Engineering Approaches to Assessing Hydration Status

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***Abstract*—Dehydration is a common condition characterized by a decrease in total body water. Acute dehydration can cause physical and cognitive impairment, heat stroke and exhaustion, and, if severe and uncorrected, even death. The health effects of chronic mild dehydration are less well studied with urolithiasis (kidney stones) the only condition consistently associated with it. Aside from infants and those with particular medical conditions, athletes, military personnel, manual workers, and older adults are at particular risk of dehydration due to their physical activity, environmental exposure, and/or challenges in maintaining fluid homeostasis. This review describes the different approaches that have been explored for hydration assessment in adults. These include clinical indicators perceived by the patient or detected by a practitioner and routine laboratory analyses of blood and urine. These techniques have variable accuracy and practicality outside of controlled environments, creating a need for simple, portable, and rapid hydration monitoring devices. We review the wide array of devices proposed for hydration assessment based on optical, electromagnetic, chemical, and acoustical properties of tissue and bodily fluids. However, none of these approaches has yet emerged as a reliable indicator in diverse populations across various settings, motivating efforts to develop new methods of hydration assessment.**

***Index Terms*—Assessment, dehydration, hydration, monitoring, water content.**

I. Background

COMPRISING 50–70% of human body mass, water is crucial for the transport of oxygen and nutrients, performance of organs, regulation of body temperature, removal of waste, and numerous other physiological functions [1]. A young adult male weighing 70 kg has 42 L of total body water (TBW), distributed between the intracellular fluid (ICF) and the extracellular fluid (ECF) compartments [2], as shown in Fig. 1. The ECF compartment is divided between interstitial fluid that surrounds tissue cells, plasma that holds blood cells in suspension, and transcellular fluid, which is enclosed by epithelial membranes (e.g., cerebrospinal fluid). Water content varies across individuals depending on variables such as sex and age. Individuals with a greater proportion of fat will have lower relative TBW, as fat by content is only ∼11% water. Those with more muscle will have higher relative TBW due to the fact that muscle is ∼75% water [3]. Water typically comprises 50–55% of a female's body weight, as opposed to 60–70% in men [1]. As a person ages, water content decreases due to reduced muscle mass and other physiological changes that will be described later [4].

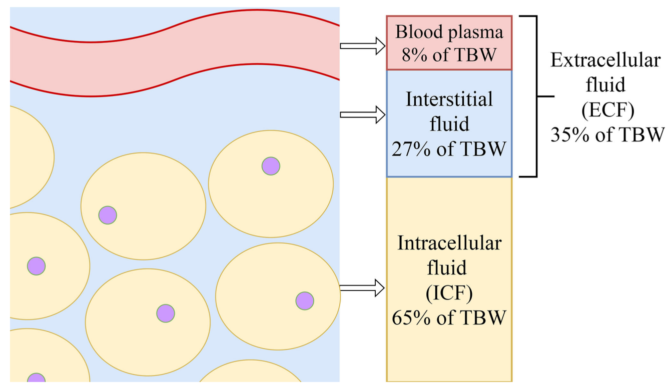

Fig. 1. Distribution of TBW between fluid compartments.Transcellular fluid content is very small and often not included in TBW calculations.

Over a 24-h period, the human body normally regulates water balance within 0.2% of body weight [5]. While the average amount of water in the body in sedentary individuals remains relatively constant, 5–10% of the TBW, or approximately 2–2.5 L, is turned over daily [2], [5], [6]. Water input comes from intake (beverages, food) and internal oxidation of macronutrients, while water output is in the form of urine, sweat, feces, and evaporation from the respiratory tract and the skin [5].

Dehydration is defined as a deficit in TBW. Dehydration is typically categorized as hypertonic, isotonic, or hypotonic based on serum sodium levels [5], [7]–[9]. Hypertonic, or water-loss, dehydration can be caused by inadequate fluid intake, excessive

Manuscript received July 28, 2017; revised September 28, 2017; accepted October 22, 2017. Date of publication November 20, 2017; date of current version July 24, 2018. This work was supported by the Natural Sciences and Engineering Research Council of Canada, Alberta Innovates Technology Futures, and University of Calgary Strategic Research Funding. *(Corresponding author: David C. Garrett.)*

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Digital Object Identifier 10.1109/RBME.2017.2776041

sweating or transcutaneous evaporation, and/or vomiting [5]. Isotonic dehydration occurs when both salt and water are lost in proportional amounts from the body as a result of, for example, diarrhea. The final category is hypotonic, or salt-loss, dehydration that occurs when salt is lost proportionally more than water. This may occur, for example, with the use of a diuretic (i.e., drug that promotes the formation of urine by the kidney) [5].

The term “dehydration” is often used imprecisely [10]. It is commonly used as a synonym for water-loss dehydration. Due to its high prevalence among exercising individuals [9] and older adults [11], the detection of water-loss dehydration is the focus of this review. However, it is advantageous for assessment techniques to be able to differentiate between water- and salt-loss dehydration as this will help guide effective treatment [9].

Maintaining a relatively steady equilibrium, or homeostasis, is integral to the body’s ability to function properly. When the body experiences dehydration, a number of compensatory mechanisms are called upon to minimize the changes that occur. For example, with the development of hypertonic dehydration, an increase in plasma osmolality ($P_{\rm osm}$) of 1% or more leads to the release of antidiuretic hormone (ADH), which leads to an increase in reabsorption of water by the kidneys. When a loss in body weight reaches 1–3%, osmotic pressure of the ECF increases. This together with elevated ADH levels induces thirst, another important protective mechanism of the body in the face of dehydration [5]. However, the body’s natural thirst mechanism develops after dehydration has occurred and becomes satisfied before hydration is fully restored by fluid consumption [12]. External factors such as strenuous exercise, extreme heat, lack of fluid access, and diuretics can disrupt or overwhelm these efforts to maintain fluid homeostasis.

The degree of dehydration is typically described in terms of the percent change in body weight. Severe symptoms become evident when body weight loss is between 3% and 5% [13]. Significant cognitive impairment has been suggested to begin at a 2% change in body weight [14], [15]. However, milder degrees of dehydration may lead to a range of acute effects that may pass unnoticed, including mildly impaired cognition, altered mood, and impaired physical performance [16]–[20]. Several other health problems may be associated with acute or chronic dehydration [21]–[24]. When dehydration occurs, hypovolemia (state of decreased blood volume) can occur resulting in a lower blood pressure and a compensating increase in heart rate. In other words, it results in a lower cardiac stroke volume with a concomitant rise in heart rate to maintain a constant cardiac output [23]. During heat exposure, thermoregulation is compromised as sweating and blood flow to skin is decreased. This increases the risk of developing heat injuries such as heat cramps, exhaustion, or stroke in order of severity [24]. Uriolithiasis (kidney stones) has been associated with chronic mild dehydration [21], [22].

Accurately assessing hydration status will likely grow in importance, as there is consensus that global temperatures will rise for decades to come [25]. Higher daily temperatures already have substantial impacts on total emergency department visits in affected communities [26]–[28]. More dire impacts have also been seen. For example, the 2003 heat wave in France resulted in an estimated 14 800 deaths [29]. Mesoamerican Nephropathy, which primarily affects agricultural workers, has led to more than 20 000 deaths in Central America [30]. Cyclic dehydration arising from working in a hot and humid environment that leads to tubular damage may be the underlying cause [30]–[32]. If confirmed, this would be one of the first diseases attributable to climate change but also one potentially preventable by providing adequate water, rest, and shade to these workers.

Dehydration can often be prevented or treated through increased consumption of fluids if detected early. This makes hydration assessment critical in regulating fluid intake among at-risk populations. We consider the detection of changes in body weight of 2% (∼3% TBW) to be of clinical use in hydration assessment. This is a commonly defined threshold for impairment in athletic and cognitive performance [14], [33]. Note that certain symptoms may be present at less severe levels, particularly in vulnerable populations such as older adults. The target population should thus be considered when defining the clinically relevant thresholds of a given method.

