Review

Assessing Hydration Status: The Elusive Gold Standard

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Key words: dehydration, osmolality, total body water, extracellular fluid, intracellular fluid

Acknowledging that total body water (TBW) turnover is complex, and that no measurement is valid for all situations, this review evaluates 13 hydration assessment techniques. Although validated laboratory methods exist for TBW and extracellular volume, no evidence incontrovertibly demonstrates that any concentration measurement, including plasma osmolality (P_{osm}), accurately represents TBW gain and loss during daily activities. Further, one blood or urine sample cannot validly represent fluctuating TBW and fluid compartments. Future research should (a) evaluate novel techniques that assess hydration in real time and are precise, accurate, reliable, non-invasive, portable, inexpensive, safe, and simple; and (b) clarify the relationship between P_{osm} and TBW oscillations in various scenarios.

Key teaching points:

- All hydration assessment techniques provide singular measures of a complex and dynamic fluid matrix, containing interconnected compartments.
- A single gold standard, including plasma osmolality, is not possible for all hydration assessment requirements.
- In the laboratory, measurement resolution and accuracy are essential.
- Field assessment of hydration requires techniques that are easy-to-use, safe, portable, and inexpensive.
- Total body water approximates "euhydration" when morning body weight is near the normal baseline, fluid intake is adequate, urine color is pale yellow, and urine volume is normal.
- Body weight change provides the simplest and most accurate index of hydration status in real time, when serial measurements are made in close proximity.

INTRODUCTION

Water is the medium of circulatory function, biochemical reactions, metabolism, substrate transport across cellular membranes, temperature regulation, and numerous other physiological processes. Fluid-electrolyte turnover and whole-body water balance change constantly because water is lost from the lungs, skin, and kidneys, and because water is gained in food and fluids. Therefore, accurate and precise laboratory and field techniques are needed to evaluate human hydration status [1]. Table 1 presents selected characteristics of 13 hydration assessment techniques that are commonly utilized in physiological, clinical, industrial, military, and athletic settings. These techniques involve either whole-body, hematologic, urinary, or sensory measurements.

Recently published review articles have evaluated these techniques from the perspectives of clinical nutrition and metabolism [2], adult nutrition [1], urine osmolality of children and adults [3], athletes [4–6] and exercise enthusiasts, laborers, and soldiers [7]. However, none of these review articles provides an incontrovertible argument for the superiority of a single hydration index for use in all situations and populations.

The purpose of this manuscript is to evaluate the characteristics (i.e., measurement resolution, accuracy, validity) of 13 hydration assessment techniques because they are essential to sound laboratory and field measurements of human hydration

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Table 1. Selected Characteristics of 13 Hydration Assessment Methods[a]

Hydration Assessment Technique	Body Fluids Involved	Cost of Analysis	Time Required	Technical Expertise Required	Portability	Likelihood of Adverse Event
Stable isotope dilution	all (ECF and ICF)	3	3	3	3	2 or 3[b]
Neutron activation analysis	all	3	3	3	3	2
Bioelectrical impedance spectroscopy (BIS)	uncertain	2	3	2	2	1
Body mass change[c]	all	1	1	1	1	1
Plasma osmolality[d]	ECF	3	2	3	3	2
% plasma volume change	blood	2	2	3	3	2
Urine osmolality	excreted urine	3	2	3	3	1
Urine specific gravity	excreted urine	1	1	2	1	1
Urine conductivity	excreted urine	2	2	2	3[e]	1
Urine color	excreted urine	1	1	1	1	1
24-hour urine volume	excreted urine	1	1	1	1	1
Salivary flow rate, osmolality, total protein	whole, mixed saliva	2–3	2	3	2–3	1
Rating of thirst	hypothalamus	1	1	1	1	1
Key to ratings:		1 = small, little 2 = moderate 3 = great, much	1 = small, little 2 = moderate 3 = great, much	1 = small, little 2 = moderate 3 = great, much	1 = portable 2 = moderate 3 = not portable	1 = low 2 = moderate 3 = high

Abbreviations: BIS = bioelectrical impedance spectroscopy; ECF = extracellular fluid; ICF = intracellular fluid.

[a] Modified and redrawn from reference 7.

[b] depending on the type of isotope involved (i.e., radioactive, stable, non-radioactive).

[c] using a floor scale.

[d] freezing point depression method.

[e] portable, hand-held meters are available [4].

status. The advantages and disadvantages of these techniques are described for laboratory and field settings.

DEFINITIONS

In this review, **measurement resolution** refers to the number of significant digits with which a value can be expressed validly (i.e., 1.0 L vs. 0.01 L). **Accuracy** is defined as the degree of conformity of a measurement to the actual (true) value.

