DOCUMENTATION

This paper reviews widely used indices of hydration status in humans. For the purposes of this review, euhydration will refer to “normal” total body water (TBW), whereas hypohydration will refer to a body water deficit. The term dehydration will be used to refer to the dynamic process of body water loss (i.e., the transition from euhydration to hypohydration) (Greenleaf and Sargent, 1965; Sawka, 1992). The term hypovolemia will define when blood volume is less than “normal.”

IMPACT ON HUMAN PERFORMANCE

Both physical and cognitive performance are impaired proportionally to the magnitude of body water loss incurred (Gopinathan et al., 1988; Sawka, 1988). However, even small losses of body water (1–2 percent body mass [BM]) have a detrimental impact on physical work and negatively impact human thermoregulation (Sawka, 1988; Sawka et al., 2001). Accordingly, dehydration may be the greatest nonadversary threat to military operations.

FLUID BALANCE, DISTRIBUTION, AND EXCHANGE

Adequate hydration is essential for maintaining effective military field operations. Several common operational stresses can result in relatively large alterations in TBW content and distribution. During most normal conditions, humans have little trouble maintaining optimal fluid balance. However, many factors, such as sickness, physical exercise, climatic exposure (heat, cold, altitude), and psychological strain, can lead to significant disturbances in water bal-

nce. Perhaps the best example of this is the combination of heat stress and physical activity. For sedentary persons in temperate conditions, water requirements usually range from 2 to 4 L/day, and water balance is regulated primarily by the kidneys. For physically active persons exposed to heat stress, water requirements can often more than double (Sawka et al., 2001), and it would not be unusual for physically active, heat-stressed individuals to incur water deficits of several liters.

Water is the largest single constituent of the body (50–70 percent of body weight) and is essential for supporting the cardiovascular and thermoregulatory systems and cellular homeostasis. TBW is distributed into intracellular fluid (ICF) and extracellular fluid (ECF) compartments. The ICF and ECF contain 65 percent and ~ 35 percent of TBW, respectively (Guyton et al., 1975). The ICF is further divided into the interstitial and plasma spaces. The average 75 kg male has ~ 45 L of TBW; therefore, ICF contains ~ 30 L of water, whereas the ECF contains ~ 15 L of water with ~ 3.4 L in plasma and ~ 11.6 L in the interstitium. These volumes are not static, but represent the net effect of dynamic fluid exchange and turnover between compartments (Guyton et al., 1975). Exercise heat stress not only stimulates fluid loss, primarily by sweating, but also it induces electrolyte imbalances and changes in renal function. As a result, fluid deficits with and without proportionate solute changes can occur. In addition, exercise heat stress alters transcompartmental and transcapillary forces that redistribute fluids between various compartments, organs, and tissues (Sawka et al., 2001). For these reasons, the accuracy of most methods used to assess hydration status is limited by the circumstances in which they are measured and the purposes for which they are intended.

DEHYDRATION AND MUSCLE WATER

Incomplete fluid replacement decreases total body water and, as a consequence of fluid exchange, affects each fluid space. For example, Nose and colleagues (1983) determined the distribution of body water loss among the fluid spaces as well as among different body organs during dehydration. They thermally dehydrated rats by 10 percent of body weight, and the fluid deficit was portioned between the intracellular (41 percent) and extracellular (59 percent) spaces. The distribution of organ fluid loss was muscle (40 percent), skin (30 percent), viscera (14 percent), and bone (14 percent). However, no significant changes occurred in liver and brain water content. Nose and colleagues (1983) concluded that dehydration results in water distribution largely from the intracellular and extracellular spaces of muscle and skin.

The measurement of TBW is the “gold standard” to assess hydration status (Lodola et al., 1998; Lesser and Markofsky, 1979). TBW can be directly measured with doubly labeled water (DLW) or other dilution techniques. The major drawbacks of the DLW and other dilution methodologies are the cost and the technical difficulties associated with isotope analyses. The requirement for an isotope ratio mass spectrometer and sample preparation systems often limits the

use of this method in most military scenarios. In addition, to obtain accurate changes in TBW with these methodologies, serial measurements are required, which further limits their use for routine assessment of TBW changes for hydration assessment. Although the choice of specific biomarker for assessing hydration status should ideally be sensitive and accurate enough to detect relatively small fluctuations in body water, the practicality of its use (time, cost, and technical expertise) is also of significant importance.