The purpose of this review is to outline existing and emerging methods of assessing hydration status. For more details on the physiology of dehydration, the reader is directed to existing reviews [9], [12], [34]. To provide context, four adult population groups at a greater than average risk of developing dehydration are considered: athletes, military personnel, workers, and older adults. The causes and consequences of dehydration are examined for each of these groups. Existing and emerging techniques of hydration assessment are then described and compared.

II. Hydration in At-Risk Populations

A. Athletes

Athletes frequently experience dehydration through a combination of increased sweating, transcutaneous evaporation, and/or inadequate fluid consumption. During strenuous exercise, the response to thirst is often not sufficient to maintain a state of euhydration (the state of being in water balance) [35]. Dehydration among athletes is especially prevalent in hot environments, where the rate of sweat production can be 1–2 L per hour [5]. When pure water is used to rehydrate following exercise, water retention is proportionally greater in blood plasma, reducing the sensation of thirst before TBW has been restored [36].

When dehydrated, the body’s capacity to dissipate heat is compromised due to a reduction in sweat production and blood flow near the skin surface [37]. Core temperature rises by 0.15–0.2 °C with every 1% weight lost [38]. This can lead to exertional heat stroke (core body temperature >40 °C) during heat exposure [39]. Dehydration also leads to reduced cardiac stroke volume [40] and increased cardiovascular strain. It was found that heart rate measured 10 min postexercise increased by 10 beats/min for every 1% loss of body mass due to dehydration [41]. Cognitive effects can also occur. For example, there can be an increase in perceived effort and tiredness [42]. These factors can affect both the performance and safety of athletes.

As athletic performance is dependent on many factors, it is difficult to precisely determine the effects of hydration status. High degrees of hypohydration (i.e., > 3–4% body mass deficit), especially when compounded by heat stress, will impair cognition, physical performance, and sport-related technical skills [43]. A blinded study using a gastric feeding tube to manipulate hydration status showed hypohydration of $\sim$2.4% body mass decreased endurance performance by $\sim$8% [44]. In certain sports, greater physical size gives a significant advantage. To level the playing field for smaller athletes, weight classes or categories are used. This has led to the pervasive practice of weight cycling where loss to "make weight" is followed by post-weighing but precompetition gain. Common techniques to lose weight include exercising in a hot environment or while wearing a rubber or plastic suit, using a steam room or sauna, and restricting fluids in the days prior to competition. In wrestling pre-event, losses can approach 5% [45]. Extremely rapid and profound weight loss impairs performance and can have dangerous consequences including death for the athlete [46].

Both amateur athletes and military personnel have a surprisingly high prevalence of dehydration prior to the start of training or testing sessions [47], [48]. Athletic performance may be impacted by pre-exercise hydration status, particularly in longer duration exercise [49]. This may be due to impaired thermoregulation, greater perceived effort, and/or altered anaerobic function such as reduced lactate threshold. Dehydration prior to exercise is common among soccer players [50], [51] and compounds normal water losses, which may lead to serious dehydration ($>$3%) despite high fluid intake during competition due to limited water absorption in the gut [51].

It is recognized that negative effects from dehydration in athletes are not universally accepted. Noakes states that the only symptom of dehydration in athletes is thirst [52], [53], and Wall *et al.* argue that athletic performance is not affected by hydration status [54]. Previous athletic guidelines may have led to overconsumption of fluids, which in turn may have increased the risk of exercise-associated hyponatremia (EAH) [55], [56]. However, there is an emerging consensus that proper hydration in athletes leads to improved performance, better heat dissipation, and improved safety. The proper assessment of hydration status could also prevent overconsumption of fluid and EAH. Furthermore, athletes competing in weight-class sports (e.g., wrestling) often undergo voluntary dehydration in the days leading up to a competition in an effort to attain a lower weight category [57]. Hydration assessment could provide better feedback and enhanced athlete safety during this process.

In monitoring hydration to ensure safe and optimal performance, athletes favor assessments that are quick, easy to perform, and do not require specialized training or technology. Some common approaches used now are: measuring weight pre- and postexercise, examining the color of a first morning urine sample, determining urine specific gravity (USG) using light refractometry, and assessing urine conductivity in order to measure osmolality [58]. These methods will be described further in Section III-B.

B. Military Personnel

Soldiers are often required to work and train in hot climates under stressful conditions with limited access to fluids. Basic military training for the U.S. Air Force occurs in the hot dry climate of Texas where dehydration during training is a common occurrence [59]. Dehydration leaves military personnel more susceptible to heat illnesses, such as heat stroke and exhaustion. Seventeen percent of heat stroke cases among U.S. soldiers are associated with dehydration [60]. An average of three heat stroke and 30 heat exhaustion cases per year occur among U.S. Air Force trainees [59]. Foot soldiers often carry their entire water supply on their backs for missions lasting one to three days. This limits the amount of water they can access [61].

Heat illness prevention programs have been introduced in some military training sites. They focus on heat acclimatization and fluid and electrolyte replacement [60]. These programs have been associated with a reduction of heat illness hospitalizations from 60 per 100 000 soldiers in 1991 to 10 per 100 000 in 2002. During U.S. Air Force basic training in Texas, it was recently found that trainees actually had an average increase in TBW of 1 L over the course of the day [59]. Trainees at this site were given either a back-mounted hydration system or a 1.1-L canteen and told to follow a regular hydration schedule of 1 L of fluid consumption per hour. This shows that proper training, together with access to adequate amounts of fluid, can effectively prevent dehydration in military personnel. Military hydration guidelines were revised in 1999 to account for the possibility of developing hyponatremia from excessive water consumption [62]. These revisions were found to minimize overdrinking in military personnel while maintaining proper hydration status [63].

C. Workers

Workers in construction, agriculture, and other occupations involving manual labor may experience thermally and physically stressful work conditions, which require increased evaporative cooling leading to an elevated risk for dehydration [64], [65]. Maintaining euhydration is especially important in avoiding heat exhaustion and stroke [66]. Bates *et al.* estimated fluid loss can be 1 L/h from sweat alone under thermally stressful conditions [66]. As the upper limit of fluid absorption from the gut is 1.2–1.5 L/h, it can be difficult for these workers to maintain euhydration.

Dehydration not only increases the risk of heat illness, but it can also have adverse effects on work capacity. Mild dehydration can cause errors in simple tasks such as monotonous driving [67], while a body water loss of as little as 1% can lead to a 6–7% reduction in work capacity [64]. Montazer *et al.* found that a 4% body water loss in a moderately stressful environment can reduce physical work capacity by up to 50%. Infrastructure insufficiencies at temporary worksites (e.g., construction), such as a lack of air-conditioned break rooms and permanent water stations, can contribute to dehydration [66]. Workers at construction sites were found to have a higher USG on average than those working at permanent industrial plants [66]. One method for circumventing this problem is by making water bottles a mandatory part of a worker's personal protective equipment and providing training on maintaining euhydration [68].

D. Older Persons

Many older persons (i.e., those 65 years of age and older) with chronic diseases and/or functional impairment are in a state of mild hypertonic dehydration due to a variety of factors [69], [70]. In general, older persons have a smaller fluid reserve, diminished thirst sensation (hypodipsia) with resultant decrease in fluid intake, and reduced ability to concentrate urine [8], [69], [71]. Additional factors that may influence hydration include various comorbidities (e.g., chronic kidney disease and impaired cognition), pharmacological interventions (e.g., diuretic use), and reduced mobility with limited access to fluids [70], [72], [73].