The term **euhydration** is synonymous with the phrase "normal body water content." Euhydration is not a specific point, but rather is best represented by a sinusoidal wave that oscillates around an average [5]. Body mass is commonly used to represent acute changes of body water [2,5–7]. For example, body mass fluctuates with a group coefficient of variation of 0.66 ± 0.24% for repeated days [9].

Although no consensus exists regarding a definition for the term **dehydration** [1–7,10], it refers to the process of uncompensated water loss via urine, sweat, feces, and respiratory vapor; this process reduces total body water below the average basal value. Lack of consensus exists, in part, because physiologists use different techniques to evaluate dehydration (e.g., plasma osmolality, urine-specific gravity, or body weight). The term **hyperhydration** refers to the state that exists when ingested fluid temporarily increases total body water above the average basal level prior to its removal by the kidneys. **Hydration,** therefore, involves the point at which the body presently resides, among states of euhydration, hyperhydration, and dehydration.

The following definitions also are germane to the study of hydration assessment techniques [11–13]. **Osmolality:** the concentration of a solution expressed in milliosmoles of solute particles per kilogram of water. **Total body water (TBW):** the fluid that occupies intracellular and extracellular spaces; ~0.6 $L \cdot kg^{-1}$ (63.3%) of body mass. **Extracellular volume:** all fluid outside of cells; includes the interstitial fluid and plasma water; ~0.2 $L \cdot kg^{-1}$ (24.9%) of body mass. **Intracellular volume:** the fluid within tissue cells; ~0.4 $L \cdot kg^{-1}$ (38.4%) of body mass.

THE ELUSIVE GOLD STANDARD

Some authorities claim that a TBW value, in combination with a plasma osmolality (P_{osm}) measurement, provide the "gold standard" for hydration assessment (i.e., provides superior accuracy, precision, and reliability) [6,14–16]. The claim regarding TBW is widely accepted; that is, the isotope dilution and neutron activation analysis techniques (Table 1) are considered to be the standards for measurements of TBW and body fluid spaces. This claim of a gold standard apparently refers to

laboratory tests; under controlled conditions (i.e., when experimental, postural, exercise, dietary, and environmental factors are controlled), the TBW, volume of body fluid compartments, and extracellular fluid concentration may stabilize and equilibrate. However, during daily activities, body fluids are rarely stable, and isotope dilution measurements of TBW (i.e., deuterium oxide dilution) require three to five hours for internal isotope equilibration and analysis. Thus, isotope dilution techniques are impractical during daily activities and multiple measurements throughout one day. Further, P_{osm} may not validly represent a gain or loss of body water because measurements of P_{osm} are influenced by several factors, as described below. Therefore, the claim that TBW and P_{osm} represent the "gold standard" must be qualified on the basis of the situation (laboratory or field). This claim would be more accurately stated, "TBW and P_{osm}, under controlled laboratory conditions when body fluids are stable and equilibrated, represent the most precise and accurate hydration assessment techniques available today." And although measurement resolution and accuracy are hallmarks of sound laboratory practice, they may not be important to a laborer, athlete, or average citizen who needs a simple estimate of his/her hydration status.

In contrast, the authors of several published review papers [2–5,7] claim that a single gold standard for hydration assessment is not possible. The following nine points support their position and complicate the quest for a gold standard.

1. The physiological regulation of total body water volume (i.e., water turnover) and fluid concentrations is complex and dynamic, as shown in Table 2. Renal, thirst, and sweat gland responses are involved to varying degrees, depending on the prevailing activities. Also, renal regulation of water balance (i.e., arginine vasopressin) is distinct from the regulation of tonicity (i.e., aldosterone) [17]. Thus, all hydration assessment techniques (Table 1) are best viewed as singular measures of a complex and dynamic fluid matrix, containing interconnected compartments.
2. The 24-hour water deficit (i.e., water requirement) varies greatly among sedentary individuals (1.1 to 3.1 L) and athletes (1.5 to 6.7 L), primarily due to activity and body size [15,16]. This deficit must be matched by dietary and metabolic sources of water to maintain TBW balance.
3. Sodium and osmolyte consumption affects the daily water requirement, due to selection of distinctive food and beverage items. This is exemplified by the data of Manz and Wentz [3]. Large intercultural differences exist for the mean 24-hour urine osmolality (U_{osm}) values of Germany (860 mOsm/kg) and Poland (392 mOsm/kg). These differences are influenced by unique regional customs involving beverages (i.e., water, beer, wine) and food items, and the fact that the daily human requirement for water (i.e., to maintain normal osmolality) increases as sodium [3] and protein intakes increase [18,19].
4. The volume and timing of water consumption alter measurements of hydration status. When a large bolus of pure water or hypotonic fluid is consumed rapidly (e.g., 1.2 L in 5 minutes), this water enters the blood and the kidneys produce a large volume of dilute urine (e.g., urine specific gravity of 1.005) before the intracellular and extracellular fluids equilibrate [20]. This protective mechanism defends against fluid overload even if dehydration exists [21]. In this situation, urine values mirror the volume of fluid consumed rather than the change of TBW and question the validity of using urine indices to assess hydration state [21,22].