Estimates of hydration status are commonly done using (1) bioelectrical impedance analysis, (2) plasma markers and fluid regulatory hormones, (3) urine indices, (4) changes in body weight, or (5) signs and symptoms. Given consideration to military field operational use, hydration assessment measurements are presented in order of increasing assessability and practicality.

METHODS FOR HYDRATION STATUS MONITORING

Bioelectrical Impedance

Recently, bioelectric impedance (BIA) has gained attention because it is simple to use and allows rapid, inexpensive, and noninvasive estimates of TBW (O'Brien et al., 2002). In practice, a small constant current, typically 800 μ A at a fixed frequency, usually 50 kHz, is passed between electrodes spanning the body. The voltage drop between these electrodes provides a measure of bioimpedance. Prediction equations, previously generated by correlating impedance measures against an independent estimate of TBW, may be used subsequently to convert a measured impedance to a corresponding estimate of TBW (Kushner et al., 1992). Absolute BIA values are well correlated with dilution TBW techniques (Kushner et al., 1992; Van Loan, 1990).

BIA does not have sufficient accuracy to assess dehydration (~ 7 percent TBW) and loses resolution with isotonic fluid loss (O'Brien et al., 2002; Van Loan, 1990). In addition, since fluid and electrolyte concentrations can have independent effects on the BIA signal, it can often provide grossly misleading values regarding hydration status (O'Brien et al., 2002). Therefore, BIA has little application for the field assessment of hydration status.

Plasma Markers

Plasma volume changes can be estimated from hemoglobin and hematocrit changes; however, accurate measurement of these variables requires considerable control for posture, arm position, skin temperature, and other factors (Sawka, 1988). If adequate controls are employed, plasma volume decreases in proportion with the level of exercise-heat mediated dehydration. Likewise, plasma volume decreases with dehydration, and this response varies due to the type of dehydration (isoosmotic or hyperosmotic), physical activity, physical fitness, and heat acclimatization status (Sawka, 1988).

Plasma osmolality is controlled around a set-point of 280–290 mOsmol/kg in euhydrated volunteers (Senay, 1979). This narrow range increases ~ 5 mOsmol/kg for every 1 to 2 percent BM of dehydration incurred (Popowski et al., 2001). Figure D-5 presents the effects of body water loss on resting plasma osmolality and plasma volume in heat acclimated persons undergoing exercise-heat mediated dehydration (Sawka and Coyle, 1999). These same levels will be maintained during subsequent physical exercise. If an isoosmotic dehydration occurs, such as with altitude or cold exposure (O'Brien et al., 1998; Sawka, 1992), then plasma osmolality changes will not follow TBW changes and much larger plasma volume reductions will occur.

Plasma sodium concentration provides an alternative to measuring osmolality (as most of the osmolality changes are usually reflective of sodium changes). However, that linear relationship may not be as strong as expected (Senay, 1979).

Osmolarity is sensed in the hypothalamus by osmoreceptors, and those neurons, in turn, stimulate the production of antidiuretic hormone. When plasma osmolarity is below threshold, the osmoreceptors are not activated and antidiuretic hormone secretion is suppressed. When osmolarity increases above the threshold for alcohol dehydrogenase release, the osmoreceptors recognize this as the cue to stimulate the neurons that secrete antidiuretic hormone. Figure D-6 shows that antidiuretic hormone concentrations rise steeply and linearly with increasing plasma osmolarity (Robertson and Athar, 1976). If hydration status changes are the result of water loss, the plasma solute concentration (osmolality) will change proportionately. However, the relationship of plasma osmolarity and vasopressin concentrations is confounded by exercise, hyperthermia, nausea, and fluid volume changes (Norsk, 1996).