In 1999, ~42 000 hospital admissions among older persons (i.e., 65 years of age and older) in the United States listed volume depletion as the primary diagnosis (i.e., the condition chiefly responsible for the hospital admission). The estimated direct cost of these potentially avoidable hospitalizations was $1.14 billion US ($1.675 billion in 2017 dollars) [74]. By 2010, the number of admissions had risen to ~149 000 [75]. These figures, though, underestimate the true burden. Many cases are missed because of the difficulty in detection, and when noted, it is usually recorded as a secondary (i.e., condition coexisting at the time of admission or developing subsequently that affects patient care during this episode of care) rather than primary diagnosis [76]. Nearly 20% of older adults hospitalized with dehydration as a primary diagnosis die within 30 days of admission [76], [77]. Even after accounting for potential confounders, dehydrated older patients are six times more likely to die in hospital than those with a normal hydration status [78]. In clinical practice, there is recognition of the need for improved approaches to assessing hydration status.

Dehydration has been shown to be common in long-term care facilities (e.g., nursing homes). While studies reporting on the frequency of dehydration among long-term care residents have shown variable results, recent studies reported high rates of both impending (28–30%) and existing (20–38%) water-loss dehydration in residents [69], [71], [79]. In these studies, impending (also called mild or early) dehydration was characterized by a serum osmolarity of 295–300 mOsm/L. Osmolarity for cases of existing dehydration was greater than 300 mOsm/L. Another small longitudinal study conducted on nursing home residents found that dehydration occurred in 31% (11/35) of participants during a six-month period [80].

Techniques commonly used to encourage adequate hydration include educating older persons on the importance of hydration, incorporating fluid consumption into daily routines, using visual prompts and providing assistance in accessing fluids and/or drinking [80], [81]. Along with strategies to prevent dehydration, many researchers have also evaluated methods of assessing hydration status in older persons. A commonly used indicator in long-term care facilities is urine color, which can be easily evaluated with a color chart [82]. However, a recent systematic review of clinical symptoms, signs, and tests for identifying impending and existing water-loss dehydration in older persons concluded that there was limited evidence for the diagnostic utility of any individual marker or combination of markers [11], [69]. Surprisingly, the features with the greatest sensitivity and specificity in detecting dehydration were the older person complaining of fatigue, and a caregiver noting that the older person was not drinking between meals [11].

TABLE I
OVERVIEW OF METHODS OF HYDRATION ASSESSMENT

Clinical Manifestations	Common Laboratory Assessments	Other Physical/ Laboratory Assessments	Emerging Methods
Thirst Blood Pressure Heart Rate	Blood analysis Urine analysis	Isotope dilution Weight analysis Bioimpedance analysis	Visual/optical Electromagnetic Chemical Acoustical

III. METHODS TO ASSESS HYDRATION

This review focuses on both approaches that are currently widely used and emerging methods (see Table I). In order to be clinically useful, hydration assessment techniques should be capable of detecting fluctuations within 3% of TBW, or about 2% of body weight for an average individual [58]. This upper limit marks a threshold for athletic performance impairment [33]. However, as previously noted, certain populations such as older adults may experience symptoms with less marked hydration changes. Current methods consist of clinical manifestations, common laboratory analysis, and other physical or laboratory assessments. The strengths and limitations of these methods are described in order to provide context for the discussion of emerging technologies.

A. Clinical Manifestations

Clinical manifestations (symptoms perceived by the person or signs detected by the practitioner) are currently the most commonly used methods for assessing hydration status. The simplest measure involves assessing an individual's thirst, using methods such as a visual analog scale or a categorical scale where the individual indicates their degree of thirst [83]. However, the sensation of thirst is not an adequate reflection of water needs in groups at particular risk of dehydration, such as older adults [84]. A combination of the degree of morning thirst sensation and urine volume has been proposed by Armstrong *et al.* as a method of identifying mild dehydration [85].

Low systolic blood pressure has a high specificity in diagnosing hypotonic dehydration but generally poor sensitivity [86]. Dehydration can also lead to increases in heart rate (both at rest and during submaximal exercise) [23], [87], [88] and orthostatic hypotension (drop in blood pressure when standing from sitting or lying) [89]. The cardiovascular response to postural intolerance has been examined as an indicator of hydration status. A common threshold for a significant change in heart rate when going from lying to standing is 20 beats/min or greater increase, but this was found to only be helpful in detecting severe hypertonic dehydration [87]. As well, these clinical signs may be caused by a number of other conditions, rendering them generally inaccurate in identifying fluid imbalance when used in isolation [6].

Clinical signs and symptoms typically have poor sensitivity and/or specificity for the detection of dehydration [7]. According to Thomas *et al.*, the only clinical manifestations with sensitivities >80% are dry mucous membranes (mouth and nose) and longitudinal furrows on the tongue [90]. Factors reported as having specificities >80% were speech incoherence, extreme weakness, dry axilla, and orthostatic hypotension. Unfortunately, these clinical signs perform particularly poorly among older adults. Fortes *et al.* evaluated seven physical signs of dehydration (i.e., tachycardia [heart rate >100], low systolic blood pressure [< 100 mm Hg], dry mucous membranes, dry axilla, poor skin turgor, sunken eyes, and long capillary refill time [>2 s]) among 130 older adults within 30 min of their admission to hospital [86]. Sensitivity for detecting dehydration ranged from 0% to 44%, while specificities were 60–99%. None of the signs alone could accurately discriminate between euhydration and dehydration. While clinical manifestations are relatively straightforward to assess, they are not in general sufficiently sensitive and specific.

B. Common Laboratory Assessments

1) Blood Analysis: Blood samples can be used to measure a variety of parameters related to hydration, including plasma osmolality (i.e., measure of the osmoles of solute per kilogram of solvent; reported as P_{osm}), electrolytes, blood urea nitrogen (BUN) to creatinine (Cr) ratio (BUN:Cr), and hemoglobin/hematocrit levels [1]. However, there are limitations with all of these measures. For example, according to Francesconi *et al.*, blood indices are only sensitive to dehydration >3% of body weight, which renders them less sensitive than urine measurements [91] and of little practical value. This is likely because the body attempts to maintain normal blood chemistry for as long as possible. Also, most of the blood indices are only applicable for hypertonic dehydration, as other forms of dehydration do not change blood composition.

The current clinical standard of hydration measurement is plasma osmolality (P_{osm}). Blood is composed of both plasma and formed elements as shown in Fig. 2. P_{osm} is measured with an osmometer using techniques such as freezing point depression. Plasma osmolarity—a measure of dissolved solutes per unit volume—is a bedside calculation derived from laboratory data measured in solutions. Since plasma has a specific gravity near unity ($1\,\mathrm{kg} \approx 1\,L$) [92], osmolality and osmolarity values are very similar and often used interchangeably [93]. Values for P_{osm} vary from 280 to 290 mOsm/kg for a euhydrated individual, with a value >290 mOsm/kg indicating dehydration [5]. An increase in P_{osm} of just 1% can initiate thirst and the release of ADH to promote water reuptake by the kidneys [5]. A study performed by Popowski *et al.* showed that P_{osm} was

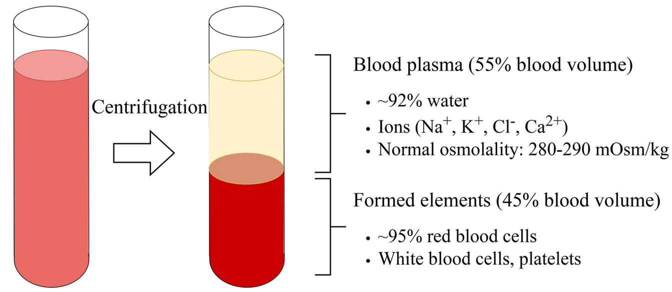

Fig. 2. Normal composition of human blood.

highly responsive to changes in hydration among male athletes [94]. A reduction in body weight of 3% after exercise resulted in an increase in P_{osm} of 5 mOsm/kg.