Table 2. The Relative Roles that Physiological Processes Play in Whole-body Fluid Balance, During Different Life Scenarios

Scenario	Relative Roles of Physiological Processes in Fluid Balance			Comments
	Renal Regulation of Fluid-Electrolyte Balance	Thirst and Drinking Behavior	Sweat Gland Secretion of Hypotonic Fluid	
Sedentary daily activities (16 h)	normal	normal	negligible	normal hormonal and CNS regulation
Brief, intense exercise (< 5 min)	negligible	negligible	minor	volume of fluid loss is small
Prolonged, strenuous exercise (5–30 min)	minor	minor-to-moderate	minor-to-moderate	volume of fluid loss is minor when compared to TBW
Prolonged endurance exercise (0.5–5 h) at moderate intensity	minor-to-moderate	minor-to-large	moderate-to-large	larger water turnover due to sweating and drinking
Continuous or intermittent exercise, or labor at low intensity (5–24 h)	minor-to-large	minor-to-large	large	fluid and electrolyte losses may exceed daily dietary intake
Consecutive days of activities, labor, or exercise (1–180 d)	Normal	normal	varied, depending on labor and exercise	adequate dietary fluid and electrolyte consumption is essential

Abbreviations: CNS = central nervous system; TBW = total body water.

5. Urine samples reflect all urine that has collected in the bladder since the previous void. This may or may not coincide with the time that elapses between fluid sampling milestones in experiments, depending on the timing and thoroughness of each void. This explains, in part, why some investigators conclude that urinary indices "lag behind" blood indices [22].
6. Differences of experimental design complicate the interpretation and comparison of published data. Hydration assessment techniques may or may not provide similar information, depending on the fluid sampled, time that elapses between measurements (i.e., hours, days, weeks), exercise duration and intensity, diet, or amount and method of dehydration (i.e., fluid restriction, exercise in a hot environment). Techniques that sample body fluids from the same site (i.e., urine specific gravity and urine osmolality) may provide closer agreement regarding hydration status than analyses of different fluids (i.e., blood versus urine) [20,23].
7. TBW techniques that utilize stable isotopes, such as deuterium oxide, are based on the assumption that the isotope distributes equally throughout extracellular and intracellular fluids. Table 1 and Fig. 1 remind us that no hydration assessment technique samples intracellular fluid directly. Therefore, the validity of TBW measurements is based on an unverifiable assumption.
8. Exercise and labor increase blood pressure, heart rate, and stroke volume while they decrease renal blood flow and glomerular filtration rate; these responses affect hydration indices. Blood and urine measurements that are made during and immediately after exercise represent perturbed, not equilibrated, fluid compartments [21].
9. Changes of P_{osm} (i.e., due to overhydration or dehydration) alter the intracellular-to-extracellular volume ratio (e.g., hypotonic hypervolemia or hypertonic hypovolemia) and thus affect some hydration assessment techniques (i.e., bioelectrical impedance spectroscopy, bromide dilution; see Table 1).

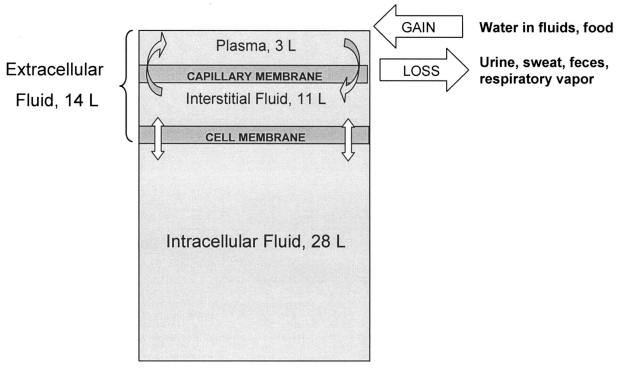

Fig. 1. Body fluid compartments that comprise 42 L of total body water in a 70 kg human, and sources of fluid gain or loss. Modified and redrawn from reference 24.