Aldosterone, secreted by the adrenal cortex, is a potent hormone regulating electrolyte balance. Aldosterone acts directly on the kidney to decrease the rate of sodium-ion excretion with accompanying retention of water and to increase the rate of potassium-ion excretion. Dehydration-mediated elevations in aldosterone secretion are confounded by heat acclimation status and exercise (Francesconi et al., 1983). The measurement of plasma volume, osmolality, sodium, aldosterone, and arginine vasopressin (AVP) requires phlebotomy (invasive), technical skill, and expensive instrumentation.

Urine

Urinalysis is a frequently used clinical measure to distinguish between normal and pathological conditions. Urinary markers of hydration status include urine specific gravity (USG), urine osmolality (U_{Osmol}), and urine color. Urine specific gravity and osmolality are quantifiable and threshold values can have some value, whereas color is subjective and can be influenced by many factors. It is important to recognize that the accuracy of these urinary indices in assessing chronic hydration status is improved when the first morning urine is used,

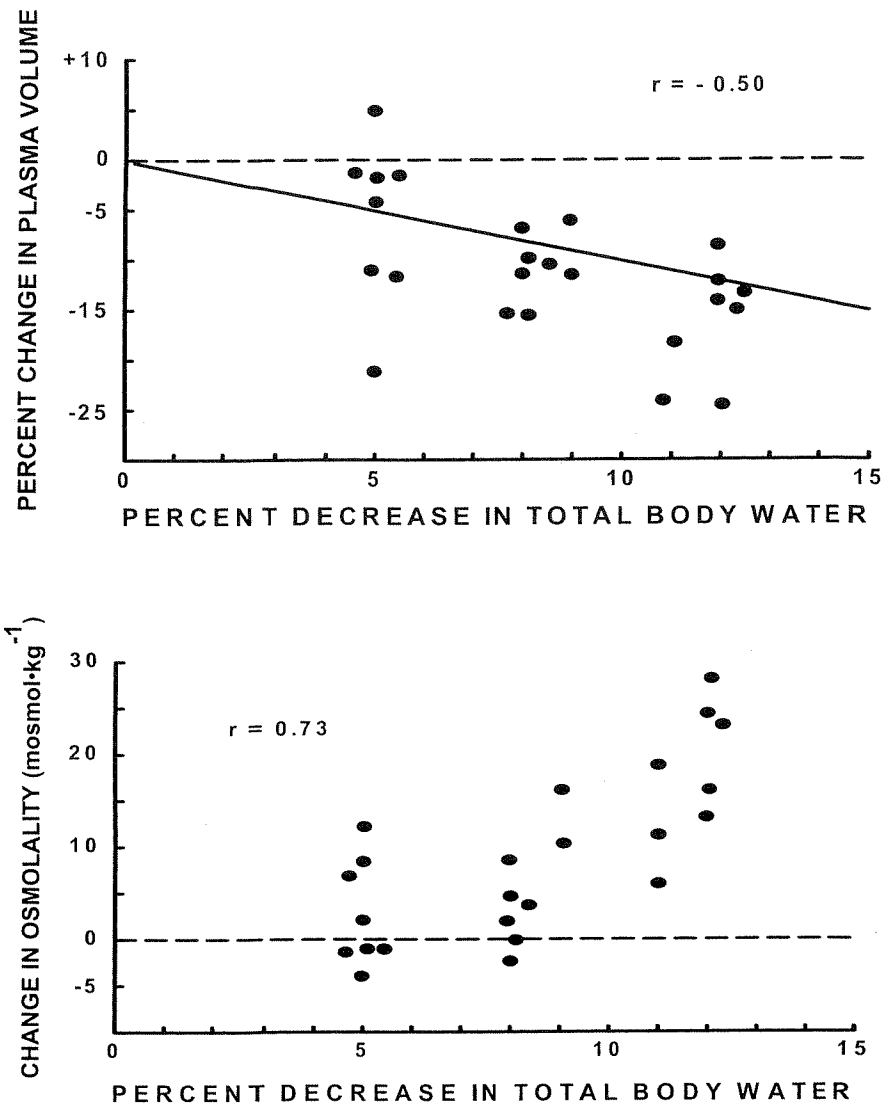


FIGURE D-5 The effects of body water loss on resting plasma osmolality and plasma volume in heat acclimated persons undergoing exercise-heat mediated dehydration. SOURCE: Reprinted, with permission Sawka and Coyle (1999). Influence of body water and blood volume on thermoregulation and exercise performance in the heat. *Exerc Sport Sci Rev* 27:167–218.