Despite being often used as a reference standard for hydration status [95], there are several limitations with P_{osm} [96]–[98]. First, there are feasibility issues. These measurements are relatively costly compared to other approaches. Tests take time to perform because a laboratory analysis must be done, and they require a venipuncture that can cause pain or bruising. Arguably, this makes blood analyses impractical for frequent, portable, and/or time-sensitive use. It has also been debated that P_{osm} does not adequately assess whole body hydration in all settings [96]. There may be particular problems when TBW, fluid intake, and fluid loss are in a fluctuating state [97], [98]. While P_{osm} is an important standard when assessing the accuracy of other approaches, these observations suggest that it may not be the ideal indicator of hydration status [98].

To assess hypotonic dehydration, the BUN:Cr ratio can be used (in Canada and Europe it is commonly referred to as a urea:creatinine ratio). A normal ratio is 10–20:1 when assessed with units customarily used in the United States and 40–100:1 with International System of Units [SI] units. Hypotonic dehydration is defined as a BUN:Cr >20:1 (>100:1 with SI units), in the absence of hypertonicity [70]. To perform this test, a whole blood sample must be collected and analyzed within 2 h of collection [86]. However, BUN:Cr may also be elevated for reasons other than dehydration such as a gastrointestinal bleed [90].

Finally, hemoglobin (Hb) and/or hematocrit (Hct) levels can be assessed. This only requires a drop of blood, and a portable machine can be used to analyze the sample. The relative change in one or both of these indices at different time points can be used to estimate changes in blood, plasma, and cell volume according to the technique of Dill and Costill [99]. With acute dehydration, the concentration of Hb and Hct rise since water content is lost but red blood cells remain in the blood. The simplicity of the test and limited amount of blood required make it more practical for field work compared to other blood indices like P_{osm}. For example, a study performed by Hackney *et al.* on mountaineers before and after a 14-day arctic mountain ascent and descent found Hb and Hct levels were well correlated with TBW [100]. However, factors such as posture and skin temperature may influence the accuracy of this technique [101], [102] and should be considered.

In summary, blood analyses may provide accurate and precise methods of assessing hydration status, but are not suitable for ongoing monitoring due to their inherent invasiveness. Furthermore, their accuracy may be impaired by factors that commonly arise outside of laboratory conditions, such as fluctuating hydration status and posture. Blood indices are, therefore, best suited for single-time clinical assessment.

2) Urine Analysis: Urinary indices are relatively easy to measure and can provide a rapid assessment of hydration [6]. There are four main indices used to assess hydration: color, USG, osmolality, and conductivity [103], [104].

The simplest method is to compare the urine color to a color chart, such as the six-point Likert scale validated by Armstrong *et al.* [104]. When dehydration occurs, urine becomes concentrated and therefore darker. Color charts are frequently used in care facilities, as they are a low-cost and simple method of rapidly determining hydration [5]. In a study performed on nine trained cyclists, urine color tracked body water loss as effectively as urine osmolality and specific gravity [105]. However, a study by Kovacs *et al.* examining the accuracy of urinary indices, including urine color, during rapid postexercise rehydration found that these indices were poor measures of hydration status [106]. Urinary indices are not suited for monitoring rapid changes in hydration status since they lag behind overall hydration. Urine discoloration can also be due to other factors, such as dyes from food, certain medications, the presence of blood in the urine, and jaundice.

USG is frequently used to look for evidence of dehydration, as previously mentioned in our review of studies evaluating dehydration in athletes and workers [27], [44], [46], [79]. USG is commonly examined using two different methods, both of which are easy to use and quickly provide an estimate of hydration [1]. The first method, refractometry, involves shining a beam of light through a sample and measuring its refraction, which relates to sample density [108]. The second method uses reagent strips of bromothymol blue to estimate specific gravity between 1.000 and 1.030, where it is generally accepted that values above 1.020 correspond to some level of dehydration [46], [72], [81]. One factor to take into consideration when assessing USG in athletes is muscle mass. In athletes with high muscle mass, the specificity of USG is reduced, increasing the possibility of incorrect assessment of dehydration [107].

Measuring urine osmolality typically requires a trained technician and a freezing point osmometer. The osmometer only detects solutes that dissociate, such as NaCl, meaning that glucose, urea, and proteins are ignored [1]. Interestingly, mean urine osmolality in healthy individuals varies widely across cultures, ranging from 392 mOsm/kg in Poland to 909 mOsm/kg in China [110]. This may be due to cultural differences in diet such as sodium intake, which must be considered when evaluating hydration status using urine osmolality. Obtaining baseline values for each individual is necessary to properly determine hydration with this methodology.

Electrical conductivity of urine is related to osmolarity and has been proposed as a method of assessing hydration status. Conductivity is a function of the total concentration of ions present in a sample and can be measured with portable devices such as the one used by Shirreffs and Maughan (Sparta 5; Assist Health and Fitness, Wrexham, U.K.) [103]. The device applies a small voltage and measures the corresponding electrical current in the urine sample. It then provides readings from 1 to 5 corresponding to ranges of conductivity. Good agreement is found between conductivity and osmolality in the first morning urine samples of 29 amateur athletes measured over ten days [103]. However, other studies have found conductivity to be less reliable, particularly during postexercise recovery [106].

Urine analyses suffer from several limitations. These indices are considered to lag blood analyses. Additionally, the results reflect the characteristics of all the urine that has collected in the bladder since the previous void [96]. Continuous monitoring is impractical due to relatively infrequent urination. Moreover, exercise prior to urine testing has been known to lead to unreliable results. Urine indices therefore present little utility for evaluating acute changes in hydration. Greater accuracy is achieved when they are performed in a steady state, where they can provide insight into longer (i.e., days-weeks) hydration changes.

Urine indicators can be further affected by unrelated factors such as food, medication, and illness. Another disadvantage is inaccuracy when it comes to certain groups of individuals. For athletes, the glomerular filtration rate decreases during exercise, meaning samples immediately after exercise may not be true indicators of hydration status [96]. Older adults have a reduced ability to concentrate urine, rendering urinary markers less useful for determining their hydration status [8]. First morning urine samples taken from an individual's first urination of the day are considered the most accurate, as fluid stores balance overnight [6], [75].

C. Other Physical/Laboratory Assessment Methods

1) Isotope Dilution: Isotope dilution is viewed as the most reliable method of assessing TBW [96]. A known amount of a stable isotope, such as deuterium oxide (^2H_2O), is first introduced into the body [83], [84]. This technique requires 3–5 h for internal equilibration before analysis can be performed [96], and TBW is then determined from the concentration of the isotope in urine after equilibration. The dosage of ^2H_2O administered is based on weight, although there is no set reference for this calculation. Note that hydration status is not directly known from a single assessment since individuals have varying baseline body composition.

Another method of determining TBW involves examining extracellular water and extrapolating based on known ratios of body water distribution. Here, for example, sodium bromide (NaBr) can be ingested at a dose of 70 mg/kg body weight, with extracellular water obtained via a blood sample 3–4 h later [113]. Both these methods are impractical for use in real-time hydration monitoring, given the cost, inconvenience, and length of time required.