Plasma Osmolality

In addition to the previous nine points, the following seven items question P_{osm} as a gold standard for hydration assessment (i.e., providing superior measurement resolution, accuracy, precision, and reliability).

1. Shore and colleagues [17] demonstrated in 1988 that P_{osm} increased during three consecutive days of controlled water restriction ($1.0\ L \cdot day^{-1}$) and decreased during days 2–4 of overhydration ($6.8\ L \cdot day^{-1}$); caloric, sodium and potassium intakes were controlled by a dietician. However, on the first day of overhydration, P_{osm} was not different from the basal (control) state despite an increased water intake of 4.1 L. In contrast, body weight decreased on all days ($0.4–0.6\ kg \cdot day^{-1}$) of water restriction but did not change during four days of overhydration. Therefore, P_{osm} was not able to detect the change of water intake throughout day one, and P_{osm} did not change in concert with body weight (i.e., body water) during overhydration.
2. Fig. 2 illustrates data from males who dehydrated by losing 4.1% of body weight (i.e., measured to ± 100 g of body mass; see upper left graph) [20]. Hydration status was represented differently by three plasma and three urinary indices during a 41-hour observation period. Interestingly, P_{osm} did not change in concert with dehydration and rehydration as well as three urine indices (e.g., compare the trends of all variables to body mass; see upper left graph in Fig. 2).
3. During prolonged living in sub-Arctic (14 days) [25] and field (44 days) [26] environments, neither hematologic (including P_{osm}) nor urinary indices produced a valid representation of hydration status.
4. During a laboratory experiment, Popowski and colleagues [22] utilized 168 minutes of exercise-induce dehydration and demonstrated that consuming a volume of fluid (equivalent to a 5% body weight loss) did not return elevated P_{osm} to baseline values within 60 minutes of rehydration. This suggested that when TBW and fluid compartments were perturbed, P_{osm} did not respond rapidly to fluid intake.
5. Fig. 3 illustrates the relationship between loss of body water (% decrease body weight) and the change of plasma osmolality. The data were compiled by Sawka and colleagues [27] from two laboratory investigations [28,29]. Although the linear regression for this graph identifies a moderate strength of correlation ($r^2 = .61$), the variability for a given body water loss is large. For example, when subjects lost 8–9% of body weight (x-axis), the change of P_{osm} ranges from −3 to +16 mOsm/kg.
6. Data from our laboratory [30] demonstrated that the relationship between P_{osm}, and body water loss varied as a function of pre-exercise hydration state, during repeated exercise trials in a hot environment.
7. The body's neuroendocrine mechanisms maintain P_{osm} within normal limits, even when total water intake (i.e., in water, beverages, and food) varies greatly. Table 3 presents