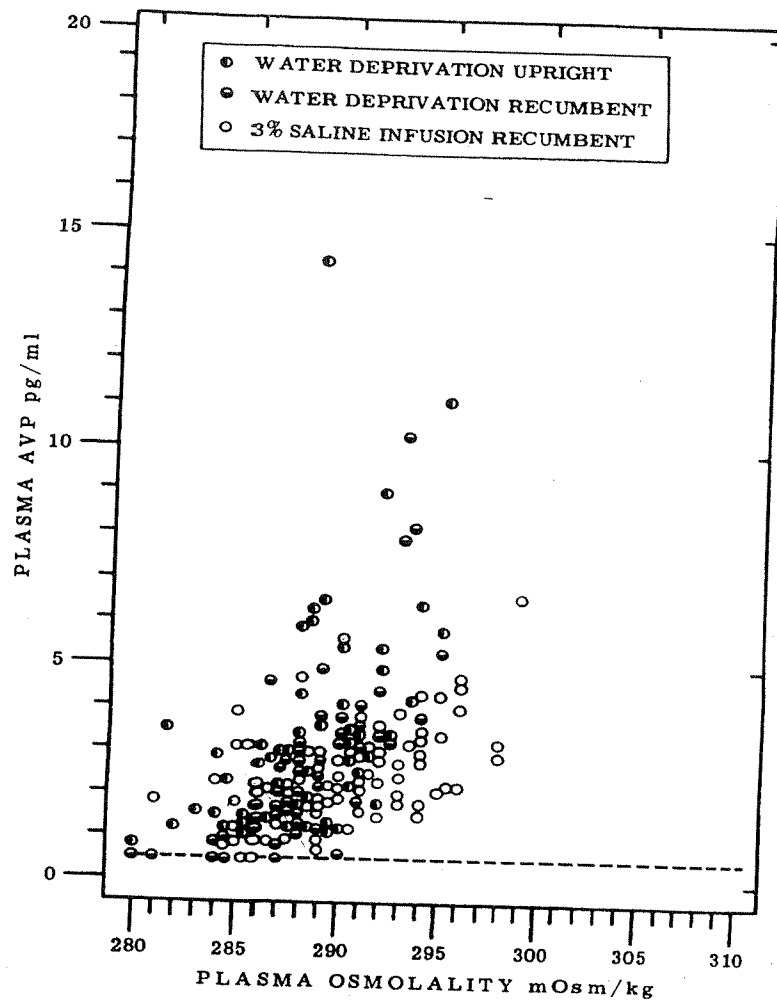


FIGURE D-6 Plasma vasopressin concentrations compared with plasma osmolality. SOURCE: Reprinted, with permission, Robertson and Athar (1976). Copyright 1976, The Endocrine Society.

because this urine has a more uniform volume and concentration (Sanford and Vells, 1962; Shirreffs and Maughan, 1998). Likewise, many additional factors, such as diet, medications, exercise, and previous climatic exposure, can confound these indices.