2) Weight Analysis: The simplest method of determining changes in TBW is measuring changes in body weight. This method is accurate over short time periods when no food or beverages are consumed, there has been no voiding of urine (or these factors are considered), and meticulous care is taken in

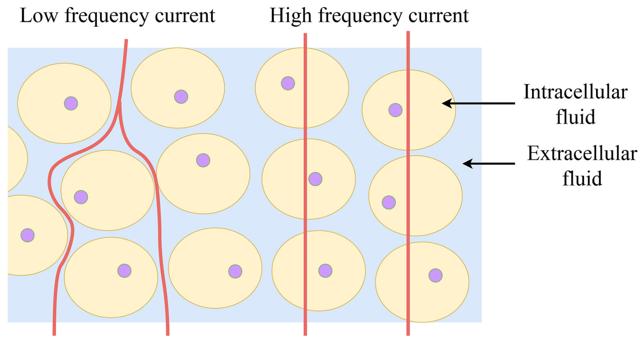

Fig. 3. Hypothesized path of low- and high-frequency current in bioimpedance analysis (adapted from [120]).

weighing the subject [5], [6], [68], [114]. Variations in body mass between successive days can also be used to estimate likelihood of dehydration, where changes greater than 2% would indicate a 95% probability [115]. There are several different prediction equations that can be used to calculate baseline TBW based on an individual's height and weight, thereby providing a reference value for comparison of measurements [116]–[118]. Caution must be taken with these equations however, owing to the large intersubject variability of tissue composition which is not captured by only measuring height and weight [112], [118], [119].

3) Bioelectric Impedance Analysis: Bioelectric impeda nce analysis (BIA) is described as a noninvasive, rapid, and accurate method for determining TBW in individuals at rest [6], [118]. Electrodes are placed on the body, and an alternating current is applied across them. Low-frequency current is hypothesized to travel primarily in the body's ECF, while high-frequency current travels through both ICF and ECF [120], as shown in Fig. 3. TBW calculations are performed by measuring the impedance to current while assuming normal fluid balance [1], [85]. Several studies have pointed out that these measurements are not accurate, particularly outside of ideal lab conditions. Sweat, skin temperature, electrode placement, and posture can easily alter measurements [5], [121]. According to a study by Jéquier and Constant, the measurement resolution of TBW using BIA is 0.8–1.0 L, making it inaccurate for detecting fluid deficiencies of less than 1 L [5]. Greatest accuracy is achieved under standardized conditions, for example, cleaning the skin with alcohol wipes before placing electrodes, taking accurate measurements of height and weight, fasting for 4 h prior to the test, and avoiding exercise [1]. These stringent conditions pose a significant barrier to using this technology in a field setting when measuring active individuals such as workers or athletes.

IV. Emerging Hydration Assessment Methods

The methods of hydration assessment described in the previous sections have been criticized as being inaccurate, insensitive, nonspecific, and/or impractical. New approaches to assessing and monitoring hydration status have been developed in response to the need for improved approaches. A variety of proposed systems are discussed in the following section. Not all approaches have been extensively validated. These emerging methods are categorized based on the technology used to detect hydration indices. The papers referenced in this review of emerging methods were identified by searching engineering and biomedical journal databases (IEEExplore, Compendex, and Medline) with the following keywords: hydration, assessment, monitoring, and sensor. Conference articles and patents were omitted.

A. Visual and Optical

Capillary refill time has been proposed as a clinical indicator of hydration status. Optical methods provide a convenient means of measurement [122]. A system was developed by Shavit *et al.* to assess capillary refill time in children with significant (>5%) dehydration. Participants lay with one hand raised slightly above the heart while a small rod was pressed into the finger for five seconds and then abruptly released. The capillary refill time was determined from a color analysis of video recovered during this process with recovery defined as when the color of the finger returned to its initial state. This method was found to be more accurate than clinical assessment among children with gastroenteritis [122]. However, it depends on having a trained technician, is strongly influenced by operator factors, and has only been validated in severely dehydrated children against conventional capillary refill times and clinical examination. Whether this technique can detect less severe levels of dehydration in adults as well as children is currently not known.

Liu *et al.* performed a study examining the mechanical properties of skin and their relation to hydration status [123]. A cellphone camera was used to capture images as the skin on the subject's hand was stretched and then released. Including a mark on the skin was found to be more accurate than tracking only skin texture. However, the camera used in the experiment operated at only 30 frames/s, which was too slow to properly capture the initial rapid skin relaxation process. This method was only validated against other methods of skin relaxation, providing only limited evidence of utility.

A system designed primarily for noninvasive blood glucose measurement has been applied to assess hydration status [124]. The method involves pulsing a green light onto the skin of the wrist and using a light sensor to observe the resulting speckle pattern (an interference pattern from different light paths). Temporal correlation between successive speckle patterns is determined, and this is deemed an "optical cardiogram" (OCG) where pulse activity can be monitored. Pilot tests were performed with subjects sitting in a 50 °C chamber experiencing water loss. The standard deviation in a specific region of the OCG and the maximum pulse amplitude are used as indicators of hydration status, and compared with weight loss during dehydration. However, little physiological interpretation of these signals was given, and inconsistent results in validation studies were found.

Several recent studies have investigated the use of near-infrared spectroscopy (NIRS) for assessing skin moisture content [125]–[129]. This skin hydration assessment focuses on a relatively shallow region of tissue, specifically the stratum corneum. The main advantage of using NIRS for assessing skin hydration is the linear correlation between NIR absorption intensity and concentration of water in skin over a wide range of concentrations [127]. NIRS has been shown to correlate well with other methods of assessing skin hydration, such as a skin capacitance measurement [128]. A study [129] reported on a portable method of NIR skin assessment, where a method similar to spatially resolved spectroscopy was applied. Measurements were performed at wavelengths between 1150 and 1650 nm. Water exhibits strong absorption near 1450 nm. A regression algorithm is then applied to relate the NIRS measurements with skin hydration. Promising results were found in mice, and the technique is proposed for use with humans. However, none of these studies support a link between skin moisture content and overall body hydration. NIRS measurements seem to be more applicable to cosmetics and dermatology (i.e., comparison of moisturizing creams).

In summary, advantages of visual and optical methods include their noninvasive nature, potential portability, and the feasibility of performing repeated measures on the same individual. All of these factors are promising for personal monitoring applications. However, these methods have so far only been tested in small groups and have not been well validated against conventional measures. Optical techniques are also generally limited to shallow assessment of skin properties due to high scattering in human tissues. Agreement between skin moisture and fluid intake has been shown in controlled environments [130], but human skin moisture is highly variable and depends on factors such as age, season, and daily routines such as washing [131]–[133]. These effects may dominate the influence of overall hydration status and should be investigated.

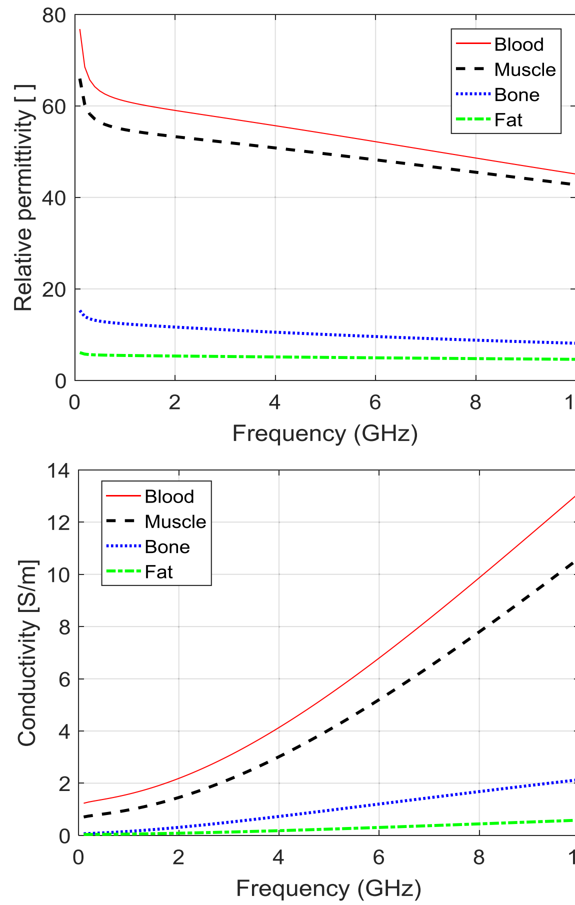

Fig. 4. Dielectric properties of human tissues at radio frequencies. Data obtained from [134].