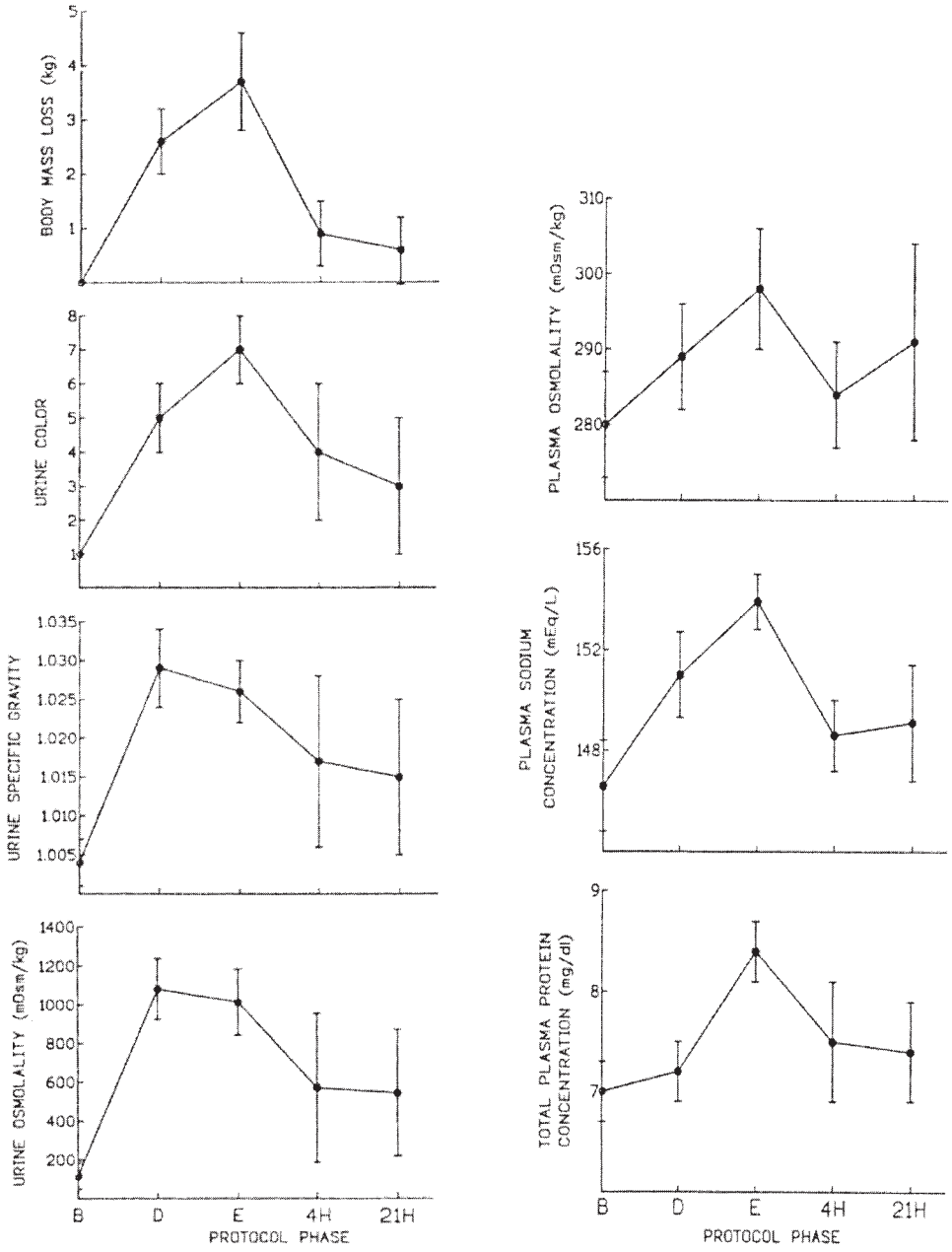

Fig. 2. Changes of body mass, plasma and urinary indices of hydration status during a 41-hour dehydration and rehydration protocol involving highly trained cyclists. Abbreviations: B, baseline state before testing; D, dehydration to −4% body mass; E, after cycling exercise to exhaustion; 4H, after 4 h of ad libitum rehydration; 21H, after 21 h of ad libitum rehydration. Reprinted from reference 20.

the mean (± SD) serum osmolality values for each decile of 24-hour total water intake in a large sample of healthy adults [15]. This table illustrates why population values for serum osmolality (or P_{osm}) cannot be used to estimate the human water requirement (i.e., on the basis of dehydration), because the kidneys regulate serum osmolality within narrow limits (277–281 mOsm · kg^{-1}) across a wide range of fluid intakes. Although individuals in the first decile may have a smaller body mass than those in the tenth decile, the data were not analyzed to address this difference or to express total water intake per kg body mass [15]. And, relevant to the issue of a gold standard, Table 3 illustrates that P_{osm} is not linearly related to habitual dietary water volume (up to 7.9 L · d^{-1} in males and 6.1 L · d^{-1} in females).

The preceding seven points indicate that P_{osm} does not assess whole-body hydration validly in all settings. This is especially true when TBW, fluid intake, and fluid loss are fluctuating.

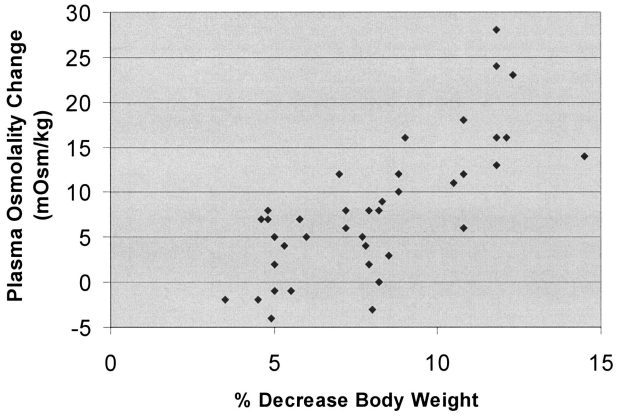

Fig. 3. The relationship between loss of body water (% decrease of body weight) and the change of plasma osmolality. Redrawn from reference 27. This graph represents the combined data from two studies [28,29].

MEASUREMENT RESOLUTION AND ACCURACY IN THE LABORATORY

Hydration assessment techniques are most effective in a laboratory setting. During experiments (i.e., when postural, activity, dietary, and environmental factors are controlled), the TBW, volume of body fluid compartments, and extracellular fluid concentration stabilize. At this time, TBW and P_{osm} provide an objective measurement of hydration status.