The most widely used urine index is USG. Measured against water as a standard (1.000 g/ml), USG represents the concentration of particles dissolved in

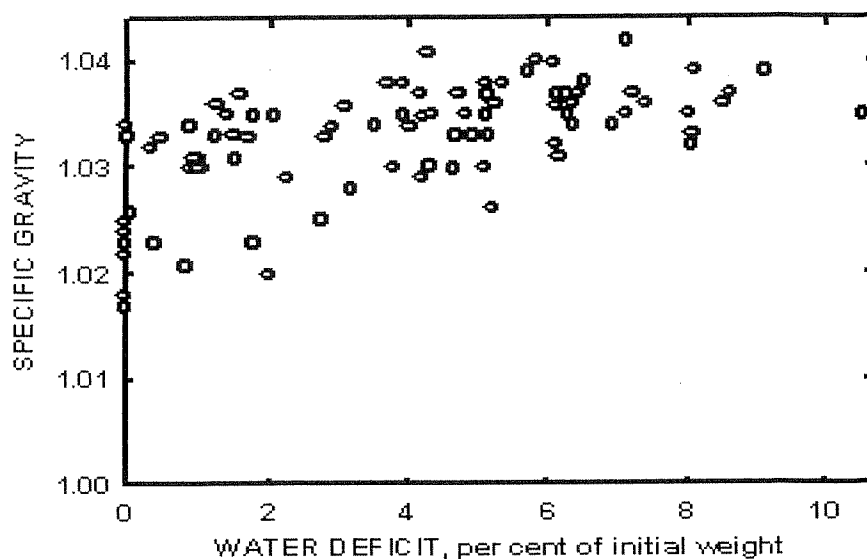


FIGURE D-7 Relation between specific gravity of urine and body water deficit.
SOURCE: Reprinted, with permission from Adolph et al. (1969).

urine and is a reflection of the kidney's ability to concentrate or dilute urine in relation to plasma. Because urine is a solution of water and various other substances, normal values range from 1.010 to 1.030 (Armstrong et al., 1994; Popowski et al., 2001; Sanford and Wells, 1962). It has been suggested that a USG of ≤ 1.020 represents a state of euhydration (Armstrong et al., 1994; Sanford and Wells, 1962). As a measure of chronic hydration status, USG appears to accurately reflect a hypohydrated state when in excess of 1.030 (Armstrong et al., 1994; Popowski et al., 2001; Sanford and Wells, 1962). However, considerable variability exists and no single value can be used to determine a specific hydration level (see Figure D-7). U_{osmol} also can provide an approximation of hydration status (Shirreffs and Maughan, 1998) as it is highly correlated with, but more variable than, USG (Armstrong et al., 1994; Popowski et al., 2001).

Endocrine responses to dehydration stimulate water and electrolyte retention by the kidney. However, while the linear rise in plasma osmolality (with hypovolemia) that occurs with dehydration (Popowski et al., 2001) stimulates vasopressin and the tubular reabsorption of water at the kidney, the renal response lags behind changes in plasma osmolality during acute fluxes in body water (2–4 hr) brought on by dehydration-rehydration (Popowski et al., 2001). In fact, when large volumes of water are consumed, a pale-colored urine with

low specific gravity is excreted long before euhydration is achieved (Shirreffs and Maughan, 1998) due to rapidly declining AVP levels triggered by the swallowing reflex. When water is consumed in excess of sweat losses during exercise, urine output increases and fluid balance is not restored unless sufficient electrolytes are also consumed (Maughan et al., 1996). Logically, U_{Osmol} is therefore also limited for assessing acute changes in body water (Kovacs et al., 1999; Popowski et al., 2001).

Body Mass

BM measurements represent the simplest technique for rapid assessment of changes in hydration status. In our laboratory, we observe very small (< 1 percent) fluctuations in first morning BM when measured over consecutive days in young men taking food and fluid ad libitum. The stability of this measurement, coupled with the known losses of fluid that occur with exercise-heat exposure (primarily eccrine sweat), allows rapid changes in BM (incurred over hours) to be correctly attributed to water loss. Acute changes in BM weight are therefore a popular and reasonable field estimate of dehydration (Cheuvront et al., 2002).

The level of dehydration is expressed as a percentage of starting body weight ($[\Delta BW / \text{startBW}] \times 100$) rather than as a percentage of TBW because TBW ranges from 50 to 70 percent of body weight. This technique assumes that (1) starting body weight represents a euhydrated state, and (2) 1 ml of sweat loss represents a 1 g change in weight (i.e., specific gravity of sweat is 1.000 g/ml). As an acute measure, first morning body weight is still limited by changes in bowel habits. Body weight is also limited as a tool for long-term assessment of hydration status since the changes in body composition (fat and lean mass) that may occur with chronic energy imbalance are also reflected grossly as changes in body weight. Clearly, the use of daily body weight should be used in combination with another hydration assessment technique to dissociate gross tissue losses from water losses if long-term hydration status is of interest.