B. Electromagnetic

Electromagnetic properties—permittivity and conductivity—of biological tissues at radio frequencies change significantly based on their water and ionic content. For instance, blood and muscle (high water and ionic content) have much higher relative permittivity and conductivity than bone and fat (low water and ionic content) [134], as shown in Fig. 4. This makes electromagnetic devices of great interest in evaluating hydration status. Several whole-body approaches have been proposed, as well as localized measurements of skin.

Resonant cavity perturbation has been proposed as a method of assessing TBW. The resonant frequency and quality factor (resonance bandwidth) of a cavity are dependent on the dielectric properties of objects within it. Since dielectric properties of biological tissues relate to tissue water content, Robinson *et al.* proposed using a resonant cavity to assess TBW in humans [135]. Subjects lie in the supine position in the center of a large metallic room acting as a resonant cavity. Resonant frequency and quality factor were measured before and after subjects drank 1.5–1.75 L of water and energy drink, and before and after urinating. A model is then fit to the change in resonant frequency in order to predict TBW from the cavity measurements [136], [137]. This method was validated for various hydration states against equations predicting TBW from measured weight. Despite offering initial promise of assessing TBW, this method does require a calibration procedure for each individual, is very sensitive to subject positioning and body size, and requires a large room with specialized equipment, which limit the feasibility of this approach.

Preliminary studies of radio frequency absorption techniques for hydration assessment were performed by Moran *et al.* [138]. A system comprised of two antennas operating from 450 to 2120 MHz was used to perform measurements through the wrist. Attenuation through the wrist was compared with lost water mass during exercise. An empirical equation relating attenuation values at different frequencies was developed to predict loss of weight due to sweating. While the empirical model did not appear to have any physical interpretation, it appeared to be capable of predicting water loss within the small group examined. No indication that this model could be generalized to other populations was given.

Recently, Brendtke *et al.* developed a patch antenna for monitoring hydration status of the skin [139]. Reflected signals from human 3-D skin equivalents were recorded over the frequency range of 7.0–9.5 GHz. These skin equivalents were made with specific hydration levels and density of matrix components. Microwave measurements produce hydration-specific spectra, allowing the hydration state of the models to be determined.

Measurements were also performed with methanol, ethanol, propanol, and sodium chloride to assess the sensitivity of the antenna to osmolality and polarity. Experiments have yet to be done *in vivo* for this device.

To measure changes in tissue water of both the skin and subcutaneous fat, a dielectric measurement device was developed by Nuutinen *et al.* [140]. The device transmits a 300-MHz signal into an open-ended coaxial probe in contact with the skin. The majority of the electromagnetic energy is absorbed by tissue water, and the remainder is reflected. From this reflected wave, the dielectric constant of the skin and subcutaneous fat is estimated. To evaluate this technology's ability to identify hydration changes, subjects undergoing hemodialysis treatment were recruited. Five measurements were taken on the forearm: an initial measurement, three additional measurements at even time intervals during treatment, and one after treatment was finished. The dielectric constant of the skin and subcutaneous fat was found to be directly proportional to the water content of the tissue, with a correlation to the fluid removed during hemodialysis treatment of $r = -0.99$. However, this method relies on overall hydration status being related to skin hydration, which has not been shown in the literature. Variation in sweat concentration between subjects and during activity may also impair accuracy.

Huang *et al.* [141] developed an impedimetric sensor as an alternative method to measure the hydration of the skin. The sensor is designed to conform to the skin, avoiding compression. It has 64 channels of planar electrode pairs that quantify skin impedance in a $15 \times 15\,\mathrm{mm}^2$ area. Contact with the skin is driven by van der Waals forces alone, eliminating the need to apply pressure. The sensor measures the impedance of the skin, which is shown to decrease with decreased hydration (as confirmed by measurements with a probe similar to [140]). Changes in frequency and the geometry of the sensors can produce measurements of hydration at different skin depths, broadening the applications of this technology.

A variation of BIA is galvanic coupling, which involves measuring electrical conduction through tissue over a frequency range from 800 kHz to 1.3 MHz. The signal is coupled galvanically on the body, and the attenuation is measured as the signal passes through tissue. Attenuation varies depending on the amount of water present, the tissue muscle-to-fat ratio, and the input signal frequency. During a study conducted by Asogwa *et al.,* subjects were measured after 12 h of fluid abstinence [142]. They were then given 600 mL of fluid and measured again 5 min after fluid intake. A sensitivity test found that the galvanic coupling device could detect a change in body water caused by subjects drinking a minimum of 100 mL of water. It was also found that baseline amplitude of signal variations in an individual was required for proper interpretation of the results, and the measurement conditions and environment required careful control.

In summary, electromagnetic approaches present an appealing method for monitoring whole body or localized tissue composition changes related to hydration status. Compared with simple methods such as body weight analysis, certain electromagnetic methods may allow for hydration assessment independent of subject clothing and equipment (e.g., in military applications) or recent food and fluid intake. However, these techniques are likely limited to monitoring acute changes in hydration of an individual since baseline tissue composition varies greatly between individuals. Furthermore, the redistribution of fluids due to blood flow and posture may dominate the effects arising from hydration changes and should be examined in future validation.

C. Chemical

A variety of chemical sensors have been developed to assess hydration status by measuring body fluids such as sweat and saliva. The advantage of these sensors is usability. For example, several sensors have been designed as thin patches that can adhere to the skin, thereby having minimal impact on an individual's daily activities.

1) Sweat: Several research groups have investigated the possibility of measuring hydration status using sensors that measure sodium ion (Na^+) concentration in sweat [143]–[145]. The concentration of Na^+ in sweat generally varies from 20 to 70 mM depending on hydration status [144], but is also influenced by factors such as fitness level and acclimation. Rose *et al.* have developed a patch in two different sizes that measures Na^+ concentration to predict the rate of sweat production. The patch is composed of a flexible printed circuit board, a coiled antenna to provide power, medical textile for exterior protection, and double-sided medical adhesive to attach the sensor to skin. Testing performed *in vitro* showed that the sensor had a sensitivity of 0.3 mV/mM when detecting Na^+, with an accuracy of 96% for a 50-mM NaCl solution. No clinical testing has been reported.

The second method uses an impedimetric tattoo sensor that is placed in contact with the stratum corneum of the skin [143]. The sensor is composed of two concentric rings of temporary tattoo paper, with an outer diameter of 20 mm, significantly smaller than the other system. The sensor is screen-printed onto the tattoo paper using silver paste ink. To calculate hydration, impedance spectroscopy is performed on sweat collected from the surface of the skin, using a frequency of 0.1 Hz to 1 MHz and amplitude of 0.01 V. This allows determination of the Na^+ content of the sweat, potentially providing an estimation of hydration status [146]. A drawback of the current design is that it is only suitable for short-term use.

Gao *et al.* have developed a device that makes use of integrated sensor arrays to monitor a variety of physiological parameters, and has been designed for use as a flexible headband or wrist cuff [147]. Sweat metabolites (e.g., glucose and lactate) and electrolytes (e.g., Na^+ and K^+) are measured, along with skin temperature to calibrate the sensor response. A substantial increase in Na^+ concentration was observed in six subjects over a period of 80 min during which subjects had lost $\sim$2.5% of their body weight. A method of analyzing sweat content is also proposed by Zhou *et al.*, where gold nanoparticles are used to monitor ion concentration [148]. The mixture has been shown to visibly change color from red to purple in different concentrations of artificial sweat; however, no human testing results are available.

In summary, sweat assessment may allow for short-term sensing using small, low-cost, and conformal devices. These evaluate the electrolyte and/or metabolite content of sweat, which may track hydration status. However, sweat may only be suitable for sensing acute changes in hydration, as baseline sweat concentration varies between individuals. Due to the reliance on sweating occurring, these techniques would likely not be useful in persons with hypohidrosis/anhidrosis from whatever cause.