Table 4 presents a comparison of measurement resolution and accuracy (see definitions above), in terms of direct assessment of fluid volume or concentration, for thirteen hydration assessment techniques. The validation methods and/or criteria standards for each technique appear in column 5.

Isotope dilution and neutron activation analysis (rows 2 to 3 in Table 4) reflect excellent measurement resolution and accuracy. Similarly, body mass change provides a measurement resolution of $\pm$0.1 L of TBW, when using a floor scale that reads to $\pm$100 g.

The proponents of bioelectrical impedance spectroscopy (BIS; row 4 in Table 4) claim that BIS measures TBW and extracellular fluid volume, and allows calculation of intracellular fluid volume [42] but these claims are based on theory [43,44], not proven biophysical principles [45]. BIS has a TBW measurement resolution of approximately 0.8–1.0 L (out of a TBW of 42 L for a 70 kg individual) and therefore is not appropriate when dehydration is less than 800–1000 ml.

Analyses of plasma osmolality using a freezing point depression osmometer (row 6 in Table 4) provide excellent measurement resolution and accuracy. But P_{osm} measurements change in response to numerous stimuli, and P_{osm} changes may not be linearly related to dehydration and rehydration (see above). This is likely true because the regulation of extracellular fluid osmolality [24] is distinct from the regulation of pure water balance (i.e., different neuroendocrine mechanisms) and does not respond rapidly. Future research is required to clarify the meaning of P_{osm} measurements in a variety of situations.

It is not appropriate to consider measurement resolution and accuracy of the seven techniques shown in rows 7 to 14 of Table 4 (i.e., % plasma volume change, five urinary indices, salivary variables, and rating of thirst) because they do not measure intracellular fluid or extracellular fluid directly. Rather, these seven techniques are mildly or strongly correlated with TBW and extracellular concentration changes. Outside the laboratory, when two or more are measured concurrently, these seven indices may provide useful information regarding euhydration and dehydration [41]. An approach to their use in field settings is considered in a subsequent section.

STRENGTH OF EVIDENCE

In recent years, the position stands of national sports medicine and scientific organizations have included evaluations of the "strength of evidence" which supports practices, clinical decisions, and viewpoints [8]. A simplified evidence-based taxonomy, for use with Table 4, incorporates the following statements: A - based on consistent and good quality data, reference criteria and/or validation methods; B - based on inconsistent/limited-quality data, no/questionable reference criteria, no/questionable validation methods; C - based on opinion or consensus.

The ratings in column 6 of Table 4 indicate that only two (i.e., isotope dilution and neutron activation analysis) of the thirteen hydration assessment techniques are strongly supported by a sizeable, consistent body of scientific evidence. These techniques quantify fluid volume but neither measures the concentration of extracellular or intracellular fluid (Fig. 1). In addition, both techniques require sophisticated laboratory instrumentation, technical expertise, time for analyses, and considerable expense.

SIMPLE TECHNIQUES IN FIELD SETTINGS

The process of selecting an appropriate technique for laboratory use is quite different from selecting one for daily activities. Measurement resolution, accuracy and reliability are essential to sound laboratory practices. In field settings, however, the seven hydration assessment techniques in rows 7 to 14 of Table 4 provide useful information about euhydration and dehydration when used in the proper context. For example, exercise enthusiasts, laborers, and military personnel may experience a large water turnover on consecutive days that eventually leads to a physiologically significant water deficit (i.e., $>$1 to 2% of body weight). To monitor hydration in the field, these individuals require techniques that involve little technical

Table 3. Relationship of Mean (± SD) Serum Osmolality to 24-hour Total Water Intake[a] in a Large Sample of Healthy Adults. Members of Other Male and Female Age Groups (i.e., Children, Senior Citizens) Exhibited a Similar Relationship [15]

Gender, Age Range	Total Water Intake Deciles	Number of Adults Observed	Mean Total Water Intake ($L \cdot day^{-1}$)[a]	Serum Osmolality ($mOsm \cdot kg^{-1}$)
Males, 19–50 y	1	380	1.7	279
	2	336	2.3	279
	3	287	2.7	281
	4	278	3.0	280
	5	296	3.3	280
	6	307	3.7	280
	7	312	4.1	281
	8	276	4.7	280
	9	304	5.6	280
	10	315	7.9	281
Females, 19–50 y	1	429	1.3	277
	2	369	1.7	277
	3	350	2.0	277
	4	347	2.3	276
	5	347	2.6	277
	6	340	2.9	277
	7	320	3.3	277
	8	306	3.7	278
	9	281	4.3	277
	10	353	6.1	278

[a] total water intake = water + beverages + water content of solid foods.