Signs and Symptoms of Dehydration

In the early stages of dehydration, no signs or symptoms are apparent. However, as greater body water losses occur, increased thirst, increased pulse rate, and increased rectal temperature present. In addition, body-water loss of 1 to 5 percent can be associated with flushed skin, nausea, sleepiness, and reductions in economy of movement. Body-water losses of 6 to 10 percent are associated with dizziness, headache, tingling in limbs, decreased blood volume, and cyanosis. Severe dehydration, 11 to 20 percent body water, results in delirium, numb skin, deafness, and spasticity. Furthermore, death is likely as greater body-water loss occurs. Assessment of dehydration via signs and symptoms is easy and quick; however, these estimates are too imprecise to accurately

TABLE D-4 Biomarkers for Hydration Assessment

Marker	Advantages	Disadvantages
Signs and symptoms	Easy, quick	Imprecise
Total body water, dilution	Valid, reliable	Premeasurement, invasive, complex
Total body water, bioelectric impedance	Easy, rapid	Premeasurement, imprecise
Plasma volume	—	Premeasurement, invasive
Osmolality	Often valid, reliable	Imprecise
Sodium	Hyponatremia	Invasive, complex
Fluid reg. hormones	Often valid	Invasive, imprecise
Urine	Easy, rapid, screen	Invasive, sometimes confounded, complex
Saliva	Easy	Imprecise, easily confounded
Body weight	Easy, rapid	Invalid

determine hydration status. Nevertheless, if any of the signs and symptoms of dehydration present, rehydration should begin immediately.

CONCLUSIONS

Under most conditions, day-to-day BM changes (> 2 percent) and first morning urine specific gravity (> 1.030), when used together, provide an approximate indication that an individual is hypohydrated (see Table D-4). However, plasma osmolality changes can provide more reliable information regarding hydration when greater precision is required. Measurement of fluid regulatory hormones for routine hydration assessment are not necessary and are often confounding. Moreover, BIA has limited utility to assess hydration status in the field for reasons previously described. It is possible that other technological advances may allow evaluation of other measures (e.g., muscle water content) that hold promise as hydration indices.

Disclaimer: The views, opinions, and/or findings contained in this publication are those of the authors and should not be constructed as an official Department of the Army position, policy, or decision unless so designated by other documentation.

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TECHNOLOGY FOR THE MEASUREMENT OF BLOOD LACTATE

David C. Klonoff, Mills-Peninsula Health Services

Glucose is metabolized by cells to produce energy. Glucose metabolism involves progressive oxidation plus breakage of carbon bonds. The oxidation process causes C-H and C-C bonds to be stripped of electrons (oxidized), which are then used to build adenosine triphosphate (ATP).

The initial steps in breakdown of glucose involve conversion of one 6-carbon molecule of glucose to two 3-carbon molecules of pyruvate. This process is known as glycolysis. Next, in the presence of oxygen, the carbon atoms in pyruvate are converted into three molecules of carbon dioxide in a process known as aerobic metabolism. When oxygen is available to serve as the final acceptor of electrons, then pyruvate is able to transfer electrons to the final acceptor, oxygen (or reduce), by way of a series of steps known as the Krebs cycle or the tricarboxylic acid cycle. When oxygen is totally reduced, it becomes water. Meanwhile, the carbon bonds of pyruvate all become oxidized to carbon dioxide.

Conversely, in the absence of oxygen, all the electron acceptors "downstream" from pyruvate are reduced and unable to offload electrons to mediators that will carry them toward oxygen. The carbon bonds are progressively oxidized in the Krebs cycle and the electrons' energy is drawn off in steps through a process known as oxidative phosphorylation. The process is analogous to water falling down a dam and turning turbines, and at the same time the turbines