2) Saliva: Analysis of saliva has the potential to monitor hydration status noninvasively and in real time. Preliminary testing has produced promising results [86], [149]–[152]. These studies suggested that saliva flow rate was not associated with dehydration, but saliva total protein concentration and osmolality were strongly correlated with body mass loss, with mean *r* values of 0.97 and 0.94, respectively [149]. Measurements of saliva osmolality were able to detect hypertonic, hypotonic, and isotonic dehydration with sensitivity of 70%, 78%, and 76%, respectively, and specificity of 68%, 72%, and 68%, respectively [86]. Walsh *et al.* determined the euhydrated range of saliva osmolality as 41–61 mOsm/kg in a study conducted with 12 healthy subjects dehydrating via exercise on a stationary bicycle [149]. After a 2.0% body mass loss, saliva osmolality exceeded this range for all 12 subjects.

To achieve the goal of a rapid, economical, and portable means of measuring saliva osmolality, embedded piezoresisitive microcantilever (EPM) sensors are being developed. The EPM is embedded into a "sensing material." When exposed to analytes, the sensing material selectively absorbs analyte molecules, resulting in a small volume change, which bends the EPM. When deformed, the resistance of the EPM changes and can be measured by an external sensing circuit [153], [154]. These sensors proved effective at measuring changes in osmolality in saliva-mimicking solutions and actual human saliva. However, the variation in saliva osmolality is not as closely correlated to hydration levels as plasma osmolality, making it more challenging to provide an accurate evaluation of hydration status.

In summary, saliva osmolality and protein concentration may be indicative of both water- and salt-loss dehydration. Initial validation studies are promising, encouraging work on miniaturizing the devices. Baseline differences between individuals may limit salivary techniques to monitoring acute hydration changes. They may also be limited to assessing subjects long after food/drink consumption.

3) Osmotic Pressure: Osmotic pressure can be assessed for a variety of different bodily fluids. As a possible alternative to the large blood samples normally required for plasma osmolality analysis, Scanlan *et al.* have proposed a micro-osmometer capable of using 15-μL samples [155]. Blood is drawn at the fingertip. Close correlation was observed with conventional P_{osm} measurements. Capillary blood measurements of P_{osm} have been found by another group to be an adequate substitute for venous measurements [156].

Fernandes *et al.* are currently preparing an osmotic pressure sensor for clinical trials, after uncovering promising results during tests with simulated physiological saline solutions [157]. The hydration sensor developed for the preliminary study measured 16×8 mm and was composed of a semipermeable membrane, a piezoresistive pressure transducer, and an electronic readout platform. Using saline solutions that mimicked the electrolyte composition of different bodily fluids, the sensor was found to have a dynamic measurement range of 220–340 mOsm/L. This range is large enough to sense both hypohydration and hyperhydration ($\pm 20\%$) in blood samples, but likely not in urine. It also takes 7 h following a change in hydration before the maximum change in signal is reached, making the device impractical for real-time monitoring. Furthermore, the sensor has a Nafion membrane inside, which quickly becomes contaminated with cations, making it suitable for use as a disposable skin patch. Despite these limitations, clinical trials are being prepared to evaluate the sensor for use as both an external skin patch and an implantable device.

In summary, osmotic pressure presents an appealing method of assessing bodily fluids that is minimally invasive. Capillary blood assessment is a promising alternative to conventional P_{osm} measurement, but suffers from the same limitations of P_{osm} analysis. The use case of osmotic pressure sensors is unclear, but may also be a viable alternative to conventional P_{osm} measurement as a patch or implanted device. Reliability and contamination over time are of concern, which may be difficult to account for outside of laboratory conditions.

D. Acoustical

A group led by Sarvazyan have developed ultrasound techniques for assessing hydration status [158], [159]. In this method, a bulk sound wave is sent through an individual's calf. The speed of the wave is determined mainly by the molecular composition of the tissue. Soft tissues, such as muscles, show a shift in ultrasound velocity with water content changes.

The first study testing this approach was conducted with athletes: 56 male wrestlers and 26 female soccer players [158]. Clinical measurements of body mass, plasma osmolality, USG, and urine osmolality were collected for comparison with the ultrasound system. Mass loss goals set for the athletes were 3% for men and 2% for women. Following attainment of these losses, ultrasound measurements were taken and then repeated 60 and 120 min after the commencement of fluid consumption. A change in propagation speed of about 1.1 m/s is observed per 1% of body dehydration. However, it was also found that elevation of body temperature due to exercise increased propagation speed by 1 m/s for every 1 °C [158]. The elevated temperature persisted for up to an hour after exercise and must be taken into consideration when evaluating the hydration level of athletes.

The second study was conducted on older persons in order to determine the normal daily variation in hydration status of those in assisted living facilities [159]. Twenty subjects ages 65 and above were recruited. Measurements were taken three times a day on three consecutive days with the ultrasound system and BIA to estimate TBW. A correlation of 0.85 between the ultrasound system and BIA was found [158]. Experiments showed ultrasound measurements were able to assess muscle dehydration with an error of about ± 1 m/s. *Ex vivo* experiments showed that velocity changed an average of 3.4 m/s per 1% change in water content of muscle tissue [159]. Difficulties were encountered in establishing a baseline ultrasound velocity due to variation between subjects. Orientation of the measurement system is also critically important in achieving accurate results, as ultrasound velocity changed by 7 m/s between measurements taken along muscle fibers compared to across the fibers. Temperature of the muscle adds further measurement variation [160].

In summary, ultrasound techniques show potential for ongoing hydration assessment. More precise and standardized measures such as changes in weight or P_{osm} should be used for future validation studies. The technique may also require both precise repositioning of transducers and control of tissue temperature, which could be difficult to reliably achieve in real-world scenarios.

V. Discussion

Dehydration is a common and serious condition that can cause impaired cognition and physical function, increased risk of heat illness, and even death if left untreated. As noted, athletes, soldiers, workers, and older persons are at higher risk of dehydration among adult populations. Strategies have been developed to prevent dehydration, but there is still no gold standard for detecting dehydration, especially at an early stage.

Signs and symptoms are typically used for the initial evaluation of hydration status in clinical settings, but most of the related characteristics have low specificity and/or sensitivity. Any one of these characteristics is not sufficiently accurate on its own to make a definitive diagnosis. The most commonly used lab-based methods for detecting and grading dehydration are analyses of blood (P_{osm}, BUN:Cr ratio, changes in hemoglobin and hematocrit levels) and urine (color, USG, and osmolality) samples. These methods have their own limitations as described above. TBW determination through isotope dilution is a widely recognized standard of hydration assessment but is impractical for field use given that an analysis of TBW can only be completed after 3–5 h of internal equilibration. BIA can be challenging, as it requires careful consideration of factors such as sweat, skin temperature, and placement of electrodes all of which can have a significant impact on the measurement obtained.

New devices are developed with the goal of improving the accuracy, reliability, and/or feasibility of dehydration detection. These approaches are based on physical properties, such as differing electrical properties, chemical composition, or acoustic properties. Direct comparison between these emerging techniques is challenging as they are at various stages of development and have used different methods for validation. Some techniques have been tested in humans, while others have only been demonstrated in phantom materials. Table II provides a summary of these techniques and validation approaches, as well as advantages and disadvantages. The desirable characteristics as outlined by Armstrong and Cheuvront were considered where possible [9], [96]. Specifically, the ideal method for hydration assessment should:

1) provide real-time results;
2) possess desirable physiometric qualities (i.e., validity, reliability, and sensitivity to change);
3) be feasible/practical (noninvasive, portable, inexpensive, safe, simple to perform);
4) be able to differentiate between water- and salt-loss dehydration.