Source: US Department of Health and Human Services, National Center for Health Statistics, Third National Health and Nutrition Examination Survey (NHANES III), 1988–1994.

expertise and sophisticated instruments. Such methods also should be easy-to-use, safe, portable, and inexpensive. Comparing Table 4 (rows 7 to 14) to columns 3 to 7 in Table 1, the likely candidate methods for field use are body mass change, urine specific gravity, 24-hour urine volume, urine color, and thirst. During daily activities, body weight change is the quickest, simplest, and most accurate technique. Details regarding these five techniques appear elsewhere [7].

It is useful to view euhydration operationally because euhydration is desirable at all times; is constantly challenged by fluid losses from the kidneys, lungs and sweat glands; and fluctuates continually around an average. Considering previous models [5–7], the following recommendations will assist healthy individuals to achieve euhydration.

- Maintain morning body weight within 1% of the normal baseline from day-to-day. This requires that an individual know her/his normal body weight. A recent investigation [9] determined that a valid, average baseline value (with daily variability of 0.51 ± 0.20 kg; mean ± SD) can be determined by measuring body weight on three consecutive days.
- Consume adequate fluid. The National Academy of Sciences [15] reports that the 24-hour dietary reference intake of total water (i.e., in drinking water, beverages plus solid food) is 3.7 L for 70 kg males and 2.7 L for 57 kg females. Higher intakes of total water will be required for those who are physically active or are exposed to hot environments [15]. Because thirst is initially perceived when a body weight deficit of 1–2% exists [39,40], fluid consumption should be adequate to avert the perception of thirst.
- Maintain urine appearance as "pale yellow" or "straw colored." These colors correspond to a state of euhydration [20,23].
- Normal urine volume should be produced by the kidneys if the three previous goals are achieved. A healthy man excretes 1.3 to 1.6 L [46] (mean ± SD), and a healthy woman produces 1.13 ± 0.42 L [31] of urine per day. This means that women and men should excrete a minimum of 0.29 and 0.48 L of urine per day, respectively, to avoid being two standard deviations below the mean (i.e., abnormal) [31].

Simply stated, TBW approaches or reaches a state of euhydration when morning body weight is near the normal baseline, fluid intake is adequate, urine color is pale yellow, and urine volume is normal.

MERGING LABORATORY AND FIELD TECHNIQUES

In real-world situations (i.e., determining the total water intake or the water requirement of citizens during daily activities), laboratory- and field-appropriate techniques can be merged to clarify our understanding of the intricacies present in human water turnover. A noteworthy model of this approach

Table 4. Laboratory Measurement Resolution and Accuracy of 13 Hydration Assessment Techniques

Hydration Assessment Techniques	Outcome Variables	Measurement resolution[a,c]	Accuracy[b,c]	Validation Methods, Criterion Standards	Strength of Evidence[d]
Isotope dilution	TBW volume	2% (0.8–1.2 L)	overestimates TBW 1–5%	calculation based on whole-body dilution[c]	A
Neutron activation analysis	fluid volumes[f] and whole-body ion content	parts per billion	considered as the reference standard for all element identification	calculation based on known gamma ray emission properties of elements	A
Bioelectrical impedance spectroscopy (BIS)	TBW, ECV and ICV	detects TBW change of approx. 0.8–1.0 L	−0.67 to −1.16L TBW; +1.07 L ECV; −2.08 L ICV[g]	TBW (deuterium oxide dilution) and ECV (Br dilution); ICV = TBW − ECV	B[g]
Body mass change	body water loss or gain	± 0.1 kg (± 0.1 liter of TBW)	excellent (brief elapsed time); poor (days to months)	direct measurement; inference is based on physiologic functions involving water loss and gain	B
Plasma osmolality	ECF concentration	1 mOsm per kg H_2O[h]	1–2%[h,i]	direct ECF sample; standard solutions with known osmolalities	B[h]
% plasma volume change	hematocrit and hemoglobin	IN	IN	—	B
Urine osmolality	urine concentration	IN	IN	—	B
Urine specific gravity	relative density of urine vs. water	IN	IN	—	B
Urine conductivity	electrical Conductivity	IN	IN	—	B
Urine color	urochrome concentration[j]	IN	IN	—	B
24-hour urine volume	daily flow rate	IN	IN	—	B
Salivary flow rate, osmolality, total protein[k]	flow rate, osmolality, protein concentration	IN	IN	—	B
Rating of thirst	perception based on ECF concentration	IN	IN	—	B

This table is based on published sources [2,4,9,11,20,23,31–40]. Abbreviations: TBW, total body water (liters); ECV, extracellular volume; ECF, extracellular fluid; ICV, intracellular volume; IN, it is not appropriate to consider the measurement resolution and accuracy of these seven techniques, because they do not measure intracellular fluid or ECF directly; these seven techniques provide useful guidance regarding body fluid balance in field settings [41].

[a] the *measurement resolution* of a technique is exemplified by the number of digits with which a value can be expressed validly (i.e., 1.0 liter versus 0.01 liter).

[b] *accuracy* is defined as the degree of conformity of a measurement to the actual (true) value.

[c] with regard to direct measurements of fluid volume or ECF concentration.

[d] evidence categories A, B and C are defined in the subsection titled, "Strength of Evidence".

[e] stable and radioactive isotopes of tritium, hydrogen and deuterium (^3H_2O, ^2H_2O, $H_2{}^{18}O$) are used to measure TBW; extracellular fluid volume is assessed via bromide dilution [11].

[f] TBW, ECF volume, ICF volume, and total exchangeable extracellular sodium, chloride or potassium

[g] , BIS is based on theory [42–44], not proven biophysical principles [45].

[h] using a freezing point depression osmometer; the validity of P_{osm} as a hydration index differs with experimental design.

[i] see section above titled "Measurement Resolution and Accuracy in the Laboratory".

[j] urochrome, a product of liver processing of dead erythrocytes, is the pigment that causes urine to have a yellow color.

[k] salivary flow rate, osmolality and total protein concentration have been proposed as hydration markers. Although few studies have evaluated changes of these variables, dehydration (−3% of body weight) reduces salivary flow rate [38].

has been published by German investigators [47] who analyzed water turnover in 479 healthy boys and girls, 4.0 to 10.9 years old. Utilizing measurements of 24-hour total water intake (range 0.90 to 0.96 ml · $kcal^{-1}$), median urine osmolality (range 683 to 854 mosm · kg^{-1}), the hypothetical maximum urine osmolality (830 mosm · kg^{-1} for healthy children with an affluent Western-type diet), and the "water reserve" (24-h urine volume minus the hypothetical urine volume needed to excrete 24-h urine solutes at 830 mosm · kg^{-1}), Manz and colleagues [47] computed the daily Adequate Intake (AI) of water. AI values for total water intake, in four age and gender groups, ranged from 1.01 to 1.05 ml · $kcal^{-1}$. These procedures hold promise for future investigations regarding the effects of chronic dehydration on well-being and disease.

SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

All hydration assessment techniques evaluate a complex fluid matrix and interconnected fluid compartments. Singular measurements are inadequate because fluid gain and loss alters TBW as a sinusoidal wave that oscillates around an average. The measurement resolution and accuracy of most hydration assessment techniques (Tables 1 and 4) is not supported by a large, consistent data base. Also, no previous publication provides incontrovertible evidence that measurements of concentration (including P_{osm}) validly represent body water loss or gain in all situations. Therefore, dynamic human water turnover is inadequately represented by (a) a single measurement in time, especially when fluid balance is perturbed, and (b) techniques that have poor measurement resolution and accuracy.

In the laboratory, certain hydration assessment techniques are effective. Under controlled conditions (i.e., when experimental, postural, activity, dietary, and environmental factors are controlled), the TBW, volume of body fluid compartments, and extracellular fluid concentration stabilize. When body fluids are equilibrated, TBW and P_{osm} provide objective measurements of volume and concentration at a single point in time.

During daily activities or exercise, when fluid compartments are constantly fluctuating (i.e., volume and concentration), a direct evaluation of a single body fluid (Table 1) will not provide valid information about TBW and the concentration of body fluids. For example, several studies are presented above in which P_{osm} does not track the gain or loss of TBW. Body weight change provides the simplest and most accurate index of hydration status (Table 1) in real time, when serial measurements are collected in close proximity. Thus, in the field, when an estimate of hydration status is needed or when a large body water loss is anticipated (i.e., exercise), one should compare information from two or more hydration assessment techniques, and evaluate body hydration status more than once each day.

Future research and development efforts should focus on novel hydration assessment techniques [4,6,7,38] that (a) measure fluid volume and concentration in real time; (b) have excellent precision, accuracy and reliability; (c) are non-invasive; (d) are interpreted in concert with other hydration indices; and (e) are portable, inexpensive, safe, and simple to use. Specifically regarding P_{osm}, future investigations should (f) evaluate the validity of the relationship between P_{osm} and body water gain/loss in a variety of settings, and (g) compare the ability of P_{osm} (and other hematologic indices) to track body water change versus other (i.e., urinary) hydration assessment techniques (Fig. 2).

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