The summary in Table II is based on our interpretation of publications to date on the approaches described in Section IV. We anticipate that "potentially portable" devices will likely become portable with further development. "Wearable" devices can be worn unobtrusively in their current form. Techniques are indicated as "simple" if they require little instruction or input from the user (e.g., watch-like devices). As none of the techniques can directly measure hydration status, we also indicate the physiological parameter estimated. Some of these parameters have been shown to relate better with overall hydration status (e.g., plasma osmolality) than others (e.g., skin water content). A parameter which has not been validated against overall hydration status is indicated as a "poor physiological parameter" in Table II. Some techniques also abandon physiological interpretation of the measurements through the use of empirical models based on the tested volunteers. This approach may present less clinically useful information, and the models may be population specific.

Table II suggests that *in vivo* validation is not consistently included in the published studies of new technologies for hydration assessment. Comparison against standardized methods such as P_{osm} or weight changes is required to validate the proposed techniques. Studies that report *in vivo* validation typically include small sample sizes, and confirmatory studies by investigators other than the developers have not been performed. This makes assessment of validity, reliability, and sensitivity to change difficult, if not impossible.

Given that the primary objective of hydration assessment is to detect dehydration early and prior to the onset of significant health effects, the measurement resolution of emerging techniques should be identified in future work. This is defined as the smallest degree of dehydration which can be detected. As noted, useful measurement resolution is 3% or less of TBW [58]. Loss of 3% of TBW ($\sim$2% of total body weight) generally marks the onset of performance impairment in healthy adults [33]. However, certain populations may be impacted with much less than 3% loss in TBW, for instance older adults and individuals with medical conditions. The population group should, therefore, be considered when defining a useful measurement resolution for a technique. Measurement resolution should be defined at a point prior to the onset of health effects.

Consideration of the test population is an important factor for establishing validity. For example, a number of the identified techniques were first validated in younger athletes with acute changes in hydration in controlled environments. However, whether these methods can be used to assess hydration status in other populations where changes develop more gradually remains unclear. We identified four at-risk populations where hydration assessment is of importance. Different physiological processes, rates of hydration change, and ambient environmental conditions are present in each group. In initial validation studies done on athletes, the laboratory testing environments

TABLE II
COMPARISON OF THE IDENTIFIED EMERGING METHODS OF HYDRATION ASSESSMENT

	Technique	Physiological parameter	Validation method†	Advantages	Disadvantages
Visual and Optical	Visual capillary refill time assessment [122]	Capillary refill time	1	Potentially portable	Operator training required Only validated in severely dehydrated (>5%) children
	Visual skin elasticity assessment [123]	Skin turgor	2	Portable	Operator training required Poor physiological parameter
	Wrist optical speckle pattern [124]	Muscle weakness	2	Potentially portable, simple	Poor physiological parameter
	Near infrared spectroscopy [125]–[129]	Skin water content	3	Potentially portable	Poor physiological parameter
Electromagnetic	Resonant cavity perturbation [135]–[137]	Total body water	1	Robust physiological parameter	Operator training required Non-portable (very bulky)
	Radio frequency absorption [138]	Tissue water content	1	Potentially portable	Limited physiological interpretation
	Microwave patch antenna [139]	Skin water content	3	Potentially portable	Poor physiological parameter
	Open-ended coaxial probe [140]	Skin and subcutaneous fat water content	2	Portable	Poor physiological parameter
	Impedimetric sensor [141]	Skin water content	3	Wearable, simple	Poor physiological parameter
	Galvanic coupling [142]	Tissue water content	1	Potentially portable Measurement resolution	Sensitive to positioning
Chemical	RFID sweat electrolytes [144]	Sweat electrolyte concentration	3	Wearable, simple, inexpensive (est. $6)	Poor physiological parameter
	Perspiration analysis [147]	Sweat metabolites and electrolytes	2	Wearable, simple	Poor physiological parameter
	Saliva protein analysis [149]	Saliva flow rate, protein, osmolality	1	Strong validation, sensitive to salt- and water-loss dehydration	Professional training required, non-portable
	Saliva EPM [153], [154]	Saliva osmolality	2	Wearable	Poor physiological parameter
	Micro-osmometer [155]	Plasma osmolality	1	Robust physiological parameter	Non-portable, invasive
	Osmotic pressure sensor [157]	Biological fluid osmolality	3	Wearable	Not real-time, unsuitable for continued use
Acoustical	Ultrasound velocity assessment [158], [159]	Tissue water content	1	Potentially portable, validated in younger/older adults	Sensitive to temperature and positioning

†Numerical scale used for validation method:
1 = In humans and compared with $P_{\rm osm}$ or weight change.
2 = In humans and compared with other hydration indices.
3 = Not validated in humans in comparison with other hydration indices.

often control for parameters that would not be possible to control in the real world. Armstrong argues that outside of laboratory settings, fluid compartments can fluctuate so much that a single measurement is insufficient to evaluate hydration status [96]. This suggests that relying on a single indicator may not be appropriate outside of laboratory conditions. Emerging techniques should therefore be assessed in the settings where the intended target population groups are found in order to account for real-world scenarios.

Insight into reliability and sensitivity to change can be obtained by considering variation of the hydration status indicator, specifically between-subject (CVb) and within-subject (CVw) variation. Low CVb allows for the determination of dehydration thresholds for different populations, where a single measurement can be used to assess hydration status. For instance, $P_{\rm osm}$ uses thresholds defining hydration status (i.e., >290 mOsm/kg). In contrast, high CVb requires the use of serial measurements to isolate changes in an individual's hydration status. An example of this is monitoring changes in weight, since baseline weights vary greatly between individuals. Serial measurements of the same individual would be required to detect changes from a baseline weight. Repeated measurements under similar conditions can be used to quantify variation due to noise or bias in the measurement system (e.g., impact of patient positioning and other operator characteristics).

Additional considerations when assessing emerging techniques include invasiveness, cost, and ability to distinguish between water- and salt-loss dehydration. Many of the identified techniques are either noninvasive or rely on very small amounts of bodily fluid. These are desirable traits. The cost of each technique is currently difficult to assess but will be an important factor in determining the scale of adoption. Many of the studies also do not identify whether the technology can differentiate between water- or salt-loss dehydration. Cheuvront argues that this is the single most important aspect of hydration assessment, as it determines whether treatment should be with either hyper- or hypo-osmotic fluid replacement [9].

We recommend that the following next steps be taken in evaluating novel approaches to assessing hydration status before clinical and/or consumer adoption is considered.

1) Perform human validation studies with the intended target population group in realistic environments.
2) Validate the method against standardized methodologies such as acute weight changes or plasma osmolality. This will strengthen the validation study and allow for the comparison of emerging techniques.
3) Identify the technique's measurement resolution and its ability to differentiate between salt- and water-loss dehydration.
4) Identify sources of variation in the measurement system and population groups in order to determine if single or serial measurements will be required.

VI. Conclusion

A review of the present approaches to assessing hydration status leads to the conclusion that there is a need for more accurate, reliable, and practical ways of assessing this important variable. New technology should focus on rapid and accurate monitoring that can be performed in the "real world." Current methods are either impractical for use outside of a laboratory setting or not sufficiently accurate. Research into hydration monitoring technology is promising, but has yet to yield a definitive solution. Further investigation into the quantitative relationship between hydration and potential indicators, such as dielectric properties or saliva osmolality, is warranted. Ideally, a novel device allowing for simple, accurate, real-time hydration monitoring would detect issues earlier and decrease the risk of dehydration-related morbidity among at-risk populations. Such a device would be capable of warning individuals of impending dehydration prior to serious health consequences and the need for aggressive and intrusive interventions.

Acknowledgment

The authors would like to thank Dr. A. Eldamak for her helpful insight and discussions and H. Ganshorn for her guidance in the literature search.

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